CONVR 2016 Hong Kong

Proceedings of the 16th International Conference on Construction Applications of Virtual Reality

11-13 / DEC
HONG KONG

香港科技大學
THE HONG KONG UNIVERSITY OF SCIENCE AND TECHNOLOGY

www.convr2016.com

CONVR 2016

Proceedings of the 16th International Conference on Construction Applications of Virtual Reality

11-13 December 2016, Hong Kong

Editors

Jack C.P. Cheng

The Hong Kong University of Science and Technology, HK

Nashwan Dawood

Teesside University, UK

JS Kuang

The Hong Kong University of Science and Technology, HK

ISBN 978-988-14032-6-1

Published at the Hong Kong University of Science and Technology, Hong Kong, by the Hong Kong University of Science and Technology.

Organizing Committee

Jack C.P. Cheng (Chair), The Hong Kong University of Science and Technology, HK

Nashwan Dawood (Co-Chair), Teesside University, UK

JS Kuang (Co-Chair), The Hong Kong University of Science and Technology, HK

Xueqing Eric Zhang, The Hong Kong University of Science and Technology, HK

Jerry Qian Wang (Conference Secretariat), The Hong Kong University of Science and Technology, HK

Jongsung Won (Conference Secretariat), The Hong Kong University of Science and Technology, HK

Mohit Mangal (Webmaster), The Hong Kong University of Science and Technology, HK

Vincent Jielong Gan (Registration), The Hong Kong University of Science and Technology, HK

Yi Tan (Resource), The Hong Kong University of Science and Technology, HK

Mandy Lam (Venue and Logistics), The Hong Kong University of Science and Technology, HK

Scientific Committee

Simaan Abourizk, University of Alberta, Canada
Changbum Ahn, University of Nebraska-Lincoln, USA
Robert Amor, University of Auckland, New Zealand
Ioannis Brilakis, University of Cambridge, UK
Eugene Ch'Ng, The University of Nottingham, China
Tracey Crosbie, Teesside University, UK
Hiroshige Dan, Kansai University, Japan
Huda Dawood, Teesside University, UK
Yichuan Deng, South China University of Technology, China
Mani Golparvar-Fard, University of Illinois at Urbana-Champaign, USA
Tomohiro Fukuda, Osaka University, Japan
Helen Giggins, The University of Newcastle, Australia
Ning Gu, The University of Newcastle, Australia
Youngjib Ham, Florida International University, USA
Amin Hammad, Concordia University, Canada
Sebastian Hollermann, Bauhaus University Weimar, Germany
Ali Ghaffarian Hoseini, Auckland University of Technology
Lei Hou, Griffith University, Australia
Shang-Hsien Patrick Hsieh, National Taiwan University, Taiwan
Yo-Ming Hsieh, National Taiwan University of Science and Technology, Taiwan
Shih-Chung Jessy Kang, National Taiwan University, Taiwan
Mohamad Kassem, Northumbria University, UK
Hiam Khoury, American University of Beirut, Lebanon
Christian Koch, The University of Nottingham, UK
Bimal Kumar, Glasgow Caledonian University, UK
Ghang Lee, Yonsei University, South Korea
Sang Hyun Lee, University of Michigan, Ann-Arbor, USA
Fernanda Leite, The University of Texas at Austin, USA
Heng Li, Hong Kong Polytechnic University, Hong Kong
Koji Makanae, Miyagi University, Japan
Juergen Melzner, Bauhaus University Weimar, Germany
Ivan Mutis, Illinois Institute of Technology, USA
Samad Sepasgozar, University of New South Wales, Australia

Willy Sher, The University of Newcastle, Australia
Ming-Fung Francis Siu, University of Alberta, Canada
Souheil Soubra, CSTB, France
Paul Stephenson, Sheffield Hallam University, UK
Ping Bo Tang, Arizona State University, USA
Sergio Rodriguez Trejo, Teesside University, UK
Menghan Tsai, National Taiwan University, Taiwan
Vladimir Vukovic, Teesside University, UK
Nobuyoshi Yabuki, Osaka University, Japan
Yoshihiro Yasumuro, Kansai University, Japan
Zhenhua Zhu, Concordia University, Canada

Foreword

Our warmest welcome to all of you who are engaged in the 16th International Conference on Construction Applications of Virtual Reality (CONVR 2016), which is jointly organized by the Hong Kong University of Science and Technology and Teesside University on 11-13 December 2016 in Hong Kong. The mission of the conference is to develop a research community that together can collaborate and develop research in the areas of construction virtual reality (VR), visualization technologies, Building Information Modeling (BIM), and others. For the last 15 years, CONVR has been organized in America, Europe, Asia, Middle East and the Far East, and has been credited with developing research and innovation in construction VR that has direct values and benefits to the built environment sector around the world.

This year CONVR is very special, as we have many of the best international researchers presenting their cutting edge projects from more than 20 countries. In addition, the conference is being held in wonderful Hong Kong, where the advancements of all aspects of visualization technologies are embedded in every aspect of construction processes. The conference has a unique blend of participants from both academia and industry. The conference provides a good platform to exchange ideas and best practices in the built environment sector, stemming from innovative research activities in the areas of BIM and visualization technologies. We believe that you would find the topics in the conference informative and insightful.

Prof. Jack C.P. Cheng
Conference Chair
The Hong Kong University of Science and Technology, HK

Prof. Nashwan Dawood
Conference Co-Chair
Teesside University, UK

Prof. JS Kuang
Conference Co-Chair
The Hong Kong University of Science and Technology, HK

Sponsors and Supporting Organizations

Acknowledgement

Diamond Sponsor

Gold Sponsor

Silver Sponsors

Backdrop Sponsor

Supporting Organizations

TABLE OF CONTENTS

ORGANIZING COMMITTEE I

SCIENTIFIC COMMITTEE II

FOREWORD IV

SPONSORS AND SUPPORTING ORGANIZATIONS V

KEYNOTE SPEECH I: BIM IN HONG KONG: WHAT IS YOUR CONTRIBUTION? 1

MS. ADA FUNG (HONG KONG HOUSING AUTHORITY, HONG KONG)

KEYNOTE SPEECH II: APPLICATIONS OF COMPUTING AND AI IN ENGINEERING 2

PROF. KINCHO H. LAW (STANFORD UNIVERSITY, USA)

KEYNOTE SPEECH III (DIAMOND-SPONSORED): BIM IMPLEMENTATION IN MAINLAND AND HK: SIMILARITY & DIFFERENCE 3

IR FRANCIS LEUNG (NEW WORLD CONSTRUCTION COMPANY LIMITED, HONG KONG)

KEYNOTE SPEECH IV: BIM AND IT IN CONSTRUCTION - THE RESEARCH AND PRACTICE GAP 4

PROF. LUCIO SOIBELMAN (UNIVERSITY OF SOUTHERN CALIFORNIA, USA)

KEYNOTE SPEECH V: BUILDING BIM CAPABILITY IN SINGAPORE 5

MR. TAI FATT CHENG (BUILDING AND CONSTRUCTION AUTHORITY, SINGAPORE)

KEYNOTE SPEECH VI: CYBER-PHYSICAL SYSTEMS IN CONSTRUCTION - DEVELOPMENT LESSONS AND FUTURE DIRECTIONS 6

PROF. CHIMAY J. ANUMBA (UNIVERSITY OF FLORIDA, USA)

KEYNOTE SPEECH VII: TOWARDS SMART INDUSTRY IN CONSTRUCTION: A PATHWAY OF CONVERGING RESEARCH 7

PROF. XIANGYU WANG (CURTIN UNIVERSITY, AUSTRALIA)

KEYNOTE SPEECH VIII: GLOBAL VDC ADOPTION - INSIGHTS INTO BEST PRACTICES AND CHALLENGES 8

PROF. CALVIN KAM (STANFORD UNIVERSITY, USA)

KEYNOTE SPEECH IX: IMPLEMENTING INTELLIGENT SEMANTIC ENRICHMENT - THE SEEBRIDGE PROJECT 9

PROF. RAFAEL SACKS (ISRAEL INSTITUTE OF TECHNOLOGY, ISRAEL)

KEYNOTE SPEECH X: INTEGRATED MANAGEMENT OF BIM DESIGN AND CONSTRUCTION IN MAINLAND CHINA 10

MR. JIAZHI KUANG (CHINA CONSTRUCTION DESIGN INTERNATIONAL, CHINA)

KEYNOTE SPEECH XI: BIM TECHNOLOGY ENABLED SMART AIRPORT DESIGN AND VR APPLICATIONS IN THIRD RUNWAY DEVELOPMENT 11

IR KEVIN POOLE (HONG KONG AIRPORT AUTHORITY, HONG KONG)

PART I: BIM ADOPTION AND PROJECT MANAGEMENT 12

A TOOL FOR ASSESSING THE COMPLIANCE OF PROJECT ACTIVITIES AND DELIVERABLES AGAINST THE REQUIREMENTS OF BIM LEVEL 2 POLICY DOCUMENTS 13

Mohamad Kassem, Mohamadreza Jenaban, David Craggs and Nashwan Dawood

BIM PERFORMANCE ASSESSMENTS AND ITS APPLICATION IN INDIAN AECO INDUSTRY – A CASE STUDY 26

Amarnath Chegu Badrinath, Shang-Hsien Hsieh and Niranjan Kumar

RISK INFORMATION BASED EXPERT SYSTEM - A PARTICIPATORY MODEL 39

Priyadarshini Das and Gangadhar Mahesh

INVESTIGATING THE RELATIONSHIP BETWEEN BIM ADOPTION AND TECHNICAL CONDITIONS OF CONSTRUCTION COMPANIES: CHINESE PRACTICE.............................. 53

Ying Hong, Samad Sepasgozar and Ali Akbarnezhad

EVOKING MALAYSIAN ARCHITECTURE CULTURAL IDENTITY THROUGH DEVELOPMENT OF PARAMETRIC BIM 67

Maisarah Ali, Norwina Mohd Nawawi, Puteri Shireen Jahnkassim, Nashwan Dawood and Saiful Nizam Mohd

BIM: A DISRUPTIVE PROCESS TOWARDS TRADITIONAL PRACTICE 80

Ahmad Mohammad Ahmad., Mian Atif Hafeez., Ahmad Muhammad Ahmad., Abdullahi Adamu Aliyu., Sergio Rodriguez and Nashwan Dawood

PART II: BIM FOR DESIGN, MANUFACTURING AND FM 94

BIM FOR MANUFACTURING: A CASE STUDY DEMONSTRATING BENEFITS AND WORKFLOWS AND AN APPROACH FOR ENTERPRISE APPLICATION INTEGRATION (EAI).. 95

Kin Ma, Nashwan Dawood and Mohamad Kassem

SUPPORTING BUILDING OWNERS AND FACILITY MANAGERS IN THE VISUALISATION OF AN INTEGRATED ASSET INFORMATION MODEL (AIM) BASED ON OPEN STANDARDS 110

Joao Patacas, Nashwan Dawood and Mohamad Kassem

STRATEGIC DAYLIGHT VISUALIZATION FOR THE GREEN BUILDING PROCESS: INTEGRATING OPTIMIZATION INTO AN AIRPORT TERMINAL DESIGN WITH SKYLIGHTS... 124

Siti Norzaini Zainal Abidin and Puteri Shireen Jahnkassim

CAN EXPERIENCE OVERCOME THE COGNITIVE CHALLENGES IN DRAWING-BASED DESIGN REVIEW? — DESIGN REVIEW EXPERIMENTS 144

Ghang Lee, Jaehyuk Park, Jongsung Won, Harrison Kwangho Park, Miyoung Uhm and Yunho Lee

AN AUTOMATIC SIMULATION SYSTEM FOR BUILDING INFORMATION AND ENERGY-SAVING DESIGN MODELING 157

Po-Han Chen, Chi-Feng Hua, Po-Chuan Chuang and Thanh-Chuong Nguyen

DESIGN CHANGE MANAGEMENT IN CONSTRUCTION PROJECTS BASED ON BUILDING INFORMATION MODELING 168

Valeh Moayeri, Osama Moselhi and Zhenhua Zhu

A BIM-BASED FACILITY MANAGEMENT FRAMEWORK FOR AUTOMATIC SCHEDULING OF MAINTENANCE WORK ORDERS... 180

Weiwei Chen, Keyu Chen and Jack C. P. Cheng

PART III: BIM, GIS AND URBAN COMPUTING.. 192

THE INTEGRATED SLOPLAND CONSERVATION AND DISASTER PREVENTION

MANAGEMENT SYSTEM, TAIWAN 193

Kuei-Lin Fu, Yu-Te Chou, Shih-Chung Kang, Meng-Han Tsai and Kun-Che Chen

NEAR-ROAD ENVIRONMENT SENSITIVITY ANALYSIS FOR HEAVY VEHICLE FREIGHT TRANSPORTATION BY BIM AND GIS INTERGRATION SYSTEM 205

Yongze Song, Xin Liu, Xiangyu Wang, Yi Tan and Jack C.P. Cheng

BUILDING POLYGON RECTIFICATION FOR AUTOMATIC GENERATION OF 3D BUILDING MODELS 213

Kenichi Sugihara and Takahiro Murase

MODELING URBAN TECHNOLOGY ACCEPTANCE: FACTOR ANALYSIS APPROACH .. 225

Sharifeh Sargolzaei, Samad M.E. Sepasgozar and Mohammad Mojtahedi

BIM AND GIS INTEGRATION: AN INVESTIGATION ON ITS SCOPE IN THE U.A.E.......... 237

Amreen Nizam, Nithin Thomas, Dr Yasemin Nielsen and Dr Hagir Hakim

SUSTAINABLE SMART CITIES: EVALUATION OF AUSTRALIAN PRACTICE 251

Fahim Ullah, Samad M.E. Sepasgozar and Muhammad Jamaluddin Thaheem

PART IV: BIM, VR AND AR FOR CONSTRUCTION AND SAFETY 268

INTEGRATING AUGMENTED REALITY AND BUILDING INFORMATION MODELLING TO FACILITATE CONSTRUCTION SITE COORDINATION.. 269

Ali Ghaffarianhoseini, Dat Tien Doan, Tongrui Zhang, Attiq Ur Rehman, Amirhosein Ghaffarianhoseini, Nicola Naismith, John Tookey, James Rotimi, Mahdiar Ghaffarianhoseini, Tianming Yu, Zhentao Mu and Yicao Qi

VIRTUAL COLLABORATIVE SAFETY TRAINING FOR CRANE OPERATIONS 284

Isik Ates Kiral, Semra Comu, Jiayu Chen and John E. Taylor

AUGMENTED REALITY BY DEPTH CAMERA FOR IMAGE-BASED PIPELINE INSPECTION 296

Takuma Yorimitsu, Hiroshige Dan, Akira Kobayashi and Yoshihiro Yasumuro

A STUDY OF ‘SITE BIM’ IMPACT ON HEALTH AND SAFETY IN CONSTRUCTION SITES 306

Raj Shah and Joel Edwards

REAL-TIME VISUALIZATION OF CRANE LIFTING OPERATION IN VIRTUAL REALITY.. 318

Yihai Fang and Yong Cho

CUT/FILL OPTIMISATION UNDERPINNED BY BIM IN LANDSCAPE SITE REALISATION PROCESS: A CASE STUDY.. 327

Huda Dawood, Nashwan Dawood, Shang-Hsien Hsieh and Yi-Wen Chen

INVESTIGATING THE USE OF BIM MODELS FOR BIM WORK STREAMS IN TRADITIONAL CONSTRUCTION CONTRACTING IN QATAR 338

Ahmad Mohammad Ahmad, Mian Atif Hafeez, Sergio Rodriguez, Vladmir Vukovic, Khalid Naji and Nashwan Dawood

A WEB-BASED CONSTRUCTION SITE RISK EVALUATION AND IFC-BASED PRESENTATION SYSTEM 351

Yo-Ming Hsieh, Shih-Hui Chang and Mao-Sheng Tsa

THE SYSTEM DEVELOPMENT AND APPLICATION SCENARIOS OF AN ON-SITE BIM VIEWER BASED ON AUGMENTED REALITY AND INDOOR POSITIONING 362

Hung-Ming Chen and Hong-Dao Lin

A CONCEPTUAL WORKFLOW FOR BIM BASED PREFABRICATION DESIGN VISUALIZATION WITH AUGMENTED REALITY 376

Shu Tang, Llewellyn Tang, Zhuoqian Wu, Weiqing Zheng and Chao Chen

IDENTIFYING CONSTRUCTION RISK SOURCES BY VIRTUAL ENVIRONMENTS.......... 385

Cem Sebzeci, Semra Comu and Isik Ates Kiral

BIM TO MITIGATE HEALTH AND SAFETY RISKS IN THE CONSTRUCTION AND MAINTENANCE OF INFRASTRUCTURE 397

Mohammed Muzafar and Darshan Ruikar

BIM-BASED SMART FACILITY MANAGEMENT VIRTUAL REALITY VIA INDOOR LOCALIZATION TECHNOLOGY... 410

Rui Liu, Yishuai Cao and Xiaolin Li

PART V: BIG DATA AND IT IN CONSTRUCTION 419

LABOR SENTIMENT ANALYSIS FOR THE CONSTRUCTION INDUSTRY: A CASE STUDY OF TWITTER IN THE USA 420

Liyaning Tang, Yiming Zhang, Fei Dai, Yoojung Yoon Yangqiu Song and Radhey S. Sharma

REAL-TIME SIMULATION OF CONSTRUCTION WORKER USING HUMAN BODY AND HAND TRACKING FOR ROBOTIC CONSTRUCTION WORKER SYSTEM.......................... 434

Manoj Kurien, Min-Koo Kim and Ioannis Brilakis

THE ENERGY PERFORMANCE ANALYSIS OF RESIDENTIAL BUILDINGS IN SAUDI ARABIA... 444

Ahmad Alkanani, Nashwan Dawood and Mohamad Kassem

DYNAMIC MODELLING OF CRANES AND CONCRETE PUMPS DIFFUSION IN THE CONSTRUCTION INDUSTRY 459

Samad Sepasgozar and Perry Forsythe

SURVEY OF THE RESEARCH OF ICT APPLICATIONS IN THE AEC INDUSTRY: A VIEW FROM TWO MAINSTREAM JOURNALS 471

Huaquan Ying and Sanghoon Lee

INTELLIGENT EMERGENCY EXIT SIGNAGE GUIDANCE SYSTEM FRAMEWORK FOR REAL-TIME EMERGENCY EVACUATION... 484

Jun Zhang and Raymond Issa

PART VI: COMPUTER VISION AND UAV 494

USING A UAV FOR A DEBRIS FAN DIGITAL TERRAIN MODEL RECONSTRUCTION: A CASE STUDY OF THE PU-TUN-PU-NAS DEBRIS FAN... 495

Cheng-Hsuan Yang, Te-Chu Liu, Er-Xuan Sung and Shih-Chung Kang

A VISION-BASED APPROACH FOR SCAFFOLDING MONITORING.................................... 506

Jian Chai, Changzhi Wu, Hung-Lin Chi, Lei Hou, Jun Wang and Xiangyu Wang

UNMANNED AERIAL VEHICLE PATH PLANNING FOR ALLUVIAL FAN DIGITAL TERRAIN MODEL RECONSTRUCTION... 514

Cheng-Hsuan Yang, Ci-Jyun Liang and Shih-Chung Kang

A UAV-BASED IMAGE PROCESSING SYSTEM FOR IDENTIFYING AND VISUALIZING CONSTRUCTION HAZARDOUS AREAS... 521

Bahaa Eddine Mneymneh, Mohamad Abbas and Hiam Khoury

THE TRAFFIC WARNING SYSTEM FOR CROSSROADS ON CONSTRUCTION SITE BASED ON COMPUTER VISION 532

Lingjing Liu, Xiaorong Zhang, Tongtong Li, Sheng Xu, Jun Wang, Dianchen Zhu, Hongyang Li and Yichuan Deng

NOVEL OCCUPANCY SENSING IN LIVING SPACES – EVALUATION OF APPROACHES USING HUMAN MOTION ANALYSIS TECHNIQUES AND THEIR EXTENSIONS 546

Arun Rajagopalan and Ivan Mutis

PART VII: DATA VISUALIZATION AND VR 559

BIM BASED VIRTUAL REALITY ENVIRONMENT FOR ENERGY CONSUMING BY END-USERS 560

Zhuoqian Wu, Llewellyn Tang, Eugene Ch'Ng, Shu Tang, Weiqing Zheng and Chao Chen

DEVELOPMENT OF A SIMPLIFIED ACOUSTIC VISUALIZATION SYSTEM USING KINECT SENSORS 570

Ryo Yamasaki, Nobuyoshi Yabuki, Tomohiro Fukuda and Ali Motamedi

IMMERSIVE VIRTUAL ENVIRONMENT AS AN APPARATUS FOR OCCUPANT BEHAVIOR STUDIES 581

Sanaz Saeidi, Yimin Zhu, Joon-Ho Choi, Chen Zhong and Qi Wang

VIRAPH: ENHANCING ARCHITECTURAL DESIGN VISUALIZATION WITH RESULTS OF VISIBILITY GRAPH ANALYSIS 593

Peiman Amini Behbahani, Ning Gu and Michael Ostwald

INTEGRATING BUILDING INFORMATION MODELING AND GAME ENGINE FOR INDOOR LIGHTING VISUALIZATION 605

Worawan Natephra, Ali Motamedi, Tomohiro Fukuda and Nobuyoshi Yabuki

APPLICATION OF REAL-TIME VIRTUAL REALITY STREAMING MOBILE DEVICES FOR INTEGRATED PROJECT DELIVERY 619

Ali Ghaffarianhoseini, Tongrui Zhang, Kai Wang, Dat Tien Doan, Attiq Ur Rehman, Fukun Ruan, Amirhosein Ghaffarianhoseini, Nicola Naismith, John Tookey, James Rotimi, Keyu Chen, Guoyong Wang, Wange Zhang, Bobing Li, Tianming Yu, Zhentao Mu and Yicao Qi

PART VIII: LASER SCANNING AND PHOTOGRAMMETRY 630

SEMI-AUTOMATIC CORRELATION FOR INTEGRATING DATA PRODUCED BY LASER SCANNING AND SFM 631

Kazuki Fujisato, Hiroshige Dan, Akira Kobayashi and Yoshihiro Yasumuro

REALITY CAPTURE FOR BIM – APPLICATION, EVALUATION AND INTEGRATION WITHIN AN ARCHITECTURAL PLAN OF WORKS 641

Michael Crilly, David Craggs and Nashwan Dawood

DIMENSIONAL QUALITY ASSESSMENT OF CONCRETE SLABS USING 3D LASER SCAN POINT CLOUDS 663

Nisha Puri and Yelda Turkan

POLYGONIZATION OF POINT CLOUD OF ELONGATED CIVIL INFRASTRUCTURES USING LOFTING OPERATION 677

Nao Hidaka, Takashi Michikawa, Ali Motamedi, Nobuyoshi Yabuki and Tomohiro Fukuda

POST-DEMOLITION LANDSCAPE ASSESSMENT USING PHOTOGRAMMETRY-BASED DIMINISHED REALITY (DR) 689

Kazuya Inoue, Tomohiro Fukuda, Nobuyoshi Yabuki, Ali Motamedi and Takashi Michikawa

AUTOMATIC REGISTRATION OF LASER SCANNED COLOR POINT CLOUDS BASED ON COMMON FEATURE EXTRACTION.. 700

Pileun Kim, Yong K. Cho and Jingdao Chen

KEYNOTE SPEECH I: BIM in Hong Kong: What is Your Contribution?

Ms. Ada Fung, BBS, JP, Deputy Director of Housing (Development & Construction), Hong Kong Housing Authority, Hong Kong

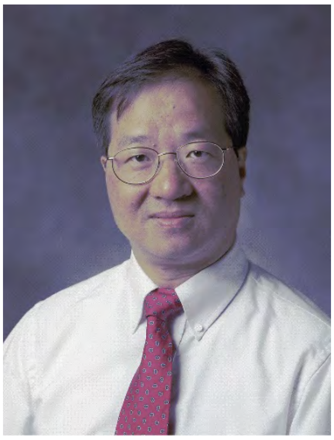
Chairperson, CIC's Committee on Construction Safety

ABSTRACT: Building Information Modelling (BIM) is a term that has become ubiquitous in the construction field in the past two decades, with significant development in many parts of the world including the United States, United Kingdom, European Union, Middle East, Singapore and China. Hong Kong has in the past, played an important part of global BIM development. With the Construction Industry Council's (CIC) Working Group on Roadmap for BIM Implementation acting as a coordinator and anchor to steer and drive BIM development in Hong Kong, we have been moving ahead steadily in the past years. It is encouraging to see that a great momentum has been gathered in recent years, both from the private and public sector.

Building on this momentum, it is imperative that we must handle BIM development in Hong Kong carefully in the coming years. We are at a very critical stage where strategic planning is required and contribution by all stake-holder is vital. In this presentation, I will share my thoughts on what are the key focus areas and how we may all contribute to shape the future of BIM development in Hong Kong.

BIOGRAPHY: Ms. Ada Fung, JP is the Deputy Director of Housing serving the Hong Kong Housing Authority. She supervises the Development & Construction Division of the Housing Department, overseeing all facets of work covering project management, planning, design and contract management, as well as establishing operational policies on procurement, design, construction, quality, performance assessment, dispute resolution, research and development, safety and the environment for public housing development in Hong Kong. She is the Chairperson of the Working Group on Roadmap for BIM Implementation at Hong Kong Construction Industry Council (CIC). She is an active member in the architectural field as well as in the construction industry in Hong Kong. She is Chairperson of CIC's Committee on Construction Safety, Chairperson of the APEC Architect Monitoring Committee of Hong Kong (2012 – 2016), one of the directors of the Hong Kong Green Building Council, past Chairperson of the Architects Registration Board (2010 – 2011), Immediate President of the Hong Kong Institute of Architects (2013 – 2014).

KEYNOTE SPEECH II: Applications of Computing and AI in Engineering



Prof. Kincho H. Law, Ph.D., M.S., B.S., B.A.

Professor, Civil and Environmental Engineering, Engineering Informatics Group, Stanford University, USA

ABSTRACT: Civil and construction Engineering has had a long and successful history in adopting computing technologies, from computer graphics, CAD, engineering analyses, virtual simulations, to project management. As technologies continue to advance, there are many new opportunities that can take advantage of information science and computing technologies in engineering. Technologies such as building information modeling, virtual reality, high definition images, sensors, etc., are now widely deployed in the civil and construction engineering industry. This presentation will provide an overview of current trends of computing technologies in the AEC domain. Recent years have also seen the re-emergence of artificial intelligence (AI) applications. This presentation will attempt to discuss some of the potential applications of AI in engineering.

BIOGRAPHY: Professor Kincho H. LAW is currently a Professor of Civil and Environmental Engineering at Stanford University. His research has been focused on computing, information and communication technologies in engineering. He has published over 400 articles in journals and conference proceedings. He was the recipient of the ASCE Computing in Civil Engineering Award in 2011. He has received a number Best Paper Awards, including ASME Manufacturing Science and Engineering Conference in 2015, ASCE Journal of Computing in Civil Engineering in 2014, ASCE International Workshop on Computing in Civil Engineering in 2013, and the 6th and the 4th International Conference on Electronic Governance (ICEGOV) in 2012 and 2010, respectively. He acts as Editorial Board Member of Journal of Engineering with Computers, International e-Journal on IT in Construction (ITCON), Journal on Advances in Engineering Software, and ASTM Journal on Smart and Sustainable Manufacturing Systems. He has also served as an Associate Editor of ASME Journal of Computing Information and Science in Engineering and a Senior Specialty Editor of ASCE Journal of Computing in Civil Engineering.

KEYNOTE SPEECH III (Diamond-Sponsored): BIM Implementation in Mainland and HK: Similarity & Difference

Ir Francis Leung, Founding Chairman, The Hong Kong Institute of Building Information Modelling, Hong Kong

Associate Director, New World Construction Company

ABSTRACT: Building Information Modelling (BIM) has been rapidly developing in the worldwide arena in the recent years. Although the principles of BIM are commonly agreeable in different countries, the ways of BIM implementation are quite diversified. Simply from our experience in New World, the objectives and demands for BIM are not exactly the same between that in HK and Mainland projects although there are also similarities. For example, in HK, we have in house Main Contractor (MC) such that the MC can participate in the design stage for the earliest access to the information. BIM is then the best tool to manage building information. In Mainland, BIM is handled by MC focused on the development of shop drawings for complex items such as facade for fancy building form and combined services for building services. In the keynote, similarities and differences in the BIM implementation in Mainland and HK will be elaborated. Audience may take reference to the cases where they have similar situation.

BIOGRAPHY: Ir Francis Leung is the Founding Chairman of The Hong Kong Institute of Building Information Modelling. He is a Fellow Member of The Hong Kong Institution of Engineers, Registered Structural Engineer. Ir Leung has been developing BIM from an engineering consultant perspective and now in an enterprise approach. In New World, a BIM team is established for the BIM modelling and information management as well as the development of BIM Standards and Workflow.

KEYNOTE SPEECH IV: BIM and IT in Construction - The Research and Practice Gap

Prof. Lucio Soibelman, Ph.D., M.S., B.S.

Professor and Chair, Sonny Astani Department of Civil and Environmental Engineering, University of Southern California, USA

ABSTRACT: It is certainly no surprise that BIM implementation varies a lot from company to company and from country to country. During his talk Professor Soibelman will first discuss BIM practice and implementation issues by introducing case studies from the US and from Brazil. He will present use cases of BIM to support better understanding of BIM benefits at all phases of facilities life cycle (design, construction, and operations) evaluating the value of BIM deployment to all stakeholders.

After that Professor Soibelman will focus more on BIM research opportunities by introducing, as example, results obtained from several studies developed by his research group. He will present a study that developed methods for integrating unstructured text documents and pictures in A/E/C model based systems. In this study, automated processes for retrieval, classification, and integration of unstructured documents in A/E/C model based systems were explored. Specifically, a combination of techniques from the areas of information retrieval, text mining, image reasoning, and computer vision were analyzed to develop visual interfaces that allow the identification of documents/pictures relevant to each component of the project model. Finally he will discuss the influence of BIM application on research developments for 3D as-build models creation, virtual reality, robotics, and additive manufacturing in construction.

BIOGRAPHY: Professor Soibelman obtained his PhD in Civil Engineering Systems at Massachusetts Institute of Technology (MIT) in 1998. He then started as an Assistant Professor at University of Illinois at Urbana Champaign. In 2004, he moved as an Associate Professor to Carnegie Mellon University (CMU) and in 2004 was promoted to Professor. In 2012, he joined University of Southern California as the Chair of the Sonny Astani Department of Civil and Environmental Engineering. His research areas include advanced data acquisition, management, visualization, and mining for construction and operations of advanced infrastructure systems. He published over 100 books, book chapters, journal papers, conference articles, and reports and performed research with funding from many different funding agencies, such as NSF, NASA, DOE, US Army, NIST, IBM, and RedZone Robotics. He is the current chief editor of the ASCE Computing in Civil Engineering Journal. He received the ASCE Computing in Civil Engineering Award in 2010 and the 2011 FIATECH Outstanding Researcher Celebration of Engineering & Technology Innovation Award in 2012. In recent years, he has been providing consulting services on BIM implementation in Brazil.

KEYNOTE SPEECH V: Building BIM Capability in Singapore

Mr. Tai Fatt Cheng, Deputy Managing Director, BCAA and BERII, Building and Construction Authority, Singapore

ABSTRACT: Singapore's vision for the construction industry is that of a highly integrated and technologically advanced sector led by progressive firms and supported by a skilled and competent workforce. To this end, BIM/Virtual Design and Construction (VDC) has been touted as one of the key technologies to improve productivity and integration across the value chain.

Even as BCA encourages the industry to adopt new technologies for construction, the built environment sector will also require a higher quality workforce equipped with technology-oriented skills and knowledge. The presentation will share how BCA drives this vision through various programmes and initiatives.

BIOGRAPHY: Mr. Tai Fatt CHENG is currently a Deputy Managing Director of two groups in Building and Construction Authority (BCA), namely BCA Academy and Built Environment Research & Innovation Institute. In BCA Academy, he oversees the various built environment training programmes from tradesman to post-graduate. In the Built Environment Research and Innovation Institute, he is responsible for driving BIM/VDC adoption in the Singapore. He helped to formulate the BIM roadmap and is tasked to drive the wide adoption of BIM across the industry to improve construction productivity. He was directly involved in the development and implementation of CORENET e-Submission system in Singapore. He is also an active member of buildingSMART Singapore Chapter.

KEYNOTE SPEECH VI: Cyber-Physical Systems in Construction - Development Lessons and Future Directions

Prof. Chimay J. Anumba, FREng, Ph.D., D.Sc., Dr.h.c. , CEng/PE , FICE , FIStructE , FASCE

Dean, College of Design, Construction and Planning, University of Florida, USA

ABSTRACT: Cyber-physical systems (CPS) enable the synergistic integration of virtual models and the physical environment and are now being increasingly recognized as vital for improved construction project information management, more efficient project delivery, and enhanced facilities management. A critical aspect of the deployment of CPS in construction is ensuring bi-directional coordination between the physical components and their virtual representations. This presentation will draw on examples from research prototypes to highlight the key features and benefits of these systems, and the steps involved in their development. The lessons learned from developing a variety of systems for various stages of a constructed facility's lifecycle will also be outlined. Following this, the future directions for CPS in construction will be discussed.

BIOGRAPHY: Professor Chimay Anumba is a Fellow of the Royal Academy of Engineering, the United Kingdom's National Academy of Engineering. He holds a Ph.D. in Civil Engineering from the University of Leeds, UK; a higher doctorate – D.Sc. (Doctor of Science) from Loughborough University, UK; and an Honorary Doctorate (Dr.h.c.) from Delft University of Technology in The Netherlands for outstanding scientific contributions to Building and Construction Engineering. His research interests are in the fields of advanced engineering informatics, concurrent engineering, knowledge management, distributed collaboration systems, and intelligent systems. He has over 450 scientific publications in these fields and his work has received support worth over $150m from a variety of sources. He has also supervised more than 45 doctoral graduates and mentored over 20 postdoctoral scholars. He is a Chartered/Professional Engineer and Fellow of the ICE, IStructE and ASCE.

KEYNOTE SPEECH VII: Towards Smart Industry in Construction: a Pathway of Converging Research

Prof. Xiangyu Wang, Ph.D., M.S., B.S.
Curtin-Woodside Chair Professor for Oil, Gas & LNG Construction and Project Management; Curtin Director of Australasian Joint Research Centre for Building Information Modelling (BIM), Department of Construction Management, Curtin University, Australia

ABSTRACT: The world is now in the early stages of the fourth industrial revolution which are bringing together digital and physical systems. Dramatic changes are all around us across all sectors, happening at exponential speed. The vision of tomorrow's construction, as part of the fourth industrial revolution is a highly dynamic, customized and resource-friendly smart industry.

Today's construction processes could become highly integrated and situation-awareness systems with a significant portion of embedded intelligences, where digital systems (e.g., design, information, communication) and physical systems (e.g., machines/equipment, raw materials, labor) are coming together within an "Internet of Everything" and cooperatively drive construction. Physical resources find their way independently through the logistics and construction processes.

To move towards the vision more effectively, inter-disciplinary approaches are not sufficient but a converging way will replace. This keynote presents a pathway of converging research that creates an eco-system which integrates industry and academia together. This partially proved pathway is also further underpinned by enumerating a variety of emerging integrations of new business models, disruptive technologies and innovative management philosophies.

BIOGRAPHY: Professor Wang is currently the College of Experts of ARC (Australian Research Council) and received 2016 nomination for Australian Academy of Technological Science and Engineering (ATSE). Prof. Wang is an internationally recognised leading researcher in the field of Construction IT, BIM, Lean, Productivity, Computational Methods for Engineering, Data Analytics, Visualization Technologies, Megaproject Management, and Training, having obtained over USD $ 10 Million research funds and published over 200 peer-reviewed journal articles. He has presented over 30 keynote and plenary speeches at international research and industrial conferences on BIM, construction and project management. He is currently the Editor-in-Chief of Visualization in Engineering which is an international research journal hosted by Springer-Verlag. His work with Woodside Energy Ltd., Shell Ltd., and other 40 industrial partners, win numerous awards and has dozens of global media exposures.

KEYNOTE SPEECH VIII: Global VDC Adoption - Insights into Best Practices and Challenges

Prof. Calvin Kam, Ph.D., AIA, PE, LEED AP

Director of Industry Programs and Adjunct Professor, Stanford University's Center for Integrated Facility Engineering (CIFE), USA

ABSTRACT: This presentation will build upon global working experiences around the world. BIM-driven groundbreaking pilots, applied research, technical developments, government mandates and standards, and international adoption of open standards and their impacts on business will be shared through first-hand experiences from Dr. Calvin Kam's team, and evaluated through the bimSCORE framework. The applicability of such approaches will provide a dynamic value proposition for researchers and practitioners to strategize and implement.

Furthermore, at Stanford University's Center for Integrated Facility Engineering (CIFE), Dr. Kam's research team is developing key performance indicators (KPIs) for innovative and industrialized construction. Pertaining to KPI, the AECOO industry has adopted pools of metrics measuring broad areas of construction performance. To identify the set of measurements that are most indicative of project performance, Dr. Kam's team is developing a CIFE Performance Dashboard with a live repository of performance indicators. Key indicators are distilled from extensive pools of metrics using statistical algorithms. Recommended indicators will be tracked on projects and the performance dashboard will help track and improve industry and project performances. Dr. Kam's presentation will also cover the roles that the industry can play in the Smart City movement and advice for the industry to better embrace for some potentially disruptive innovations.

BIOGRAPHY: Dr. Calvin Kam is the Founder and CEO of Strategic Building Innovation | bimSCORE—the "GPS Navigator" for construction innovation. He is an Adjunct Professor at Stanford University's Center for Integrated Facility Engineering (CIFE), where he specializes in Virtual Design and Construction (VDC), Smart City Developments, and Management Scorecards. He is the Senior Program Expert and a Co-founder of the National 3D-4D-BIM Program with GSA Public Buildings Service. He is an appointed international BIM expert for Singapore Building Construction Authority, Shanghai Municipal Government's BIM Center, and the only international Honorary Director of the China National BIM Union and Standards. He is serving on the Research Advisory and International Practice Committees of the American Institute of Architects; he was AIA's former National Co-Chairman of AIA Center for Integrated Practice and AIA-TAP Knowledge Community. He was a recipient of various AIA, ASCE, SOM, Stanford University and ENR's "20 under 40" honors/awards.

KEYNOTE SPEECH IX: Implementing Intelligent Semantic Enrichment - the SeeBridge Project

Prof. Rafael Sacks, D.Sc., M.S., B.Sc.

Associate Professor, Civil and Environmental engineering, Israel Institute of Technology, Israel

ABSTRACT: Building Information Modeling is a powerful technology, but transferring information among applications is still limited by the diversity of their internal representation schema. The goal of 'Open BIM' with fully interoperable models remains elusive despite development of the IFC standards. For similar reasons, model-checking and functional simulations using building models is hampered by the need for careful tailoring of the content of model files exported from BIM authoring tools. Semantic enrichment is a novel approach to this problem. It applies expert system technology to interpret and enrich the semantic content of models so that they can be re-used for multiple purposes with minimal rework. The technique will have application in a wide variety of situations. Among those being developed in current research are precast concrete detailing, cost estimation, compilation of as-built models of bridges for bridge surveys, and acquisition of building data for facility maintenance.

Semantic enrichment is a core technology in the SeeBridge project, a multinational research project funded by the EU Infravation Program. A semantic enrichment prototype named SeeBIM 2.0 has been developed and is being applied to aid in compiling building models of highway bridges from point cloud data that can be used for survey and recording of damage to the bridges. This large scale experimental application has yielded important insights into the ways in which rule sets can be compiled rigorously, to ensure that they can accurately classify model components based on feature vectors and topological relationships. It has also contributed deeper understanding of the potential application of semantic enrichment to scan to BIM conversion, which requires classification, naming and numbering, treatment of occlusions, inference of missing components, aggregation of components in systems, and inference of structural support and flow systems. Prof. Sacks' talk will explore the need for semantic enrichment, its technology aspects, the ways in which it can contribute to providing interoperability, and the promise of a more advanced approach. For more information on the SeeBridge project, visit http://seebridge.net.technion.ac.il

BIOGRAPHY: Rafael Sacks' research focuses on the synergies of Building Information Modeling (BIM) and Lean Construction. Research at his Virtual Construction Lab at the Technion includes development of BIM-enabled lean production control systems; innovative approaches to BIM interoperability; BIM systems for earthquake search, rescue and recovery; and design for safety. Prof. Sacks was Head of Structural Engineering and Construction Management in the Faculty of Civil and Environmental Engineering from 2012-2015. He is a co-author of the "BIM Handbook".

KEYNOTE SPEECH X: Integrated Management of BIM Design and Construction in Mainland China

Mr. Jiazhi Kuang, General Manager (Department of Architectural Digitalization and BIM), China Construction Digital International, China

ABSTRACT: Civil and construction Engineering has had a long and successful history in adopting computing technologies, from computer graphics, CAD, engineering analyses, virtual simulations, to project management. As technologies continue to advance, there are many new opportunities that can take advantage of information science and computing technologies in engineering. Technologies such as building information modeling, virtual reality, high definition images, sensors, etc., are now widely deployed in the civil and construction engineering industry. This presentation will provide an overview of current trends of computing technologies in the AEC domain. Recent years have also seen the re-emergence of artificial intelligence (AI) applications. This presentation will attempt to discuss some of the potential applications of AI in engineering.

BIOGRAPHY: Mr. Kuang, is currently a certified Senior Engineer and General Manager of the Department of Architectural Digitalization and BIM at China Construction and Design Institute (CCDI), the largest private design company in China. He oversees research, technical advancement, project management, quality assurance and standards drafting of BIM for the company. He holds a BA degree in Engineering of Thermal Energy from Northeastern University (China). He has devoted himself in the AEC industry for over 20 years, and in building digitalization and BIM for over 10 years. He also act as the Vice Director of Beijing Exploration and Design Information Committee, Special Consultant of Tsinghua University National BIM Research Group, and Member of the Drafting Committee of Beijing Civilian Architecture BIM Standard. He supervised the utilization of BIM for a serials of iconic building projects in China, such as Tianjin Ship Terminal (2008), Wanda Xishuangbanna Theater (2012), Longfor Changyingtianjie Residence Area (2012), Shenzhen Pingan Tower (2012), and Beijing Z15 Tower (2013).

KEYNOTE SPEECH XI: BIM Technology enabled Smart Airport Design and VR Applications in Third Runway Development

Ir Kevin Poole, Executive Director, Hong Kong Airport Authority, Hong Kong

ABSTRACT: Airport Authority has been utilizing BIM for design and construction since 2006, commencing with the "North Satellite Concourse" project continuing through to the recently completed "Midfield Concourse". BIM is adopted for all our current capital works projects related to Three-Runway System.

Appropriate use of relevant BIM strategies and technology can assist in achieving the Authority's commitment to Smart, Green & Sustainable airport design. This can be through effective and efficient space utilization, facilities visualisation and analysis that supports a shorter design iteration cycle and decision making process, for example: passenger flow study, means-of-escape, illumination coverage and heat & ventilation analysis etc. The analytical results can be updated quickly with design changes and optimized results obtained from the integrated BIM model that allow stakeholders to visualize solutions and thereby aid decision making.

AAHK is also exploring the use of VR for projects in the various stages of design, construction, operation and maintenance. With pre-defined project requirements in VR collaboration formats, it makes VR integration ready for our projects by plugin to appropriate VR platform and devices. The immersive VR environment, with intuitive eyesight direction by head tracking technology, may provide a better sense of space and object relationship than from a monitor. At the same time, realistic lighting, texture mapping and rendering technology improves the level of realism that would benefit a design review in a VR guided walkthrough. In the future, it may be that life-like operational experiences can be simulated in the virtual environment such as the check-in process, travel on the APM system, emergency escape route, complex equipment maintenance or even training.

BIOGRAPHY: Kevin Poole is an Executive Director of the Hong Kong Airport Authority and independently responsible for the direct management of the planning, concept development, feasibility study, engineering, design, procurement and implementation of all capital works projects undertaken by the Authority. He has more than 30 years of experience in the building and civil engineering field specializing in major multi-disciplined infrastructure and building projects. In the UK, he was involved in the construction management teams on the London Docklands' Connaught Crossing and the Queen Elizabeth II Bridge over the Thames at Dartford. Experience in Hong Kong includes as a senior member of a consultant team working for Government clients of tube tunnel, highway and reclamation projects. He is a member of the Construction Industry Council (CIC) in Hong Kong and Chairman of the Committee on Environment at CIC.

Part I: BIM Adoption and Project Management

A TOOL FOR ASSESSING THE COMPLIANCE OF PROJECT ACTIVITIES AND DELIVERABLES AGAINST THE REQUIREMENTS OF BIM LEVEL 2 POLICY DOCUMENTS

Mohamad Kassem, Associate Professor, Northumbria University,

Mohamad.Kassem@northumbria.ac.uk

Mohammadreza Jenaban, KTP Associate, Sotech Optima & Teesside University,

mj@sotech-optima.co.uk

David Craggs, KTP Associate, DKS Architects & Teesside University

dcraggs@dksarchitects.com

Nashwan Dawood, Professor, Technology Futures Institute, Teesside University

n.n.dawood@tees.ac.uk

ABSTRACT: *Public and private procurers around the world are either mandating or encouraging the adoption of BIM within their construction sectors and projects. For example, in the UK, BIM (i.e., 'BIM Level 2') is mandatory on all government centrally procured projects. 'BIM Level 2' is a collaborative way of working, in which 3D models with the required data are created in separate discipline models according to a set of guides, standards and specifications.*

Mandating BIM Level 2 required the development of a range of guides, standards and specifications[1]*. These policy documents are intended to guide and facilitate the adoption of BIM by the project supply chain. They are considered complex as evidenced from the large amounts of requirements included within each of them and from the strenuous discussions around their implementation in professional networks and specialised blogs. Tools for assessing the compliance of project activities and deliverables these against requirements of these policy documents do not exist.*

This research proposes a tool, which enables a project team to determine the compliance of project activities and deliverables with BIM Level 2 policy documents at every phase of the project lifecycle. The tool was built by extracting all requirements from the policy documents. This paper will present the tool and demonstrate its application in a case study. The results show that the proposed tool can help in assessing the compliance of project activities with the policy documents and in simplifying their complexity. The two limitations of this research include the following: a) the used requirements were added to the matrix without any prior processing (e.g. semantic and ontological development); and b) an assumption was made that the policy documents used to build the matrix are trustworthy despite several of them are still at the specification stage – a stage that precedes their conversion into standard – and are untested from research perspective.

KEYWORDS: *BIM, BIM Level 2, Compliance.*

---

[1] All these document types are referred to as 'policy documents' in the remainder of the paper.

1. INTRODUCTION

BIM is now considered as the current expression of digital innovation within the construction industry (Succar and Kassem, 2015). When BIM is implemented properly, it facilitates many of the functions and activities required across the whole project lifecycle (Eastman et al., 2011). It is changing the workflows across all the construction project phases from planning and design through construction to operation. This impact on the entire project lifecycle is evidenced by the development of model use taxonomies - e.g. by Succar et al. (2016) and Kreider et al., 2015 – that include uses of BIM for each and every phase of the project lifecycle.

The UK Government has mandated the use of BIM – i.e., BIM Level 2 - since April 2016 on all centrally procured projects. To provide guidance for the supply chain involved in BIM-enabled projects, several policy documents and one tool – the digital Plan of Work (dPoW) - were developed. This sheer volume of policy documents were produced in a relatively short timeframe – less than three years – which immediately preceded the BIM mandate effective date (4 April 2016). As a result of this intensive and hasty development and launch of policy documents, the industry was left with much to ponder and many unanswered questions. A key area of concerns is the complexity of the policy documents which is resulting in a limited understanding of the requirements and expectations from the project supply chain. The complexity is partly caused by the approach used to organise the policy documents that 'deliberately' abstained from providing detailed levels of granularity. To date there have been no attempt to address this challenge within research. The dearth of studies in this area can be justified as: 1) it requires an action research approach (interventionist approach to the acquisition of knowledge which requires more generous timeframes to conduct research with the involved organisations) that is generally difficult to implement in construction-related research, and 2) the short time elapsed since the policy documents were issued. This research has been conducted as part of an initiative called 'KT4BIM' (Knowledge Transfer for BIM). The initiative brought together individuals from several organisations (Table 1) with the common aim of simplifying the complexity surrounding the implementation of BIM-enabled projects according to BIM Level 2 and its policy documents. The initiative was led and sponsored by the BIM4SME Group – BIM4SME is one of the UK BIM Task Group working groups composed of individuals from Small and Medium Enterprises (SMEs), public agencies and academia. In this paper, we report the results from the development and application of a tool for the checking of the compliance of project activities and deliverables against the requirements of BIM Level 2 across all project phases of the RIBA Plan of Work 2013. The paper shows the proposed tool and demonstrates its application in one case study at the Strategic Definition project phase.

Table 1 Consortium involved in the KT4BIM initiative

Academic Partner	Industry / Public Partner

Heriot Watt University Reading University Teesside University University of Central Lancashire University of Reading University of Salford University of Westminster University of Wolverhampton	BSRIA Links Project M+W Hargreaves Sotech Optima Ltd BWB Consulting Henry Riley LLP Frank Whittle Partnership (FWP) Nunelah Design Consultant Kent Council DKS Architects Elliottwood

2. LITERATURE REVIEW

The escalating coverage, connotation and impact of BIM concepts and tools have led to the proliferation of BIM-focused publications (e.g. BIM strategy documents, BIM adoption reports, data exchange standards, and model-based collaboration protocols) emanated by Industry associations, governmental bodies and academic communities across several countries (Kassem et al., 2016). In parallel with the deepening interest in BIM, industry and academia have been attempting to develop tools for assessing and improving its adoption. These efforts were targeted at different levels ranging from studies investigating BIM adoption at market-wide level (Succar and Kassem, 2015), through organisational scale (e.g., Geil, 2013; CIC, 2013; BRE, 2015; VICO, 2011) and individuals/teams (Change Agents AEC, 2013), to projects (Arup, 2014; bimSCORE, 2013; NIBS, 2015; Nepal et al., 2014). A review and an appraisal of available methods across the three different organisational scales is available in Azzouz et al. (2015). The assessment scale (organisation vs. project) affects the definitions of the used metrics. For example, the assessment at organisation scale is often focussed on assessing the vision, plans, culture change, collaboration and strategies of BIM within organisations, while assessment at project scale evaluates the different BIM implementation facets at project level, e.g. data richness, data exchange/interoperability and model use (Azzouz et al., 2015; Bougroum and Copping, 2016; Mansson and Lindahl, 2016). As this paper is focussed on BIM implementation at project level, only the methods addressing the scale will be reviewed.

The ARUP BIM Maturity Measure (BIM-MM) is used to assess different organisational (e.g. vision, objectives, availability of defined BIM roles, etc.) and project aspects (e.g. data richness, data exchange, model deliverables, etc.) using a five-level index: 0. Non-existent; 1. Initial; 2. Managed; 3. Defined; 4. Measured, and 5. Optimised. Both the project and the involved trades (e.g. Mechanical, Electrical and Structural) can be assessed and their score is compared with an established target level (Arup, 2014).

The Virtual Design and Construction (VDC) Scorecard evaluates projects using 4 scorecard areas (i.e., planning, adoption, technology, and performance) that are further divided into 10 divisions which includes 56 measures

(Kam et al., 2013). The percentage score uses a tier of 'Maturity Levels of VDC Practice' which includes: Conventional Practice (0%-25%); Typical Practice (25%-50%); Advanced Practice (50%-75%); Best Practice (75%-90%); Innovative Practice (90%-100%). An online commercial tool (i.e., bimSCORE) was developed based on the VDC score and is used to assess the performance of new projects against past projects (bimSCORE, 2013).

The Interactive Capability Maturity Model (I-CMM) establishes 'a tool to determine the level of maturity of an individual BIM as measured against a set of weighted criteria agreed to be desirable in a Building Information Model' (Suermann, et al., 2008, p. 2; NIBS, 2007; NIBS, 2015). The ICMM has 11 'areas of interest' measured against 10 maturity levels.

From this review it can be concluded that tools and methods for the evaluation and assessment of BIM-enabled project are still very limited. More importantly, much of the available methods and tools for the assessment of BIM-enabled projects do not seem to be based on a solid theoretical foundation. While the proposed methods and tools claim to be able to determine the 'maturity' of project, our research is focussed on assessing 'compliance'. In projects, assessing or checking compliance is often considered a project 'audit' activity which aims to identify issues and non-compliance with policies, procedures and processes, and ensures that appropriate controls are in place.

3. TOOL FOR COMPLIANCE ASSESSMENT

Several policy documents have been developed between 2012 and 2016 in the UK to prescribe the processes and requirements for participating in BIM Level 2 enabled projects and to educate the supply chain. However, there has been significant debate in the industry and academic communities about whether these policy documents are effective in achieving these targets. A key challenge that is often cited in such debates is the clarity of the policy documents with regards to the requirements and responsibilities of each of different project stakeholders at each of the project lifecycle. To address this important challenge, an industry initiative called 'KT4BIM' was collaboratively formed by a group of organisations and universities to develop a tool for assessing the compliance of project activities and deliverables with BIM Level 2 policy documents. The methodology adopted an action research approach in which the practitioners – who simultaneously play also the role of researchers as they work on joint projects between industry and academia that are funded by Innovate UK – spent six months working on a case study of a BIM-enabled project. The remainder of this paper will illustrate the tool for compliance assessment and its application at the Strategic Definition (Stage 0 of the RIBA Plan of Work 2013).

3.1 Development of the Compliance Tool

The approach (Figure 1) used to develop the compliance tool consisted of manually mining the requirements and clauses from the policy documents and mapping them against the applicable project stage. Details about the policy documents used to mine the requirements are included in Table 1. Several practitioners and researchers participated in this mining exercise, each with a responsibility for mapping a particular policy document. The results were merged into a unique file – a spreadsheet with multiple sheets – which formed the compliance tool. All practitioners and researchers followed an agreed upon process to build the matrix. For a given policy document, the requirement mining process included these steps: 1. identify the requirement within the document's text; 2. identify applicable project stage; 3. input the requirement attributes into the spreadsheet (i.e., requirement code/number in the original document, category/class, and requirement description). For each requirement (each line in Table 3) and for each stage, the additional columns are:

- 'Comment Stage x[2]': it includes commentary to explain how the project activities/deliverables meet or deviate from the requirement;
- 'Pass Stage x[2]': a binary score of 1 (Pass) or 0 (Fail) for the project activity/deliverable when it is checked against the requirement;
- 'Assessment Stage x[2]': This column is used to verify that the requirement being assessed is applicable to the stage. It is filled automatically by referring to a different table (see Tables 4 and 5) that maps requirement against applicable stages. If the requirement is not applicable to the stage, it will return N/A (Not Applicable) to the corresponding cell. It is a mechanism to ensure accuracy in the application of the matrix;
- 'Validation Stage x[2]': This cell enables a second layer of verification by cross checking the values in the aforementioned two cells. It automatically transposes the value of pass or fail from 'Pass Stage x[2]' only if the requirements is applicable to stage (i.e., only if the value in Assessment Stage x[2] is different from N/A),
- 'Unjustified Fail': it is a field that is filled automatically to check whether an applicable requirement to the current stage is failed without a commentary (empty value in the 'Comment Stage' call).

After performing these steps on all BIM Level 2 policy documents except the PAS 1192-5 2015, the compliance tool was developed. It was implemented as a spreadsheet with multiple sheets. Each sheet is reserved for checking the compliance against one policy document. Table 4 shows the number of requirements from all policy documents that are applicable across all the project stages. The results from all sheets are automatically amalgamated in a summary sheet in which the compliance of project activities/deliverables is monitored against all requirements at every project stage. The summary sheet represents a dashboard for visualising the status of compliance of project activities/deliverables with the policy documents across all project stages. Across all project stages, the policy documents included 3487 requirements (Table 4) – not unique requirements as they include recurrences – which makes the compliance assessment a time and resource demanding process. The next paragraph illustrates the application of the matrix in a case study.

Table 2. BIM Level 2 policy documents

Code	Title
BS 1192:2007[3]	Collaborative production of architectural, engineering and construction information. Code of practice

[2] x denotes the project stage number (0 to 7).

[3] This was updated in 2016 and has become BS 1192:2007 + A2:2016

PAS 1192-2:2013	Specification for information management for the capital/delivery phase of construction projects using building information modelling
PAS 1192-3:2014	Specification for information management for the operational phase of assets using building information modelling (BIM)
BS 1192-4:2014	Collaborative production of information. Fulfilling employer's information exchange requirements using COBie. Code of practice
PAS 1192-5:2015	Specification for security-minded building information modelling, digital built environments and smart asset management
BS 8536-1:2015[4]	Briefing for design and construction. Code of practice for facilities management (Buildings infrastructure)

Table 3. Requirement mining from the BS1192-2007

Requirement number	Requirement Category	Requirement description
4.1.2	Roles and Responsibilities	Roles and responsibilities should be agreed.
4.2.1	Common Data Environment	Information, once prepared, should be placed into the WORK-IN-PROGRESS (WIP)
4.2.2	Common Data Environment	The data continues to be updated in the WIP area and should be indexed to indicate minor version changes, e.g. P02.1, etc., until next published to the SHARED area
4.2.3.1	Common Data Environment	When a model has reached a status that is "fit for co-ordination" it should be uploaded to the SHARED area of the CDE.

[4] This document was not issued when this research has started and a reference was made to the 'Government Soft Landing' – a methodology for the smooth transition from the design and construction phase to the operational phase of a built or refurbished asset. It proposes a lifecycle view of asset cost and value.

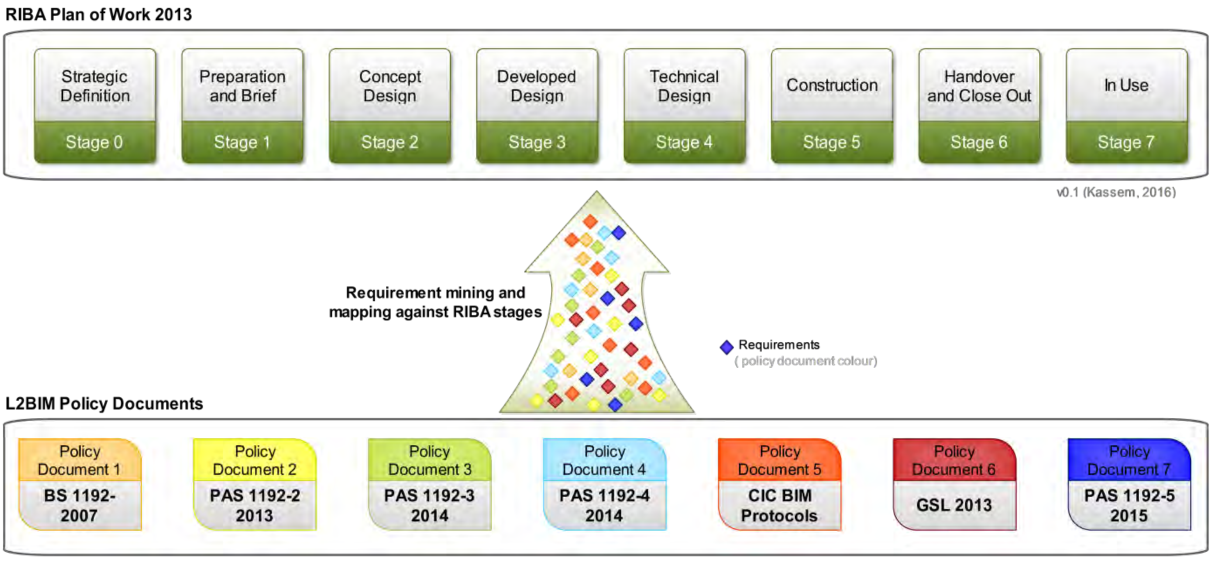


Figure 1. Approach for mining requirements from BIM Level 2 policy's documents and their mapping against the project stages

Table 4. Mapping of the 18 requirements – each line represents one requirement – from the BS 1192-2007 against the project stages

Requirement Code	Requirements from the BS 1192-2007
R1	Roles and responsibilities should be agreed
R2	A "Common Data Environment" (CDE) approach should be adopted.
R3	Information, once prepared, should be placed into the Work-In-Progress (WIP)
R4	The data continues to be updated in the WIP area and should be indexed to indicate minor version changes, e.g. P02.1, etc., until next published to the SHARED area
R5	When the data is SHARED with the other members of the project team, the data is checked and issued to the CDE and the revision code is updated to indicate a major revision, e.g. P01.
R6	When a model has reached a status that is "fit for co-ordination" it should be uploaded to the SHARED area of the CDE.
R7	Before uploading to the shared area, a model should be reviewed and checked according to compliance requirements in order to be fit for a specific purpose
R8	The "issue" status should be used to identify the suitability of the information provided. The "suitability" code gives ownership to the design teams and restricts access by others until information is sufficiently developed, co-ordinated, approved and authorized.
R9	The data shared with status "Fit for Co-ordination" should be in the changeable formats. All information having a different status should be produced as documents in non-changeable formats

R10	Models that are downloaded by others should never be re-uploaded to the SHARED area. When a model is used as background information by others, it is important to ensure that this does not result in information in models being duplicated. Therefore, a procedure should be agreed that ensures information occurs only once in the SHARED area.
R11	Before information in the shared area of the CDE is made available to the wider project team, for example for tender or construction, it should be formally checked, approved and authorized. Suitable checking and approvals processes should be defined and applied. These should apply to consultants and subcontractors' documents.
R12	Once the document has been approved and authorized, it passes to the contractor for "Action" and the revision changes from "Preliminary" to "Construction".
R14	Archive folder: all data should be kept and maintained for possible future use
R15	Naming Convention: Directories
R16	Naming Convention: Files
R17	Naming Convention: Containers
R18	Spatial Coordination: common origin and orientation

Table 5. BS 1192-2007 requirements and applicable stages

Requirement Code	Stage 0	Stage 1	Stage 2	Stage 3	Stage 4	Stage 5	Stage 6	Stage 7
R1	●	●						
R2	●	●						
R3	●	●	●	●	●	●	●	●
R4	●	●	●	●	●	●	●	●
R5	●	●	●	●	●	●	●	●
R6	●	●	●	●	●	●	●	●
R7	●	●	●	●	●	●	●	●
R8	●	●	●	●	●	●	●	●
R9	●	●	●	●	●	●	●	●
R10	●	●	●	●	●	●	●	●
R11	●	●	●	●	●	●	●	●
R12	●	●	●	●	●	●	●	●
R14	●	●	●	●	●	●	●	●
R15	●	●	●	●	●	●	●	●

R16	●	●	●	●	●	●	●	●
R17	●	●	●	●	●	●	●	●
R18			●	●	●	●		

Table 6. The number of requirements extracted from the policy documents and mapped against project stages

	BS 1192:2007	PAS 1192-2:2013	PAS 1192-3:2014	BS 1192-4:2014	PAS 1192-5 2015	CIC Protocol	CIC Info manager	GSL	Requirements-Total
Stage 0	17	139	53	8	177	8	24	34	460
Stage 1	17	58	46	23	168	2	28	90	432
Stage 2	16	61	45	28	166	5	23	128	472
Stage 3	16	63	45	38	166	5	22	152	507
Stage 4	16	65	45	37	166	5	22	139	494
Stage 5	16	37	45	11	167	1	22	101	400
Stage 6	15	16	45	13	166	1	23	70	349
Stage 7	15	16	47	6	169	1	4	114	372

3.2 Case Study

A project brief given was given to a multi-disciplinary team of architects, structural engineers and MEP (Mechanical Electrical and Plumbing) engineers. The brief required the design of a self-build module that can accommodate a living space, a kitchen, a bathroom, a bedroom and a parking for up to four vehicles. The brief specified the maximum construction and materials budget at £40,000 excluding land, professional and local authority fee, service connections, insurances and warranties. The site is 15m wide and 30 m deep and can accommodate up to three storeys. The multi-disciplinary team aimed to deliver this brief across the RIBA Plan of Work 2013 design stages from the Strategic Definition (Stage 0) to the Technical Design (Stage 4).

The paper illustrates the results from the case study for Stage 0 (Strategic Definition) only. During this stage, the multidisciplinary team collaboratively worked and endeavoured to develop the project according to a fully enabled BIM Level 2 project. An appointed Information Manager monitored the compliance of the project activities/deliverables using the proposed compliance tool. An extranet as a Common Data Environment for collaboration and other tools for model authoring, costing and virtual meetings were all in-kind provided by the industry partners. Weekly meetings were used by the Information Manager to assess the compliance of project deliverables/activities using the proposed matrix. A binary score of either 'Pass' or 'Fail' was used to assess project activities/deliverables against each individual policy document. However, when the compliance of the entire project stage is assessed, the final decision is based upon a 'Stage Compliance Rate' (SCR in %) which is not binary. Using the SCR and the supplementary comments that explains the reasons for not achieving full compliance, the Information Manager can objectively decide whether the project can proceed to the next stage. In this case study, the results from compliance checking against all the applicable requirements to Stage 0 are described in Figure 1. Based on the compliance score achieved (76.2%) and the additional comments, the Information Manager considered Stage 0 as compliant and authorised the project to proceed to the next stage provided that some minor corrective actions and changes are addressed (i.e. the generation of a MIDP - Master Information Delivery Plan; the generation of IMP to manage information related to the operational phase of an asset). The non-full compliance was also attributed to several requirements that are not applicable to the current context of a virtual case study. The results in Figure 2 amalgamates the results from 8 tables / sheets (one for each policy document) with a total number of line exceeding 3487 lines (a line for each requirement). The tool successfully allowed the checking of compliance of project deliverables and provided transparency to all involved parties. However, there are a number of issues and challenges facing the use of the proposed tool. These are discussed in the next section.

Stage 0 Monitoring

Policy Document	Stage compliane (%)	Reasons for not achieving 100% compliance	Requirement number	Stage Pass	Un-Justified Fail	Justified Fail
BS_1192-2007	81.25%	There is no process in place to check and review the data before it is moved/issued outside of IM.	16	13	0	3
PAS_1192-2	87.77%	Clause5.1.5 BIM Protocol is yet to be mapped to the EIR. MIDP (Master Information Delivery Plan) to be generated. This will affect numerous requirements thus when it is completed the compliance percentage will increase significantly.	139	122	0	17
PAS_1192-3	64.15%	A robust IMP plan needs to be implemented to regulate the CDE and how the information is being managed from within the AIM, and between AIM and outside.	53	34	0	19
BS_1192-4	75.00%	The remaining clauses in this document relate to existing structures on the project. As this Virtual site has no exisiting structures the remaining clauses are not applicable	8	6	0	2
PAS1192-5	73.45%	No Built Asset Security Manager appointed. Need-to-know basis of security docs not respected. No contracts issued with security clauses included. The team didn't look into the other governement standards regarding security.	177	130	0	47
CIC_BIM_Protocol	50.00%	Client has not delivered the following information (Copyright agreement, Sustainability Standard). One of the requirements needs multiple conditions to be satisfied thus it would not be objective if we passed that item. Also due to the nature of the project being a virtual case study, copyright elements of the Protocol do not apply here	8	4	0	4
CIC_Information_ Manager	95.83%	Information Manager still uncomfortable with the Level of Information specified at each stage and would like to re examine the specifications.	24	23	0	1
GSL	82.35%	1. meeting and feedback lessons learnt to GSL Champion Stewardship Group has not been identified. 2. There are some action points relevant to existing buildings and not a new-build. However, The roles for carrying out the actions are identified and set in the client documents. 3. Different cost sources (which are more comprehensive) than the suggested one will be used for benchmarking.	34	28	0	6

Stage 0 Monitoring Total

Stage total compliance (%)	Reasons for not achieving 100% compliance	Requirement number	Stage Pass	Un-Justified Fail	Justified Fail
76.23%	See details above	459	360	0	99

Figure 2. Results of the project compliance with the policy documents at Stage 0 (Strategic Definition).

4. DISCUSSION & CONCLUSION

Several policy documents surfaced in the UK to support the BIM mandate represented by the so-called ‘BIM Level 2’. All these documents were developed and launched within less than 4 years, separating the announcement of the mandate in 2011 from its effective date in 2016. The construction industry in the UK and SMEs in particular have expressed their apprehension about the complexity of these policy documents. Typical discussion items that often emerged in forums and networking events are: what are the compliance requirements for BIM Level 2 projects?; How do we know if a requirement have been met?; how can compliance issues be identified and resolved?; How and when do we progress through stages?, etc. The KT4BIM initiative was set as a collaborative effort between several industrial and academic partners to address these concerns. The proposed tool was developed within the KT4BIM initiative as a tool for enabling compliance checking against all the policy document at every project phase.

The tool successfully enabled the compliance checking at the design phase of a virtual project. The testing of the tool in a virtual project has limitations compared to its deployment in a real life project. Issues that inhibit collaboration such as trust, legalities and intellectual properties (Azhar, 2011; Ghassemi and Becerik-Gerber; 2011; Sebastian, 2010; Kassem et al., 2013) and their impact were eliminated in the virtual project. Therefore, the impact of these issues on the adoption of the tool remain unclear and warrants future investigations. Nevertheless, the tool showed several benefits and limitations in the illustrated case study. For example, the whole multidisciplinary team had a shared access to the tool and all project stakeholders were informed about the compliance levels and the issues that requires attention. This allowed the team to constructively collaborate on the resolution of the identified compliance issues. However, the interim uses of the matrix within each project stage often showed low compliance levels as the progression of project activities/deliverables was partial. In such cases, the compliance checking resulted in unnecessary pressure for the involved team. Interim uses have also made the application of the matrix challenging given the high number of requirements that are applicable to each stage. To address this issue, it is suggested to define an event-driven process (e.g. at submittal of deliverables, at key project milestones) for performing the compliance checking across the project stages.

The proposed tool can also enable the comparative analysis of compliance across projects – when results are available from numerous projects – and may be used to establish industry benchmarks or targets for project compliance. More importantly, data from the adoption of the tool from many projects can provide a feedback loop to both policy makers and the project supply chain. Indeed, aggregated data from several projects can help policy makers understand the areas of policy documents that require improvement. For example, if one part in one of the policy documents is always revealing difficult to comply with (e.g. unrealistic requirements), the policy maker can review and improve that part. The project supply chain can use prior compliance results as lesson learned to exploit in new projects.

The number of requirements (i.e., 3487) applicable to a level 2 BIM project across all stages is very high which makes the compliance checking a time and cost demanding effort. It would be also very challenging to perform this process on a project using one information manager only. However, the development of the proposed tool did not consider: requirement recurrences (e.g. same requirement but expressed using different terms within the same policy document or across multiple policy documents), linked and transitive requirements (e.g., compliance with requirement A affects the compliance with requirement B, and compliance with requirement B in turn affects the compliance with requirement C, then compliance with A is related to compliance with requirement C) or nested requirements (e.g. identification of requirement subcomponents). All these issues can be addressed through the creation of a specialised ontology which formally defines: 1) the compliance concepts – e.g. policy document, requirement, role; 2) the attributes – e.g. values and qualifiers associated with the concepts, and 3) the relations between the concepts. The proposed work can be considered as an early proof-of-concept before embarking on the development of a tool which is based on a specialised ontology. The outlined ontology and the tool can help in reducing the current complexity of BIM Level 2 policy documents and facilitating BIM adoption on projects.

ACKNOWLEDGEMENT

We are thankful to all individuals who supported this research and their organisations (Table 1). We particularly acknowledge the contribution of the BIM4SME working group who initiated and managed the KT4BIM initiative. Last but not least we thank the InnovateUK for funding the Knowledge Transfer Partnerships that are involved in the KT4BIM.

REFERENCES

Azhar, S. (2011). Building information modeling (BIM): Trends, benefits, risks, and challenges for the AEC industry, Leadership and Management in Engineering, 11(3), pp. 241–252. http://doi.org/10.1061/(asce)lm.1943-5630.0000127

Azzouz, A., Shepherd, P. and Copping, A. (2016). The Emergence of Building Information Modelling Assessment Methods (BIM-AMs), Integrated Design Conference, University of Bath, Bath, UK, June 2016.

bimSCORE, (2013). bimSCORE, available from: https://www.bimscore.com

Bougroum, Y. (2016). An analysis of the current Building Information Modelling assessment methods, Research dissertation, University of Bath, Bath, UK.

BRE, (2015). BIM Level 2 Business Systems Certification. available from:
http://www.bre.co.uk/page.jsp?id=3389

Change Agents AEC, (2013). BIM Excellence Performance Measurement Corporate Services, available from: http://bimexcellence.com/services/

CIC (2013). BIM Planning Guide for Facility Owners. Version 2.0. The Pennsylvania State University, University Park, PA, USA.

Eastman, C., Teicholz, P., Sacks, R. and Liston, K. (2011). BIM Handbook: A Guide to Building Information

Modeling for Owners, Managers, Designers, Engineers and Contractors, 2nd Ed., John Wiley & Sons, Inc., New Jersey

Ghassemi, R. and Becerik-Gerber, B. (2011). Transitioning to Integrated Project Delivery: Potential Barriers and Lessons Learned, Lean Construction Journal, 2011, 32-52.

Giel, B.K., (2013). Framework for Evaluating the BIM Competencies of Building Owners. Gainesville, Fla: University of Florida.

Kam, C., Senaratna, D., Xiao, Y. & McKinney, B., (2013). The VDC Scorecard: Evaluation of AEC Projects and Industry Trends.

Kassem, M., Iqbal, N., Kelly, G., Lockley, S. and Dawood N. (2014). Building Information Modelling: protocols for collaborative design processes. Journal of Information Technology in Construction (ITcon), Vol. 19, pg. 126-149, http://www.itcon.org/2014/7

Kassem, M., Succar, B., & Dawood, N. (2014). Building Information Modeling: analyzing noteworthy publications of eight countries using a knowledge content taxonomy' in R. Issa & S. Olbina (Eds.), Building Information Modeling: applications and practices in the AEC industry, ASCE Technical Council on Computing and IT. University of Florida.

Kreider, Ralph G. (2013). An Ontology of the Uses of Building Information Modeling. The Pennsylvania State University, University Park, PA, USA.

Mansson, D. and Lindahl, G. (2016). BIM performance and capability, in: Sanches, A., Hampson K.D. and Vaux S. ed. Delivering value with BIM: a whole-of-life approach, Eds., Oxon, Routledge, pp. 46-57.

NIBS (2007). National Building Information Modeling Standard: Version 1.0- Part 1: Overview, Principles, and Methodologies, National Institute of Building Sciences, Washington, DC, U.S.

NIBS (2015). National BIM Standard- United States Version 3, National Institute of Building Sciences, Washington, DC, U.S.

Succar, B. Saleeb, N. and Sher, W. (2016). Model uses: foundations for a modular requirements clarification language', Language, Australasian Universities Building Education (AUBEA2016), Cairns, Australia, July 6-8, 2016.

Succar, B., & Kassem, M. (2015). Automation in Construction Macro-BIM adoption : Conceptual structures. Automation in Construction, 57, 64–79. http://doi.org/10.1016/j.autcon.2015.04.018

Suermann P, Issa R. (2009). Evaluating industry perceptions of building information modelling (BIM) impact on construction, Journal of Information Technology in Construction, 14, 574-594

VICO (2011). Calculation your BIM score, available from: http://www.vicosoftware.com/resources

BIM PERFORMANCE ASSESSMENTS AND ITS APPLICATION IN INDIAN AECO INDUSTRY – A CASE STUDY

Amarnath Chegu Badrinath, Shang-Hsien Hsieh

National Taiwan University, Taiwan

Niranjan Kumar

Visvesvaraya Technological University, India

ABSTRACT*: Globally, built environment sector has been experiencing notable development with Building Information Modelling (BIM). Public sectors in several countries are playing major roles in BIM adoption because they have seen the benefits of BIM adoption for their Architectural, Engineering, Construction, and Operation (AECO) projects. Recently, Indian AECO industry shows considerable movement towards BIM. Survey findings of RICS School of Built Environment, Amity University and KPMG in 2013-14 revealed that 22% BIM adoption was undertaken in Indian AECO Industry. Once a technology is adopted, assessment is needed to understand the status of its adoption. BIM in the AECO industry is of no exception and BIM performance measurements can be conducted at different scales, i.e. individual stakeholder, team, organization, project and market scale. As a preliminary case study, we identified existing BIM Assessment Methods (BIM-AMs) at project scale and tested two of them, namely NBIMS interactive capability maturity model (NBIMS-ICMM) & Arup's BIM maturity measure model (Arup's BIM-MMM), on a selected Indian BIM project (located in Bangalore, Karnataka). NBIMS-ICMM & Arup's BIM-MMM were adopted due to their free accessibility and wide acceptance in the global market. Before the project assessment, BIM competencies of organization (with Bew & Richards model) and key stakeholders (with BIM self-assessment tool) involved in the selected project were known. Assessment results were documented and compared for identifying the suitable Project AM for the selected project & organization. Also, a series of interviews were made with the stakeholders of the selected project and organizational head to capture their ideas towards these BIM-AMs, assessment results, and their plan on improving their organization and project BIM performance.*

KEYWORDS: *Building Information Modelling (BIM), BIM-Assessment Methods (BIM-AMs), Indian AECO projects, BIM performance measurements.*

1. INTRODUCTION

In India, Architecture, Engineering, Construction and Operation (AECO) industry is the second largest industry after agriculture industry. Indian AECO industry employs more than 35 million people, has second highest inflow of foreign direct investment after services sector, and contributes to about 11.1% of India's GDP (Mohideen 2015).

Recent initiatives set by Indian government, such as Make in India, is serving to grow the AECO industry. There are many mega projects undertaken recently, e.g. high-end road ways or express ways, metro train projects and proposed bullet train project between two cities of India, i.e. Mumbai and Ahmedabad. The initiation of these projects necessitates focus on various technical and non-technical aspects along with technologies, especially the infrastructure for these initiatives.

Regarding technologies and project delivery process within the AECO industry, Building Information Modelling (BIM) is one of the most notable one, with its ability to reduce project time delays, cost over runs and litigations. Countries like the United States, the United Kingdom, the Netherlands, Singapore, South Korea, Japan, Hong Kong, and Australia have mandated the usage of BIM in public sector (Cheng and Lu 2015). Many countries in the regions of the America, Europe, Asia and Oceania have high percentage of BIM users for their AECO projects. This transformation from traditional practices toward BIM has enabled several benefits to AECO industry with respect to project delivery (DCAMM 2015; MPA 2015; Harvard UCMC 2016). Concerning BIM adoption in Indian AECO industry, RICS India (Sawhney 2014) had conducted a survey on the status of BIM in Indian scenario and described the importance of BIM for Indian AECO industry. However, adopting new technologies like BIM involves complex procedures. In order to realize and overcome the complexities during BIM diffusion in projects, BIM technology and process of diffusion need to be measured and monitored at regular intervals. Hence, there is a need for measuring and improving BIM maturity in Indian AECO projects.

BIM maturity of individual stakeholders, teams, organizations and projects can be measured using Assessment Methods (AMs) developed by BIM researchers, professionals and AECO organizations (Azzouz, et al. 2016). Recently, research findings from Erik, et al. (2015) revealed that BIM has a positive effect on projects by increasing the predictability of total project cost. Also, they described on how BIM-AMs can lead to better predictability on BIM performance maturity. To realize the BIM maturity within individual stakeholders, teams, organizations, projects and markets, several assessments are essential at different BIM performance measurement scales. Several project AMs associated with BIM are existing for global scenario. However, how these BIM project AMs can benefit Indian AECO projects is still beyond exploration. Conducting BIM performance assessment on a selected Indian BIM project and realizing a suitable AM for the project is the major objective of this study. Project assessments were carried out on the selected project by adopting two BIM project AMs, i.e. NBIMS-ICMM and Arup’s BIM-MMM, because of its free accessibility and wide acceptance.

2. LITERATURE REVIEW

The demand for BIM-AMs is increasing with the BIM adoption by public sectors in more than 14 countries. Larger acceptance of BIM in recent days by global AECO industry has fostered the development of BIM-AMs for different measurement scales. BIM assessments within individuals, teams, organizations, projects and markets indicate current BIM performance measurement scales that can help project stakeholders to realize their individual BIM competency, teams’ BIM capability, and BIM maturity of their projects, organizations and markets. Furthermore, it is needed to educate and train these project stakeholders, their organizations and project teams for improving BIM performance and maturity levels. Educating and training the project stakeholders benefits AECO organizations in delivering BIM projects with expected BIM maturity. Detailed BIM project assessment facilitates in assisting project stakeholders with relevant education and training to reach required BIM maturity (NIBS 2015). BIM-AMs can be categorized into five measurement scales: (1) the individual stakeholder competency assessments; (2) the stakeholder teams' capability and compatibility assessments; (3) the organizational capability and maturity assessments; (4) the project AMs; (5) market scale maturity assessments. Through extensive literature study, twenty-seven (27) BIM-AMs were identified in this study, including four individual stakeholder competency assessments, one stakeholder teams' capability and compatibility assessment, eleven organizational capability and maturity assessment, seven project AMs, and four market scale maturity. Each of these BIM-AMs has different strengths and weaknesses. Some of these AMs are user friendly, are freely accessible and offer case study projects. Some of the existing BIM-AMs are conceptual, lack instructions, or requires external examiners and fees for implementing assessments.

Recently, BIM researchers have categorized a few existing BIM-AMs in the AECO organizations and projects. They have pointed out the key differences among these BIM-AMs (Dakhil et al. 2015; Azzouz et al. 2016). Existing AECO project AMs include NBIMS-ICMM (NIBS 2015), characterization framework (Gao 2011), VDC scorecard (Kam et al. 2013), bimSCORE (bimSCORE 2013), BIM excellence project assessment (Change Agents AEC 2013), Arup's BIM-MMM (Arup 2014) and goal driven method for evaluation of BIM projects (Lee and Won 2014). Table 1 provides a comparison among the existing BIM project AMs. Four out of seven project AMs were of USA origin, i.e. NBIMS-ICMM, characterization framework, VDC scorecard and bimSCORE. Only three of the existing project AMs are accessible as tools, i.e. NBIMS-ICMM, bimSCORE and Arup's BIM-MMM. Among these three project AMs, only NBIMS-ICMM and Arup's BIM-MMM are freely accessible. Also, these two BIM project AMs are widely accepted in the global market. All the seven BIM-AMs at project scale were validated with case study projects. During application of NBIMS-ICMM and Arup's BIM-MMM, we realized that these AMs are easily understandable. Hence, these two AMs were adopted for assessing the selected BIM projects' (hereinafter project-x) process and performance maturity.

Further study on selected BIM project AMs was performed considering few measures, such as time taken for assessment, ease of understanding the terminologies in AMs, depth of assessment and number of participants required for assessments. Areas of interests (AOIs) and maturity levels in NBIMS-ICMM and Arup's BIM-MMM were studied. Furthermore, our study is on how these AMs can be adopted for training project teams to achieve project's expected BIM maturity. BIM Performance Assessments (BIMPAs) at different phases of the project result in several benefits (Gao 2011; Kam et al. 2013; Change Agents AEC 2013; Azzouz et al. 2016): (1) disclosure on whether usage of BIM leads to cost, quality and time efficiency, (2) Progressive assessment of BIM performance ensures that the project is on track and progress is as per plan or expectation, (3) Measuring BIM maturity in projects assists in upgrading BIM usage within projects, organizations and teams.

Table 1: Comparison among existing BIM project AMs reviewed

BIM-AMs V/S Factors for comparison	NBIMS-CMM	Characterization framework	BIM excellence PPPA	VDC scorecard	bimSCORE	Arup's BIM MMM	Goal driven method for BIM project evaluation
Number of measures	11	74	73 BIM Uses	56	56	23 (11 proj.+12 discipline)	34
Maturity levels	10	N/A	Model richness value 0-1	5	5	6	N/A
Status of project AMs.	Free	Research prototype	Commercial	Research prototype	Commercial	Free	N/A
Accessibility format	Tool	Framework	Framework	Framework	Tool	Tool	Framework
Depth of Assessment	less detailed	Most detailed	More detailed	More detailed	More detailed	Most detailed	Less detailed
Guidelines	Available	Available	Available	Available	N/A	Available	N/A
Evaluation style	External certified evaluator/ Self-evaluation	N/A	External certified evaluator to evaluate project's MUs	Multiple types of evaluation offered	Multiple types of evaluation offered	External certified evaluator/ Self-evaluation	N/A
Ease of use	User friendly	Need specialists	Need specialists	Need specialists	User friendly	User friendly	Need specialists
Key elements & category	Project level elements	Context, implementation & performance impacts	MUs & model based deliverables	Planning, technology, adoption & performance	Planning, technology, adoption & performance	Project & AECO discipline level elements	Project KPIs
Evaluation criteria	Project documents & models	External audit of project documents & interviews with BIM personnel	External certified evaluator can evaluate project's 73 MUs as an implementation template/Performance metric	Excel input form/web-based dashboard; full version includes an audit by consultant	Excel input form/web-based dashboard; full version includes an audit by consultant	Stakeholder explanation in an excel template	External audit of project doc. & interviews with BIM personnel

NOTE: This may not be an exhaustive list of the BIM project AMs available. It is not our intent to endorse any particular commercial product, but rather to provide suggestions for available options to evaluate project's BIM maturity & benchmark BIM performance. While *each AM is unique in terms of its evaluation context & intended users, similarities exist between their assessment criteria at the macro level. Readers can select the best AM for their needs based on their project's desired goals and vision for BIM execution.*

3. METHODOLOGY

Figure 1 shows the methodology for BIMPAs proposed in this study. It is expected that BIMPAs can benefit AECO industry in realizing current BIM performance levels and assist in achieving expected BIM maturity. The BIMPA process includes six major steps. First, a suitable BIM case that requires performance assessments is identified. The second step is the process of selecting a BIM performance measurement scale needed by the selected BIM case. During BIMPA scales selection process, it is essential to specify which of the five maturity scales, i.e. individual, team, organization, project and market scale, requires BIMPA for the selected BIM case. However, this study is limited to exploration of project scale BIMPAs.

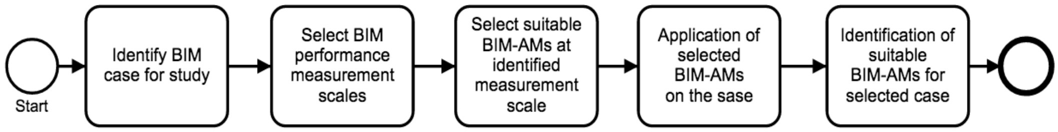


Figure 1: BIM performance assessment methodology

Each of the BIM performance measurement scales has several corresponding BIM-AMs developed by BIM researchers and organization for it. Selecting suitable BIM-AMs for the desired scale of performance measurement on the selected project is the third step. In the fourth step, the selected BIM-AMs are applied following the available guidelines. Then, the current BIM maturity level of the selected BIM case can be identified following the assessment procedures provided by the selected AMs in the fifth step. The final step is the identification and provision of suitable BIM-AMs for the selected case study. Later, it is essential to provide education and training for the selected BIM case associated stakeholders at different project lifecycle phases for reaching the expected BIM maturity.

4. CASE STUDY

In this study, a suitable BIM case has been identified and the above stated BIMPA methodology is applied. Process of applying the BIMPA methodology in the selected BIM case is described here. Initially, identification and selection of a BIM project was performed. Later, interactions with the key project stakeholders of the selected project for collecting their views on BIM adoption in project delivery process were undertaken. Subsequently, identification of BIM-AMs for the selected BIM case at different BIMPA scales was performed. With project assessments as the main focus of this study, the process and performance assessments of the selected BIM project were carried out. Finally, a suitable BIM project AM for the selected BIM case was identified by considering factors of various aspects, such as ease of understanding, time taken for assessment, detailed assessment capability, consistency in results for assessment objectivity, etc. Also, education and training for the selected BIM project associated stakeholders is a basic requirement. This BIMPA-driven education and training for the project stakeholder team and organization can facilitate the organization to achieve expected BIM maturity in delivery of its BIM projects.

4.1 Identification and selection of BIM projects in India

Necessary procedures for identification and selection of BIM projects in India were performed. Initially, survey was carried out to identify Indian AECO organizations that had adopted BIM in their project delivery process. Because construction market is booming in major metropolitan cities of India, our survey was limited to identification of BIM organizations in these metropolitan cities. Subsequently, BIM organizations and associated BIM projects were identified through BIM job websites for assessing BIM maturity of their projects. Further, we had an interaction with few of the Indian AECO industry field players. Our survey resulted in documentation of twenty-four (24) organizations in Bangalore, twenty-two (22) in Delhi and NCR, twenty (20) in Bombay, eighteen (18) in Ahmedabad, fifteen (15) in Chennai and thirteen (13) in Hyderabad, respectively. Even though we had identified BIM organizations in six (6) selected Indian cities, this study considered only BIM organizations within Bangalore as a preliminary study because, it has faster construction growth. We contacted these twenty-four (24) organizations in Bangalore through phone calls, emails and with direct meetings. Among them, seven (7) organizations refused to interact, twelve (12) organizations were hesitant to share the data of their projects and five (5) organizations accepted for BIM performance and maturity assessments of their projects. Among the five (5) BIM organizations that had accepted, one (1) organization was selected for our case study, this is because of the selected organization's project stakeholders' eagerness in realizing their project's process and performance maturity. And, for this organizations' eagerness in taking steps to improve the BIM maturity level of their projects.

4.2 BIM-AMs for the selected BIM case

In order to assess the BIM maturity of AECO projects, it is necessary to assess also the current BIM maturity of the organization and its key stakeholders involved in delivering BIM projects (Change Agents AEC 2013). Hence, we performed BIM performance assessments at three measurement scales in the selected BIM organization: (1) individual stakeholder competency assessment with BIM self-assessment tool (Landscape Institute 2016); (2) project assessment with NBIMS-ICMM and Arup's BIM-MMM; and (3) organizational assessment with Bew-Richards BIM maturity model (Bew and Richards 2008).

Organizational capability and maturity assessment can be performed by studying the BIM competency level of expertise in organization, level of BIM implementation, level of BIM engagement, and maturity level of the organization in BIM diffusion (Tamera and Pittenger 2016). Understanding the organizational capability and BIM maturity is a key for realizing the level of BIM maturity delivered in their projects. We performed interview with managing director in our first meeting to understand the BIM performance in their organization. This BIM organization, with an interest to improve their projects' BIM maturity had accepted for cooperating with us for assessing one (1) of their project.

Organizational BIM adoption needs support from its stakeholders and associated teams. BIM Expertise in the AECO organizations drive organization towards matured BIM adoption, effective BIM engagement, that can result in matured process of BIM project delivery and operation (Tamera and Pittenger 2016). Thus, second meeting was carried out with key stakeholders (participants) of the selected project (project-x) i.e. BIM manager (project manager), senior BIM expert (architectural and structural team head) and BIM expert (MEP team head). Individual stakeholder competency assessments were performed using BIM self-assessment tool on these key project stakeholders. Key participants in this assessment were given a brief introduction to BIM self-assessment tool. BIM self-assessment tool has fourteen questions with "yes/no" type and four (4) maturity levels, with results describing BIM competency levels of each participant.

Third meeting was performed with the key stakeholders of the project-x, to identify the suitable project AM. Here, NBIMS-ICMM and Arup's BIM-MMM were chosen. Project-x was at concept stage and key stakeholders involved in assessment process were not aware of the existing BIM-AMs. Hence, BIM manager and senior BIM expert involved in assessments as project participants were given a brief introduction on both the project AMs by the assessor. Through the results obtained from the comparison of assessment performed, the objectivity of both the AMs can be revealed. Also, via comparing the assessment results performed using both the AMs, features of these AMs can be discussed (such as ease of understanding, time taken for assessment, number and type of participants required during assessments and detailed assessment capability). Assessment results obtained will be used to compare both AMs by taking into account the ratings given by the participants and overlapping AOIs.

4.3 Results and discussions

Among the twenty-four identified Bangalore's BIM organizations, one organization with BIM project was chosen as BIM case based on the selection process described in previous sections. BIM performance measurements was conducted at three scales i.e. at individual stakeholder, organization and project with selected BIM-AMs.

In our first meeting, BIM maturity assessment of selected organization was performed with Bew-Richards maturity model i.e. UK's BIM maturity model including four maturity levels (level 0-3). Here, maturity levels were used as a benchmarking tool for assessing BIM maturity in selected organization and its project. Organizational BIM maturity in this case was found to be at level-1. This BIM stage can also be described as object based modelling stage, i.e. this organization and its team members had migrated from 2D to 3D and object based modelling & documentation. However, the BIM models in the projects they were delivering were single-disciplinary and deliverables were CAD documents. They did not have BIM based data sharing or collaboration. BIM was commonly used for communicating project plan, visualization and clash detection in this organization. This organization is using BIM in all their projects with major AECO disciplines involved. In simple words, BIM was diffused in all projects to an extent and organization teams were discovering the barriers for further diffusion.

In second meeting, individual stakeholder competency assessment was performed with key project stakeholders (i.e. BIM manager, senior BIM expert and BIM expert of project-x) by adopting BIM self-assessment tool. From the assessment results, we realized that all these participants BIM competency was at level-1. Normally, level-1 is the desired BIM competency level for basic BIM users. The BIM competency of these participants can be transferred towards level-2 by providing them essential training and top management support.

In third meeting, project-x's process and performance assessment was performed to identify BIM maturity in the project and for identifying the suitable BIM-AMs associated with projects. Project-x is a commercial building and located at Indiranagar zone of Bangalore. Project was at conceptual stage on the day of assessment. This project assessment includes two BIM-AMs (NBIMS-ICMM & Arup's BIM-MMM), two project participants (BIM manager and senior BIM expert) and one assessor (Co-author of this paper), to guide the participants on using AMs for grading BIM project-x. This assessment process developed into four results. By conducting this experiment, it was easy to realize which BIM-AM is comprehensive, easily understood and objectivity of the AMs (i.e. provides same results no matter who is involved in assessments).

First, the results of BIM assessments performed on project-x with NBIMS-ICMM is presented in Table 2. From the results attained, we realized that both the participants (P1 & P2), i.e. BIM manager and senior BIM expert had different views on the project's BIM maturity. And, their (P1 & P2) different views on project's BIM maturity is clear from the different ratings provided for six (6) AOIs. AOI ratings data provided by both the participants revealed that, they had different way of understanding on these BIM-AMs. Besides, they have same ratings for three (3) AOI, i.e. for data richness, timeliness/response and delivery method. The overall scores of project-x rated by BIM manager and senior BIM expert are 55.9 (Certified) and 79.7 (silver) respectively. We measured minimum level of BIM usage in project-x with NBIMS minimum BIM table. This minimum BIM level was measured by considering the views of BIM manager and senior BIM expert on project-x. As per NBIMS-CMM minimum BIM table, minimum level BIM assessment process resulted in "above minimum BIM level" by BIM manager and "below minimum BIM level" by senior BIM manager. BIM manager and senior BIM expert were from project-x and assessment was carried out in the same office. Even with this closeness in environment, the assessment results showed quantifiable variation. This raised the question on acceptance of NBIMS-ICMM assessment results in this BIM case. This assessment results indicated the need for suitable BIM-AM that can generate same assessment results, no matter which project stakeholder is participating in assessments, i.e. satisfying the subjectivity requirements of the tool.

Table 2: NBIMS-ICMM results of project-x from both the participants.

Area of Interest (AOI)	**BIM Manager (P1)**		**Senior BIM expert (P2)**	
	Rank order	Ratings	Rank order	Ratings
Data Richness	1	6.7	1	8.0
Life cycle views	7	5.0	9	7.0
Change Management	4	6.3	11	6.3
Roles or disciplines	6	5.4	8	7.2
Business process	3	6.4	7	7.2

Timeliness/Response	10	3.6	10	6.4
Delivery Method	5	5.5	5	7.4
Graphical Information	2	6.5	6	7.4
Spatial capability	9	3.8	4	7.5
Information accuracy	8	3.8	3	7.6
Interoperability/IFC	11	2.9	2	7.7
Overall score		55.9		79.7
Maturity level	Certified		Silver	

Second, the results of assessments performed on project-x using Arup's BIM-MMM is presented (see Table 3). Highlighted scores are for comparing the differences in scores between P1 and P2. In Arup's BIM-MMM, project BIM maturity can be measured by aggregating the results obtained in each AECO disciplines. Hence, both the participants, i.e. BIM manager and senior BIM expert were asked to take the help of project-x's Architectural, Structural and MEP services head for drawing results on selected project's BIM maturity and for further comparison. Project assessment results indicates that, both the participants had similar views on the project. AOI's target and current level scores data generated by BIM manager and senior BIM expert reveals that, they have similar way of understanding on Arup's BIM-MMM. And, the project-x's BIM maturity scores, i.e. AOI scores were similar, except minor variation in BIM execution plan AOI scores. We also measured the targeted level of BIM usage by these participants and results were similar, i.e. project target level overall score is 100% by P1 and 89% by P2. In Table 3, we have marked the differences in current and target level results by both participants P1 and P2. Project-x current level overall scores rated by participants P1 and P2 were 61% and 63% respectively. Arup's BIM-AM proving to be comprehensive and producing similar results in this BIM case, i.e. satisfying the subjectivity requirements.

Table 3: Arup's BIM-MMM results of project-x from both the participants

Area of interest	**BIM manager (P1)**		**Senior BIM expert (P2)**	
	Target level	Current level	Target level	Current level
Employee information requirement	5	4	5	4
BIM Design Data Review	5	3	5	3
BIM Execution Plan (BEP)	5	3	5	4
Project Procurement Route	5	3	5	3
Common Data Environment (CDE)	5	3	4	3

Document/Model Referencing, version control and Status	5	2	3	2
Marketing Strategy	5	4	5	4
Virtual Design Reviews (VDR)	5	2	3	2
Open Standard deliverables	5	4	5	4
BIM Contract	5	2	4	2
BIM Champion	5	4	5	4
Overall Score in percentage	100%	61%	89%	63%

Further, as part of the detailed study, both the BIM-AMs were compared considering few measures such as time taken for assessment, ease of understanding the terminologies in BIM-AMs, depth of assessment and number of participants required for assessments (see Table 4).

Table 4: Criteria comparison of NBIMS-ICMM and Arup's BIM-MMM AMs

Criteria	NBIMS-ICMM	Arup's BIM-MMM
Time Taken for assessment	30 min	60 min
Ease of understanding the terms in the AM	Participants involved in assessment process found the terms in AM as difficult to understand	Participants involved in assessment process found the terms in AM as easy to understand
Depth of Assessment (level of details)	Assessment at project scale	Assessments at individual disciplines and project scale
Number of participants required	One project stakeholder, i.e. project manager assessed the project's BIM maturity	Multiple project stakeholders, i.e. BIM Manager and individual discipline BIM experts assessed the project's BIM maturity

And, Table 5 provides the comparison of both the BIM-AMs using common AOI's and project's current maturity level in these AOI's. From comparison it is evident that, even though similar areas are taken for comparison, the rating level, i.e. project's current maturity level descriptions are different for each area. This further enhances the differences in understanding the terminologies in both AMs.

Table 5: Comparison of both the BIM-AMs using common AOI and current project stage in these AOI's

NBIMS-ICMM		Arup's BIM-MMM	
Area of interest	**Project's current maturity level**	**Area of interest**	**Project's current maturity level**

Data Richness	Maturity level 7: Completely authoritative information	Level of Development	4, measured: Consistent LODs for most similar elements, aligned with BEP
Delivery method	Maturity level 8: Web enabled services-secure	Common data environment (CDE)	3, Defined: Internal company team using recognized CDE adhered to common BIM standards
Interoperability/ IFC	Maturity level 8: Expanded information uses IFC's for Interoperability	Open standard deliverables.	4, measured: Successful import/reimport

Performing these BIM maturity assessments can benefit selected BIM organizations, individual stakeholders of selected project and the project as a whole in several ways: (1) The project participants involved in assessments can benefit from realizing their current level of maturity in BIM usage for identifying key lagging areas and training needs; (2) To identify the suitable AMs for selected BIM organizations future projects and for improving its BIM maturity; (3) To identify which BIM-AM gives correct results, i.e. based on consistency in results from key project participants and which BIM-AM is suitable for this organizations' BIM performance assessments necessities. Project-x's stakeholders have diffused BIM in architecture, structural and services disciplines, however their process of delivering BIM projects is at BIM stage-1. This organization and its stakeholders requires assistance on how to reach BIM stage 2 (i.e. model based collaboration). They need to be trained for designing and managing a building in an integrated data communication and sharing process. This process requires smooth communication and collaboration among all the stakeholders in the project. Project-x's team also needs assistance in BIM uses based project delivery. Even though assessment with this method involved more project participants and duration in comparison with NBIMS-ICMM. For project-x, Arup's BIM-MMM proves to be more comprehensive with its detailed assessments including 31 primary disciplines, 11 AOI and 6 maturity levels. And, Arup's BIM-MMM is easily understandable and producing similar results no matter who carries out project assessments. However, NBIMS-ICMM has its own benefits, like faster assessment process, few project participants required during assessment and quicker results for training the project stakeholders.

For delivering the BIM projects with next maturity level within this organization, it is essential to educate and train the project stakeholders in identifying and delivering key BIM uses for their project. First, we need to educate them on BIM object attributes that need to be updated, extracted and utilized during project design and construction process. Second is the process of delivering BIM models with expect level of detail at each project stage. Third, this organization had file based collaboration among project stakeholders, which need to be replaced by integrated web services. Fourth is the training project stakeholders on BIM as a collaborative process, means of communication and technology by software stimulating experiment, group research and team collaboration.

5. CONCLUSION

Global AECO industry is seeing a rapid transition from 2D drafting and 3D modeling into the BIM era. This shift requires owner organizations to assess, the level of BIM delivered in their projects and project stakeholders competency. BIMPAs at different scales are essential for realizing the current status of AECO organizations and corresponding projects. Meanwhile, choosing the suitable BIM-AMs is critical. This study classifies existing BIM-AMs into individual stakeholder, stakeholder teams, organizational, project and market scale. Further, 112 BIM organizations were identified from six major metropolitan Indian cities and these data will be made use for assessing BIM maturity at market scale in future work. For the present preliminary study, Bangalore's BIM organizations were considered for its faster growth in construction sector. Among them, one was selected for assessing its selected BIM project maturity.

BIMPAs were carried out at three measurement scales in the selected BIM organization: (1) Individual stakeholder competency assessment with BIM self-assessment tool; (2) Project assessment with NBIMS-ICMM & Arup's BIM-MMM; (3) Organizational assessment with Bew-Richards maturity model. Organizational capability and BIM maturity were found to be at level-1, i.e. object based modelling. The results from individual stakeholder competency assessments revealed that three BIM project stakeholders, i.e. BIM manager, senior BIM expert and BIM expert, are all at level-1 BIM competency. Project-x BIM process and performance assessment revealed two main outcomes: (1) The overall scores of Project-x in NBIMS-ICMM rated by participants 1 and 2 were 55.9 (Certified) and 79.7 (silver), respectively; (2) The overall scores of Project-x in Arup's BIM-MMM rated by participants 1 and 2 were 61% and 63%, respectively. NBIMS-ICMM has its unique benefits for the project assessment, e.g. faster assessment process, fewer project participants required in assessments and quicker results for training the project stakeholders. Meanwhile, Arup's BIM-MMM has benefits for project assessments with its ease of understanding, complete and detailed assessments. The selected organization's project stakeholders considered that Arup's BIM-MMM was suitable for their Project-x because its comprehensive assessments and satisfying subjectivity requirements.

Future work can include maturity assessment at market scale, i.e. collection of representative sample in Indian AECO industry and identification of Indian AECO project characteristics and special need for BIM performance AMs. Existing BIM project AMs are designed for different project types and requirements, with each AM having its benefits and limitations. Hence, there is also a need for categorizing the existing BIM-AMs based on project types.

6. REFERENCES

Arup (2014). Arup's BIM Maturity Measure Model. URL: http://www.arup.com/services/building_modelling [Accessed 3rd Nov 2015].

Landscape Institute (2016). BIM self-assessment tool.

URL:http://www.landscapeinstitute.org/knowledge/BIMSelfAssessment.php [Accessed 420th Oct 2015].

Azzouz, A., Shepherd, P. and Copping, A. (2016). The emergence of Building Information Modelling Assessment Methods (BIM-AMs). Proceedings of Integrated Design International Conference, 29th June – 1st July, Bath, UK.

bimSCORE (2013). bimSCORE [online]. URL: https://www.bimscore.com/index.php/welcome [Accessed 4th Nov 2015].

Bew, M. and Richards, M. (2008). Bew-Richards BIM Maturity Model. [Accessed 10th Sep 2015]

URL: http://res.cloudinary.com/engineering-com/image/upload/v1458324590/bew-richards_dqgxez.png

Cheng, J.C. and Lu, Q. (2015). A review of the efforts and roles of the public sector for BIM adoption worldwide. ITcon, Vol. 20, pg. 442-478.

Change Agents AEC (2013). BIM excellence performance measurement corporate services. URL: http://bimexcellence.com/ [Accessed 5th Oct 2015].

Mohideen, Kaja (2015). An overview of construction sector in Indian economy. International journal in management and social science. Vol. 3, Issue 2, pg. 217-226.

DCAMM (2015). BIM guidelines for design and construction. Division of capital asset maintenance and management. Commonwealth of Massachusetts.

Gao, J. (2011). A Characterization Framework to document and compare BIM implementations on construction projects. Doctoral dissertation. Stanford University, CA, USA.

Harvard UCMC (2016). BIM Uses Guide. Harvard University Construction Management Council. Harvard planning and project management division, Harvard University, Boston, MA, USA.

Lee, G. & Won, J., 2014. Goal-driven method for sustainable evaluation of BIM project. In: A. Mahdavi & B. Martens, eds. European Conference on Product & Process Modelling (ECPPM). Vienna, Austria Taylor & Francis

Kam, C., Senaratna, D., Xiao, Y. and McKinney, B. (2013). The VDC Scorecard: evaluation of AEC projects and industry trends. CIFE, Maharashtra, India.

MPA (2015). BIM Guidelines for vertical and horizontal construction. Capital programs and environmental affairs, Massachusetts Port Authority, MA, USA.

NIBS (2015). National BIM Standard-United States-version 3. URL: https://www.nationabimstandard.org/ [Accessed 4th Oct 2015].

McCuen, T.L. and Pittenger, D.M. (2016). Building Information Modeling for Airports (Project No. A11-03, Topic S09-07). URL: http://www.trb.org/Main/Blurbs/174386.aspx [Accessed 28th May 2016].

Sawhney, A. (2014). State of BIM adoption and outlook in India. RICS Research, Delhi.

RISK INFORMATION BASED EXPERT SYSTEM - A PARTICIPATORY MODEL

Priyadarshini Das & Gangadhar Mahesh

Department of Civil Engineering, National Institute of Technology Karnataka, India

ABSTRACT: *Construction involves processing of numerous inter-dependent risks. But risk management in the sector is still largely intuitive and mere system compliance. Meticulous efforts towards a system based approach is lacking. These lapses emphasize the need for developing an easy to use participatory model for risk management at construction project sites. A model that would not only enhance the effectiveness of the risk management process but also generate essential organisational knowledge that can be preserved for future use.*

The Risk Information Based Expert System (RIBES) presented in this paper has an user interface, a rule based inference engine and a knowledge base. The user interface is comprised of three modules namely, 'Risk Review', 'Query' and 'Solution' through which knowledge is banked, retrieved and created respectively. The Query Module can be used by all users to search for mitigation measures of risks they are unfamiliar with. Data entry through the Query Module initiates the Inference Engine to search for the risk in the Knowledge Base. This is made possible by a Rule Based Expert System. The Solution Module is an expert interface through which queries that could not be answered from the database are answered by knowledge engineers. The Knowledge Base eventually becomes a hub of organisational learning.

A set of rules is required by the expert system to retrieve data. Rules are conditional statements where every risk has a unique mitigation attached to it. The Rule Based Expert System invokes rules on the basis of multi-level attributes defining the risk. Rules are also created along with knowledge through the expert interface. The preliminary database comprises of a list of seventy five unique risks and mitigation measures classified into the following categories; Design, Community, Execution, Financial, Interface, Resource & Safety. The interfaces, rules and knowledge base are all arrived at by conducting several workshops & interviews across the hierarchy in a greenfield airport project.

KEYWORDS: *Expert Systems, Risk Management, Knowledge Management, Rule Based Systems*

1. INTRODUCTION

The construction sector to this day remains largely unorganised. Construction projects involve the processing of a wide range of information, the handling of imprecise data, and the managing of intricate interdependencies within the dynamic project environment (Hajdasz 2014). The increasing complexity as well as the difficulties imposed by on-site work, create the need for intelligent ways of supporting construction personnel in effective planning and management (Behzadan et al. 2008). The paper draws from two vital project management concepts namely 'Risk Management' and 'Knowledge Management' for building a model, which uses a 'Rule-based Expert System', to support construction personnel in their day to day decision making process.

In a construction project risk could severely constrain the primary objectives: time, cost, scope and quality (Serpella et al. 2014). Risk management is defined as the process of identifying and assessing risk, and to apply methods to reduce it to an acceptable extent (Tohidi 2011). To make an effective and efficient risk management it is necessary to have a proper and systematic methodology and more importantly, knowledge and experience of various types. Literature shows that risk management in construction projects is full of deficiencies that affect its effectiveness as a project management function and in the end, projects' performance (Serpella et al. 2014). Moreover, risk assessment practices involve high level of subjectivity due to their reliance solely on intuition, judgement or individual experience (Yildiz et al. 2014) of the construction personnel. A central element for the failure of the risk management process is the way in which knowledge in an organisation is managed (Perera et al. 2009). Therefore, the risk management process should adopt a continuous learning approach (Marshall et al. 1996) relying on past projects as real time scenarios to gain experience from and mitigate risks more effectively in future projects. Therefore, past knowledge becomes an important function of the risk management process and knowledge management plays an important role as a potential enabler of working skills (Rodriguez and Edwards 2008) with respect to managing risks.

Knowledge Management is a systematic and organized approach to improve the organisation's ability to mobilize knowledge to enhance decision making, take actions and deliver results in support of the underlying business strategy (Hsu and Shen 2005). In other words, organisations create, capture and utilize knowledge to achieve organisational objectives (Sommerville and Craig 2006). Post Project Reviews (PPR) are the most predominantly used form of Knowledge Management in a construction organisation. The ineffectiveness of a PPR is primarily due to its ad hoc nature, the unavailability of key staff during its preparation as they have been transferred to other projects and inefficient dissemination (Carrillo et al. 2011). Knowledge generated within each project is also lost when key staff resign, taking with them not only tacit knowledge, but also a potential source of competitive advantage (Kivrak et al. 2008, Anumba et al. 2005).

During shared activities, four modes of knowledge conversion take place by the exchange of tacit and explicit knowledge leading to a spiral effect of knowledge creation; They are named as socialization (tacit to tacit), externalization (tacit to explicit), combination (explicit to explicit) and internalization (explicit to tacit) (Nonaka and Takeuchi 1995). In construction projects when project teams manage change situations, knowledge is converted to form new knowledge through various interactions (Senaratne and Sexton 2008). Tacit knowledge could be analogous to day to day learnings at site with respect to managing risks which is not disseminated throughout the organisation. This kind of knowledge is generated regularly during construction activities but it is not well documented. As a result they are diluted with various other issues that the project teams need to manage daily. This research talks about the conversion of tacit site knowledge to explicit organisational learning i.e. 'Knowledge Banking' and vice versa i.e. 'Knowledge Retrieval' with the help of a Rule-based Expert System.

Rule-based expert systems solve problems using codified human expertise within a particular domain. Every domain has its own knowledge and reasoning humans, which can be emulated through automated rule-based systems (Engin et al. 2014). The collected knowledge forms the database of the system. The other major component of rule-based systems is the inference engine. It draws conclusions from the knowledge based on a set of rules. The properties of such systems that enable them to combine factual knowledge with judgement and communicate with users in their natural language make them valuable decision support tools for construction management (Mohan 1990). There are several advantages of such systems. They are permanent in nature and involves onetime cost. A single knowledge base can be used for several systems enhancing its functionality. Often these systems are designed by more than one expert thereby increasing the reliability of the knowledge base. These systems lack human emotions, which are sources of mistakes in most human based systems. Research on the use of intelligent systems in the construction industry has seen a significant rise in the previous decade (Irani and Kamal 2014). Such systems have been used for dispute resolution in the Egyptian context (Elziny et al. 2015) and to aid civil engineering students in cement concrete construction problems in Malaysia (Mosa et al. 2013) to name a few. The novelty of this research effort lies in the implementation of expert systems in a knowledge-based risk management process.

2. RESEARCH METHODOLOGY

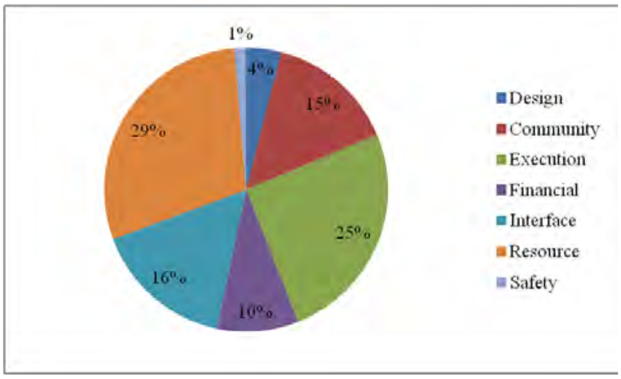
The research involved three phases of work namely knowledge acquisition, knowledge representation and system building. Knowledge acquisition involved the study of risk dynamics at a greenfield airport project. Knowledge representation involved the classification of risks and representation of the same through a risk register and risk matrix. The same register was to be used as the initial knowledge base (KB) for the expert system. System building comprised of developing a Risk Information Based Expert System (RIBES).

2.1 Knowledge Acquisition

A core team comprising of construction managers, planning engineers, frontline engineers, safety, quality and industrial relations personnel was formed. It was made sure that there is representation from the entire site hierarchy. The first phase of knowledge acquisition involved a preliminary workshop wherein all core team members were required to enlist the risks they have faced, are facing and expect to face in the future along with mitigation measures. From the list of risks obtained, critical area for each member was identified. They were interviewed to understand the intricacies of the critical area. The preliminary database comprising of 75 unique risks and mitigations was obtained from the workshop and detailed interviews. Information regarding other attributes like root cause, frequency, severity, ownership of risk etc. was also gathered during the detailed interviews. The second phase of knowledge acquisition involved an open forum where the idea of a digital platform for risk and knowledge management was introduced. The forum saw participation from frontline engineers, supervisors and construction managers alike. The forum came up with interesting value addition to the proposed digital platform in the form of an "Instant Risk Help Desk".

2.2 Knowledge Representation

A Risk Register was prepared wherein the risk information was documented and risks were classified into the following categories; Design, Community, Execution, Financial, Interface, Resource and Safety (Fig. 1a). The project was critically hit by the reluctant supply chain due to its remote location as about 29% of the risks were related to resources. One in every four risks was related to execution. The difficult terrain and prolonged monsoons were causes behind the same. Interdependent schedules of the major contractors led to interface issues. The area being politically sensitive, the project saw stoppage of blasting and quarrying operations by locals. To assign frequency and severity to the risks, standards defined by the organisation carrying out said construction were used. Frequency values 0.1, 0.25, 0.5, 0.75 and 1 denoted Remote, Unlikely, Occasional, Likely and Most Likely risks. Impact was classified as Insignificant, Minor, Significant, Major and Catastrophic and the corresponding values were 0.1, 0.25, 0.5, 0.75 and 1 respectively. Any risk causing a delay greater than 5 weeks was considered catastrophic while a delay of less than a week was considered insignificant. A Risk Matrix with frequency on the X-axis and severity on the Y-axis was prepared. The matrix was divided into three zones namely High Risk, Medium Risk and Low Risk indicated by the gradient of green, yellow and red colours as shown in Fig. 1b.



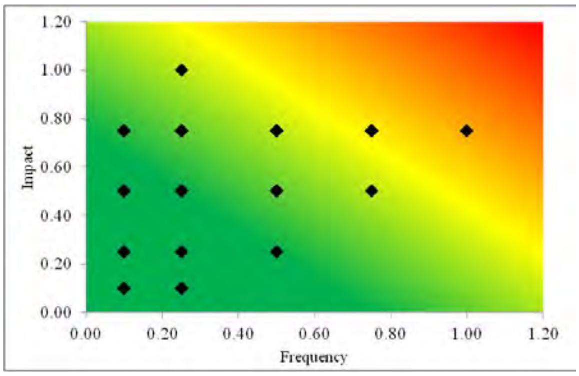


Fig. 1a, b: Classification of Risks and Risk Matrix Showing High, Medium and Low Risk Zones

All seventy five risks from the database were plotted on the matrix. Each plot on the matrix represents tasks which have similar frequency and severity values. The plots shown on the matrix appear fewer than seventy five because a lot of risks tend to have similar frequency and impact values. Fig. 1b shows that majority of the risks are in the Low and Medium Risk Zones. Inaccurate initial geotechnical survey due to which the execution team encountered large cavities during excavation was in the High Risk Zone.

The risk management process flow as observed from relevant documentation at site involved preparation of a risk register by the planning engineer and submission of the same to regional or cluster office for review. The entire process was unidirectional and restricted to the planning team. However, interactions with the Deputy Project Manager brought into light the fact that risks were identified and mitigated by frontline engineers regularly and the same were discussed in review meetings but the gap was in documenting the same in a manner that can be of use at a later point of time. The lapses observed at site emphasized the need to develop a system based approach involving participation from the entire hierarchy in order to prevent such valuable information from getting diluted among million other issues that regularly arise at site. Such a system would not only cater to the current project but also be a knowledge base for future projects of the similar kind.

2.3 System Building

The idea was to develop a model that derives from typical knowledge based architecture. The objective of the model was multifold. Firstly, to transform the risk management process into a cyclic flow of information rather than being unidirectional as explained in the previous section. Secondly, all the information generated in the system should be channelized into a database where it should be classified and stored for retrieval later on. Thirdly, the model should make the risk management process participatory that is garner participation from the entire hierarchy and not limit itself to just the planning and project management team. Finally, the entire process should be automated and hence rule based. To sum it up, the model should serve the purpose of a learning organisation to capitalize on their risk experience and build on it.

A rule based system was used instead of a case based system because case based systems be it structural, textual or conversational need lengthier and time consuming data entry. A rule based system facilitates ease of operation. Further, case based systems demand analytical reasoning to a much higher degree during data entry than a rule based system. As the system aimed to be participatory in nature, a rule based systems was opted for.

2.3.1 Risk Information Based Expert System (RIBES) Model

The function of the User Interface was to provide a platform for the user to communicate with the system. The User Interface comprised of three modules namely the Risk Review Module (RRM), Query Module and a Solution Module. Primary data entry point was through user at site. This included front line engineers, planning and estimation engineers, construction managers, project managers and stakeholders thereby rendering a participatory and inclusive nature to the model. Entry of project related information like type of project, Work Break-down Structure (WBS) etc. and risk related information like risk category, description, mitigation, ownership etc. occurred through the RRM interface. The same information stream flowed into the Risk Calculator where qualitative risk analysis took place. The Risk Calculator returned classified information like the Risk Register and Risk Matrix to the user. Thus, the functionality of the RRM was to give the user a holistic idea of the risk dynamics at site. The Working Memory was analogous to the Random Access Memory of a computer and it stored temporary data.

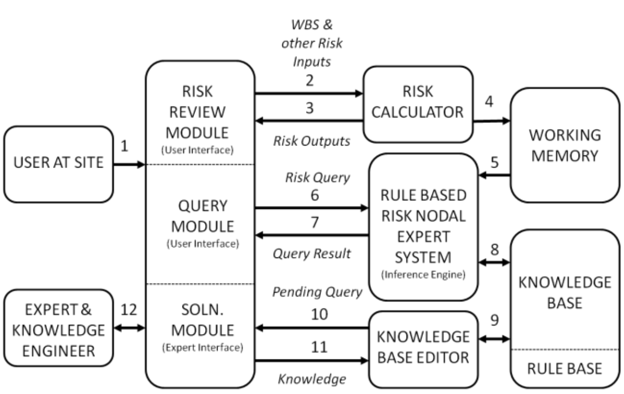


Fig. 2: The Risk Information Based Expert System (RIBES) Model

The Query Module was designed for date retrieval. Data entry through the Query Module initiated the search for the same in the Knowledge Base. This was made possible by a Rule Based Nodal Expert System. The Rule Based Nodal Expert System or the Inference Engine invoked rules on the basis of multi-level attributes defining the risk as shown in Table 1. Rules are conditional statements and were derived from the attributes. They were stored in the form of a Rule Base as shown in Fig. 2. Table 2 at the end of this paper elaborates the rules used in the proposed system. The rules enabled the system to come up with mitigation measures for a specific risk.

The Solution Module was an expert interface through which queries that could not be answered from the database were answered by knowledge engineers. Every unanswered query was stored and the system enabled user to answer the same through the Solution Module. Every time such a stored query was answered a rule was added to the system. It is to be noted that just like during initial data entry, a user was required to define the risk in terms of two attributes, even in the Solution Module, the user was required to do the same. Thus, the rule base also grew with the knowledge base. The credibility of the solution was validated by a Knowledge Base Editor consisting of a team of construction personnel who were experts in the field. The KB eventually became a hub of organisational learning.

Table 1: Two level attribute system

Risk	Attribute 1	Attribute 2	Mitigation
Lack of accessibility in the transportation of aggregate	Lack of access	Transportation	Sequential Planning of Logistics or Alternate Route
Non – availability of approved drawing at site	Non- availability	Drawings	Depute a single point contact for regular co-ordination between design team and execution team

Implementation of the above model not only facilitated systematic risk management in the organisation but also functioned as a tool for Knowledge Management. The model included the following knowledge conversions: Knowledge Banking, Knowledge Retrieval and Knowledge Creation. In Fig. 2 the path 1-2-4-5-8 shows the process of knowledge banking in which information from the lowermost level of operation is collected and stored as knowledge in the data base. The path 1-6-8-7 shows the flow in which a query is floated, the same searched in the database and the result returned. Thus, knowledge retrieval takes place. The above mentioned paths involve conversion of site learning to organisational learning and vice versa. The longest path is the knowledge creation path which is 1-6-8-9-10-12-11-9-8-7. It illustrates the process by which a query not found in the database is answered by a knowledge engineer or expert. This initiates the conversion of tacit organisational learning to explicit.

2.3.2 RIBES Web-based Application

Implementation of the model was made possible by developing a web based application namely RIBES. Linux

Operating System with Apache 2 web server was used with PHP as programming language. MySql was used as the RDBMS (Relational Database Management System) for storing data. The application was developed to the extent of a minimum viability product. Data entry was made possible using a drop down menus. Fig. 3 illustrates the main screen of RIBES comprising of three modules namely Risk Review, Query and Solution. A tab for Stakeholder Perspective was an additional feature. Also, by clicking on RIBES on the left hand top corner, it was possible to return to the main screen from anywhere in the application. The right hand top corner had similar navigation buttons, to return to main screen, risk review module or stakeholder module respectively from anywhere in the application.

Fig. 3: Main Screen of the RIBES web - based application

The 'New Risk Entry' form served as the preliminary data entry point for the entire application. This made the application participatory as data could be entered by front line engineers, planning engineers, construction and project managers alike. It was required to enter a risk description followed by the risk category. As mentioned in the previous section risk categories consisted of Design, Community, Execution, Financial, Interface, Resource and Safety. Data entry was made possible using a drop down menus.

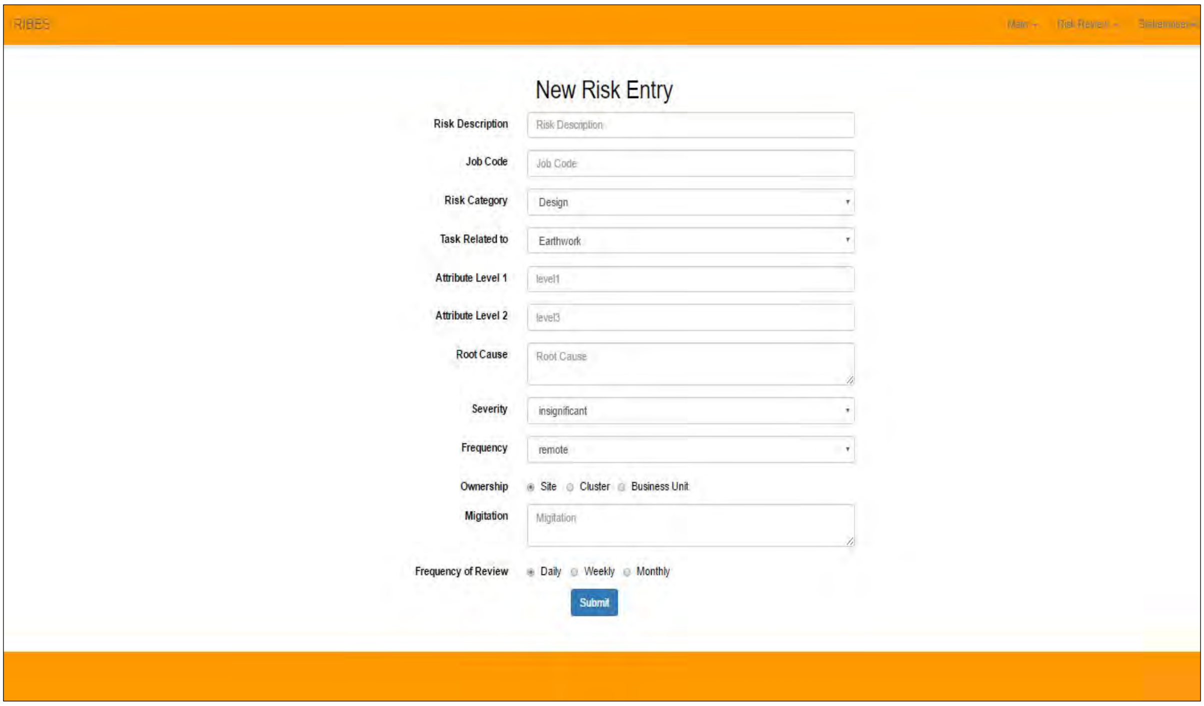


Fig. 4: New Risk Entry Form of the RIBES web - based application

Similarly, user was required to select which task the risk is related to. Options available were Earthwork, Structural Concreting, Pavement Concreting, Cross Drainage Works, Land Hand Over so on and so forth. After this user had to define the entered risks in terms of two level attributes. This would later on be required for Risk Query Search. If user queried for the same attribute names, the entered risk should be returned. Following the attribute names, user was required to enter a possible root cause of the entered risk. Severity and Frequency was needed to be entered pertaining to the risk. Severity drop down menu consisted of Insignificant, Minor, Significant, Major and Catastrophic and Frequency consisted of Remote, Unlikely, Occasional, Likely and Most Likely. Assigning the ownership of the risk is of prime importance in any risk management process hence the user was required to specify who would take care of the risk; Site, Cluster or the Business Unit. Then the user is required to specify a mitigation measure that has been adopted to resolve the entered risk and finally user needed to specify whether the risk and the effectiveness of its mitigation measure is to be reviewed on a daily, weekly or monthly basis. Fig. 4 illustrates the 'New Risk Entry' form.

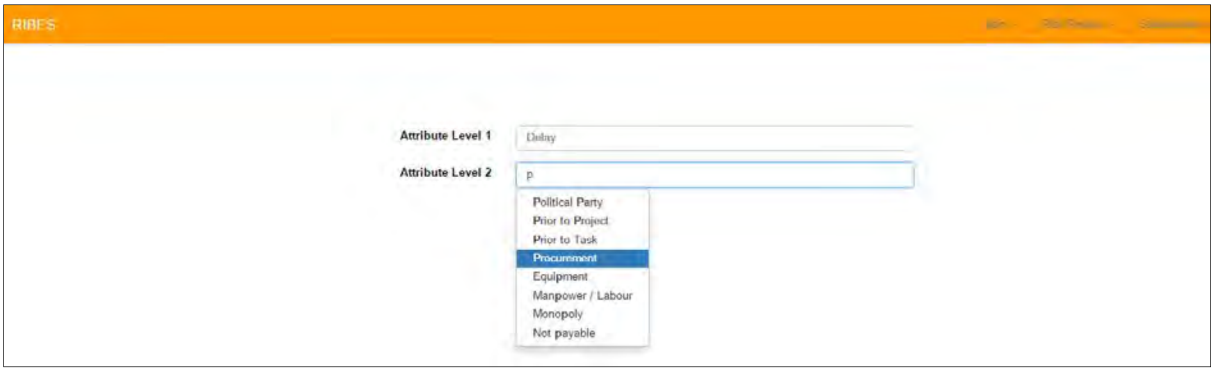


Fig. 5: Query Module Enabling Selection of Attributes Levels

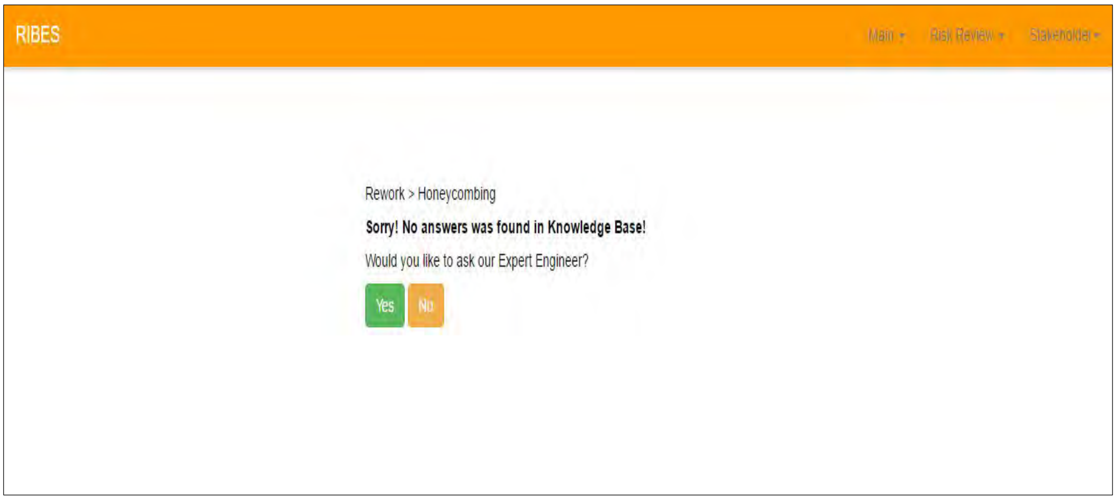


Fig. 6: Query Module prompting User to submit a Query to Expert Engineer

In the Query Module, the user was needed to select which task the queried risk would be related to. Once, the task was selected user was further needed to streamline by defining which category the queried risk would belong to. It is to be noted that 'Task related' and 'Category' were both entered during 'New Risk Entry' form and was stored in the 'Risk Register'. The application matched the same and a result was returned. Once the task related to and category was selected, the user was required to define the risk to be queried in terms of two attributes. Attribute 1 described the event of risk and Attribute 2 most often described the causative or further specified the risk query. Fig. 5 illustrates the same. If query was not found in the data base, the Query Module retuned a screen as illustrated in Fig. 6. The application facilitated answering of such queries through the solution module.

The Expert Engineer is required to click on the 'Answer Question' tab which displayed the 'Answer the question' form as illustrated in Fig. 7. This was similar to the 'New Risk Entry' form with predefined Category, Task, Description and Root Cause fields as the same had already been entered in preceding operations. Once necessary information was entered by Expert Engineer, the same was saved in the Knowledge Base. The same was validated by viewing the Risk Register from the Risk Review Module (Main Screen) as illustrated before.

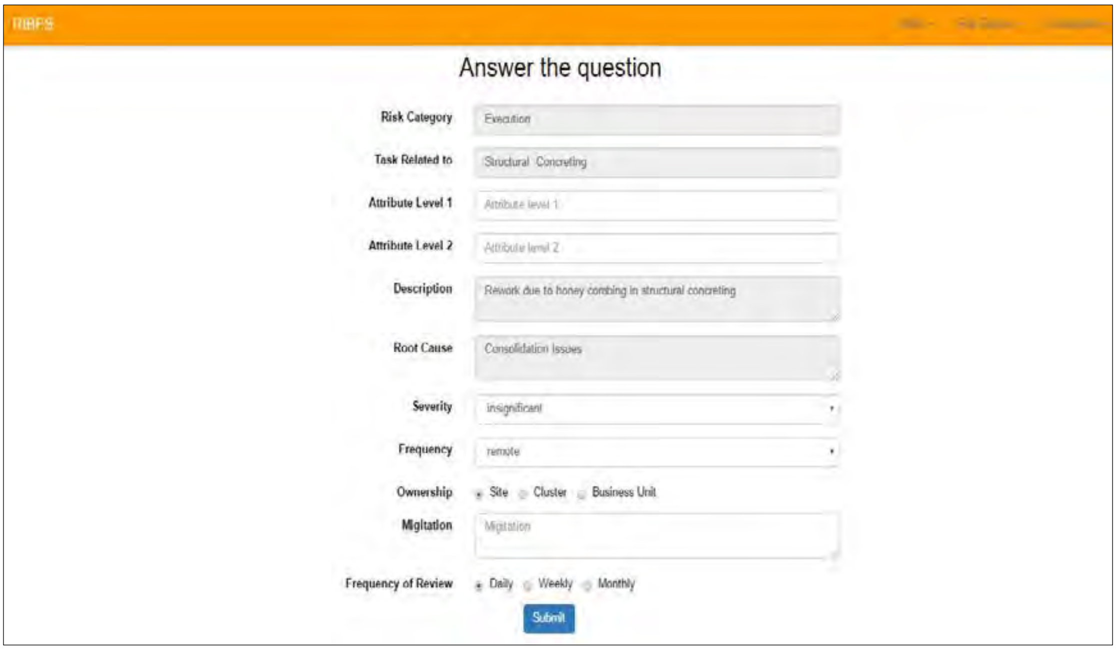


Fig. 7 - Solution Module Displaying the 'Answer the Question' form

2.3.3 Rule Base

Rules enabled the application to retrieve data when queried. Table 2 contains few rules used by the application to retrieve data based on category, attribute levels 1 and 2. The entire rule base contained 52 rules.

Table 2: The Rule Base

Rule ID	IF	Category	Attribute Level 1	Attribute Level 2	THEN	Mitigation
R1	IF	Design / Specification	Delay / Inconstructible	Prior to project	THEN	Check for critical structures, outsource / transfer to third party
R2	IF	Design /	Delay /	Prior to task	THEN	Outsource / transfer to third party

		Specification	Inconstructible			
R3	IF	Design / Specification	Delay / Inconstructible	During task	THEN	Depute a single point contact for daily co-ordination with design team
R4	IF	Resource	Delay	Prior to project	THEN	Streamline specialized items and prioritize them in the schedule
R5	IF	Resource	Delay	Prior to task	THEN	Search for alternatives, purchase locally
R6	IF	Resource	Delay	During task	THEN	Purchase locally
R7	IF	Execution	Delay	Prior to project	THEN	Ensure all statutory pre-requisites are attended to timely, analyse phenomenon such as over moisture, provision for time buffer in schedule
R8	IF	Execution	Delay	Prior to task	THEN	Try to alter to parallel tasks, when situation favourable put it more resource to complete on time
R9	IF	Execution	Delay	During task	THEN	Over time, pump up the resources
R10	IF	Interface	Delay	Prior to project	THEN	Establish an interface document at project commencement with approval from all stakeholders
R11	IF	Interface	Delay	Prior to task	THEN	Ensure all requirements of the interface document are fulfilled, position a one point contact for correspondence regarding issue
R12	IF	Interface	Delay	During task	THEN	Position one point contact and carry out continuous correspondence regarding issue
R13	IF	Resource	Non-availability / Shortage	Equipment	THEN	Prior preparation of resource allocation chart and ensure procurement of equipment on site before hand

Rule ID	IF	Category	Attribute Level 1	Attribute Level 2	THEN	Mitigation
R14	IF	Resource	Non-availability/ Shortage	Consumable	THEN	Purchase locally, find alternate sources
R15	IF	Resource	Non-availability / Shortage	Manpower / Labour	THEN	Outsource, skill development
R16	IF	Resource	Non-availability / Shortage	Contractor	THEN	Re-negotiate with existing contractors or arrange through centralised negotiations from other projects of the company
R17		Resource	Non-availability / Shortage	Staff	THEN	Reassign roles, hire locals on contract
R19	IF	Resource	Non-availability / Shortage	Earth / Soil	THEN	Identification of borrow area satisfying criteria at a much advanced stage, quality testing and stock piling of the same
R20	IF	Resource	Non-availability / Shortage	Water	THEN	Purchase or Additional purification / RO plant from sources otherwise not suitable

3. CONCLUSION

The research investigates shortfalls in the existing risk management process flow of construction organisations and proposes a participatory model namely RIBES that not only facilitates meticulous risk management at site but also caters to the Knowledge Management of the organisation. The developed model performs threefold functions namely Knowledge Banking, Knowledge Retrieval and Knowledge Creation. The same is facilitated by an expert system with three user interface modules namely Risk Review, Query and Solution.

Technology intervention in Construction Project Management especially Risk Management has immense potential. Said research is an attempt to initiate the use of automation in Risk and Knowledge Management in construction organisations. The web-based application developed is a minimal viability product and can be furthered into a full version prototype with better user experience. Additional parameters can be incorporated during data acquisition.

For example if cost is hampered or schedule is compromised. A feedback mechanism can be initiated which will keep track of whether risk was mitigated by the mitigation measure prompted by the system or not. This will in turn help in measuring the accuracy of the Knowledge and Rule bases.

The Knowledge & Rules bases have been developed by conducting workshops and interviews at a single project. The said application when implemented across projects and business units will lead to a massive encapsulation of information and effectively become valuable asset for the company. Such databases can then be used for data analytics for example seasonal risks, regional risks, most threatened activities on the schedule etc. Further, other already automated project management functions like schedule and cost performance monitoring can be clubbed into the system for holistic management of project situations at all times.

4. ACKNOWLEDGEMENT

The authors gratefully acknowledge Larsen and Toubro Constructions for facilitating the study.

5. REFERENCES

Anumba, C., Egbu, C. and Carrillo, P. (2005). *Knowledge management in construction*. Oxford: Blackwell Pub.

Behzadan, A., Aziz, Z., Anumba, C. and Kamat, V. (2008). Ubiquitous location tracking for context-specific information delivery on construction sites. *Automation in Construction*, 17(6), pp.737-748.

Carrillo, P., Harding, J. and Choudhary, A. (2011). Knowledge discovery from post-project reviews. *Construction Management and Economics*, 29(7), pp.713-723.

Elziny, A., Mohamadien, M., Ibrahim, H. and Abdel Fattah, M. (2016). An expert system to manage dispute resolutions in construction projects in Egypt. *Ain Shams Engineering Journal*, 7(1), pp.57-71.

Engin, G., Aksoyer, B., Avdagic, M., Bozanlı, D., Hanay, U., Maden, D. and Ertek, G. (2014). Rule-based Expert Systems for Supporting University Students. *Procedia Computer Science*, 31, pp.22-31.

Hajdasz, M. (2014). Flexible management of repetitive construction processes by an intelligent support system. *Expert Systems with Applications*, 41(4), pp.962-973.

Hsu, S. and Shen, H. (2005). Knowledge management and its relationship with TQM. *Total Quality Management & Business Excellence*, 16(3), pp.351-361.

Irani, Z. and Kamal, M. (2014). Intelligent Systems Research in the Construction Industry. *Expert Systems with Applications*, 41(4), pp.934-950.

Kivrak, S., Arslan, G., Dikmen, I. and Birgonul, M. (2008). Capturing Knowledge in Construction Projects: Knowledge Platform for Contractors. *Journal of Management in Engineering*, 24(2), pp.87-95.

Marshall, C., Prusak, L. and Shpilberg, D. (1996). Financial Risk and the Need for Superior Knowledge Management. *Proceedings of California Management Review*, pp.77-101.

Mohan, S. (1990). Expert Systems Applications in Construction Management and Engineering. *Journal of Construction Engineering and Management*, 116(1), pp.87-99.

Mosa, A., Taha, M., Ismail, A. and Rahmat, R. (2013). An Educational Knowledge-based System For Civil Engineering Students in Cement Concrete Construction Problems. *Procedia - Social and Behavioral Sciences*, 102, pp.311-319.

Nonaka, I. and Takeuchi, H. (1995). *The knowledge-creating company*. New York: Oxford University Press.

Perera, B., Dhanasinghe, I. and Rameezdeen, R. (2009). Risk management in road construction: The case of Sri Lanka. *International Journal of Strategic Property Management*, 13(2), pp.87-102.

Rodriguez, E. and Edwards, J. (2008). *Before and after Modeling: Risk Knowledge Management is required*.

Senaratne, S. and Sexton, M. (2008). Managing construction project change: a knowledge management perspective. *Construction Management and Economics*, 26(12), pp.1303-1311.

Serpella, A., Ferrada, X., Howard, R. and Rubio, L. (2014). Risk Management in Construction Projects: A Knowledge-based Approach. *Procedia - Social and Behavioral Sciences*, 119, pp.653-662.

Sommerville, J. and Craig, N. (2006). *Implementing IT in construction*. London: Taylor & Francis.

Tohidi, H. (2011). The role of risk management in IT systems of organisations. *Procedia Computer Science*, 3, pp.881-887.

Yildiz, A., Dikmen, I., Birgonul, M., Ercoskun, K. and Alten, S. (2014). A knowledge-based risk mapping tool for cost estimation of international construction projects. *Automation in Construction*, 43, pp.144-155.

INVESTIGATING THE RELATIONSHIP BETWEEN BIM ADOPTION AND TECHNICAL CONDITIONS OF CONSTRUCTION COMPANIES: CHINESE PRACTICE

Ying Hong& Samad M. E. Sepasgozar

University of New South Wales, Australia

Ali Akbarnezhad

University of New South Wales, Australia

ABSTRACT: *Construction companies have been strongly encouraged to use Building Information Modelling in real practice. However, the progress of BIM implementation is still relatively slow. The focus of previous studies has been placed mainly on exploring different BIM applications and identifying barriers of BIM usage based on individuals' intention to use the relevant software programs. However, few efforts have been made to investigate the effects of company intention which is mainly related to the BIM performance in practice. This study aims to identify factors that affect the BIM adoption process at the company level regarding perceived need, ease of maintenance, and downtime during the construction life cycle. Quantitative and qualitative information are collected through survey and face-to-face interview of Chinese professions. Structural equation modelling analysis is used to quantify the relationships between influential factors and company's intention towards BIM utilization. Results presented in this paper shows five factors (BIM awareness, perceived need to use BIM, perceived usefulness, technical condition and downtime) affect the companies' intention of BIM adoption.*

KEYWORDS: *BIM adoption, awareness, downtime, perceived need, Chinese construction industry.*

1. INTRODUCTION

Building Information Modelling (BIM) has been advocated as the development and use of a computer software model to simulate the construction and operation of a facility by Associated General Contractor of American (2006). Benefits associated with BIM implementation in construction projects include savings of project costs and duration (Gledson et al., 2012, Azhar, 2011), improved product quality (Newton and Chileshe, 2012, Hanna et al., 2013), more efficient working processes (Yan and Damian, 2008), and improved project team collaboration (Poirier et al., 2015, Sebastian et al., 2009). By realizing benefits associated with BIM implementation, facility owners are dedicated to using BIM in their projects, especially healthcare projects (Chen et al., 2011). Meanwhile, Ministry of Housing and Urban-Rural Development of China aimed to achieve the digitalization goal within construction firms in the 12th National Five-Year Plan (Jin et al., 2015). With the huge demands of BIM utilization, understanding factors affecting BIM adoption decision in Chinese construction companies is becoming necessary. However, there is currently a lack of studies that focusing on evaluating relationships between BIM performance and company intention in implementing BIM. Previous studies placed more attentions on investigating BIM adoption in architectural firms (Ding et al., 2015), while contractors as the information consumer in construction activities are also playing critical roles in wide-spreading BIM utilization. Various adoption studies (Frambach and

Schillewaert, 2002, Koebel et al., 2003, McCoy et al., 2010, Hameed et al., 2012) discuss the importance of the adoption process in ensuring the success of the implementation of such advanced technologies. However, there has been less attention to the investigation of BIM adoption by comparing construction companies' behavior in developing and developed countries at the organization level. Investigation of such a process would be complicated as construction activities have been widely recognized as a complex system and distinctly different from other industries (Dubois and Gadde, 2002, Straub, 2009). For example, much research (Park et al., 2012, Rampersad et al., 2012) focus on the application or extension of technology acceptance model (Motamedi and Hammad) (Davis et al., 1989) to predict adoption of information communication technologies (ICT) in construction. The original TAM model focuses on the acceptance of technology by individuals, not adoption by organizations. It does not consider the role of accumulated management experience and the competitive attributes, nor is it tailored to the construction context. The process is even more complicated in construction. This complexity originates from the lack of uniformity of project decision makers and the variety of differentiated activities involved in any construction project (Cooper, 1998, Dubois and Gadde, 2002, Straub, 2009, Ozorhon et al., 2013). That is why simple extensions of adoption models from other fields of study to construction have been limited. As such, this paper fills a gap in knowledge by a systematic investigation of two construction industry practices and provides an empirical model for understanding this process in construction. Thus, this study aims to formulate a BIM adoption model via identifying factors affecting BIM adoption decision throughout the project lifecycle. Structural equation modelling analysis will be used in validating proposed model in this study. This paper contains three main parts; the first part summarises potential factors affecting the BIM adoption decision and proposes a generic BIM adoption model. The second part explains research approach and analysis methods. The last part presents analysis results and major findings of this study.

2. LITERATURE REVIEW

The technology acceptance process refers to a series of behavioural states that a technology user passes through, which leads to the adoption or rejection of an information technology (Howard and Moore, 1988). It is an act of a user within a company during the technology implementation into current daily operations (Damanpour and Schneider, 2006, Hartmann et al., 2008). Studies from the psychological viewpoint have been developed based on the technology acceptance model for example (Featherman and Pavlou, 2003, Mirchandani et al., 2008). Technology acceptance model is proposed by Davis (1989) to predict individual behaviour regarding the use of technology through two constructs: usefulness and ease of use. Where customer behaviour as potential adopters has been pursued in construction, it has been almost exclusively about predicting information technology usage. The most detailed examination of new technology adoption has occurred in the information technologies (e.g. Amoako Gyampah and Salam (2004); Adriaanse et al. (2010); and Park, Son et al. (2012)). These studies neglect construction onsite technology adoption (i.e. tools, plant and equipment) and the vendor side of the process. In addition, according to Yousafzai et al. (2007), TAM does not consider external factors (e.g. vendors' co-operation, social influence, and task-technology fit) on individuals' perception of its constructs. Theory of Reasoned Action (TRA) (Ajzen and Fishbein, 1977) is the base of psychological theories. TRA concerned with the factors of conscious intention and attitude towards a behaviour defined by salient beliefs about the consequences of performing the behaviour multiplied by the evaluation of those consequences (Davis et al., 1989). TAM, as a predictor of the adoption of new information systems, theorizes that individual's acceptance of new technology is psychometrically impacted by two external factors Perceived Usefulness and Perceived Ease of Use.

Lee et al. (2013) investigates BIM adoption in Korea and identifies factors affecting BIM acceptance from an individual and company perspective. They examine the relationship on perceived usefulness, perceived ease of use, and company's intention to accept BIM. In contrast to previous studies, the results of their study show that neither perceived usefulness nor perceived ease of use has a direct relationship with company intent to accept BIM. As this study investigated the BIM acceptance in Korea, and the result is against previous findings, the generalizability of the model is questionable. Ding et al. (2015) targets on identifying key factors influencing BIM adoption in large Chinese architectural firms. The proposed model in this study assesses the relationships between the main factors and Behavioural Intention. However, factors identified in this model mainly cover the pre-implementation area. While previous studies notice that companies may face significant challenges in operating and maintaining BIM files in early adoption phase (Mutai, 2009). Therefore, a model should be developed based on the previous reliable models such as Davis (1989) and Rogers (2003), and covers overall process of BIM implementation; meanwhile examine the model in different countries, particularly large construction industries such as China. In this proposed model, Companies' Intention to use BIM (CI) is regarded as the ultimate factor that receives influences from other factors and representing the strength of a company's willingness in adopting and implementing BIM. Table 1 summarises the focuses of other studies in corresponding variables, as well as their limitations.

2.1. Technical Condition

Technical Condition refers to technical supports which are available for company and individuals during BIM implementation. This variable is measured in following four aspects: received professional support in hardware/ software selection, received technical support in BIM implementation, training that has been provided to staff, and offered rewards to encourage the usage of BIM. The hypothesis is proposed as following:

H1: Technical Condition (TC) has positive effects on Companies' Intention to Use BIM.

2.2. BIM Awareness

Technology awareness has been reported as an important factor influencing the user intention towards accepting a new technology. While BIM awareness (AW) can be different as some of users or companies may be aware of BIM and its function. However, they may not be aware of the technical function of BIM and its applicability to resolving different construction problems. Also, the awareness of various levels of managers can differently affect the BIM adoption. Therefore, the AW can positively affect the construction companies' support technical condition and finally their intention to use BIM as summarized here:

H2a: BIM Awareness (AW) has positive effects on Technical Condition.

H2b: BIM Awareness (AW) has positive effects on Companies' Intention to Use BIM.

2.3. Perceived Need

Perceived Need, in this study, is described as a company feels the need to adopt BIM. (Manley, 2008) found that the implementation of intellectual innovation in construction firms helps to establish stronger external relationships with other project participants and attracts attentions of advanced clients. Factors that may initiate a company's perceived need include leaderships' innovativeness (Lee et al., 2013), building up company competitiveness (Sexton and Barrett, 2003), contractual requirements from clients (Adriaanse et al., 2010), and influences from other project participants.

H3a: Perceived Need has positive effects on Technical Condition.

H3b: Perceived Need has positive effects on Companies' Intention to Use BIM.

2.4. Perceived Usefulness

Perceived Usefulness, originated from Technology Acceptance Model (Davis, 1989). PU has been defined as the degree to which an individual belief that using a system would enhance his/her job performance. In this study, Perceived Usefulness mainly covers direct and indirect benefits associated with BIM implementation. In this case, the PU can positively affect the construction companies' support and eventually their intention to use BIM as summarized here:

H4a: Perceived Usefulness (PU) has positive effects on Technical Condition.

H4b: Perceived Usefulness (PU) has positive effects on Companies' Intention to Use BIM.

2.5. Ease of Operation and Maintenance

In technology acceptance field, Ease of Operation and Maintenance is termed as Perceived Ease of Use, which was defined by (Davis, 1989) as the degree to which a person believes that using a particular system would be free of effort. In this study, EOM focuses on the BIM software operation, BIM models maintenance, and hardware upgrading. Hypothesises are summarised here:

H5a: Technical Condition has positive effects on Ease of Operation and Maintenance (EOM).

H5b: Ease of Operation and Maintenance (EOM) has positive effects on Companies' Intention to Use BIM.

2.6. Down Time

Down Time refers to a period that BIM fails to provide or perform its primary function either planned or unplanned. The transition from traditional CAD drafting to BIM modelling causes higher requirements of hardware's capability. The study of Rogers et al. (2015) found that the failure BIM adoption was significantly apportioned to the cost of downtime. Hence, hypothesizes are summarised as following:

H6a: Technical Condition has positive effects on Down Time (DT).

H6b: Down Time (DT) has positive effects on Companies' Intention to Use BIM.

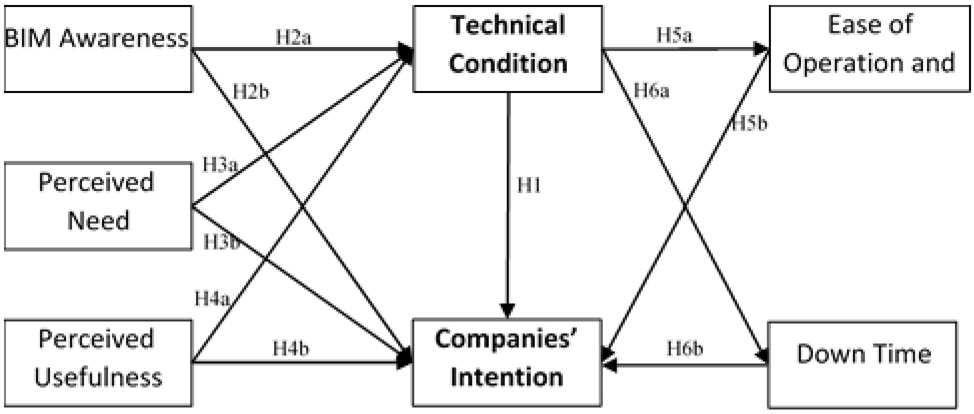


Figure 1 Research Model

Table 1 Variables' definitions in previous studies

Latent Variable	Similar term in previous studies	Focus of similar term
Technical Condition	Technical Support (Ding et al., 2015)	Ding et al. (2015) focuses on technical supports that an organization received during BIM implementation.
	Organizational Support (Lee et al., 2013)	Lee et al. (2013) placed more attentions about how much effort that an organization has endeavoured to achieve a better implementation results.
BIM Awareness	Knowledge (Rogers, 1995)	Rogers (1995) mainly measures this variable regarding individual user's knowledge about technology capability, its feature and potential use.
	Top manager's knowledge (Parida et al., 2010)	(Parida et al., 2010) focuses on top manager's knowledge in ICT tools.
Perceived Need	Subjective Norm (Son et al., 2015)	Son et al. (2015) believe that individual's acceptance of BIM is influenced by people who are important to them.
	Motivation (Ding et al., 2015)	The study of Ding et al. (2015) terms Perceived Need as motivations of BIM adoption, which consists of two parts personal motivation of BIM usage and external motivations like contract obligation. Similar with Son, Ding puts more focuses on individual perspective.
Perceived	Perceived Usefulness	Lee et al. (2013) believes that perceived usefulness of BIM

Usefulness	(Lee et al., 2013)	implementation can be reflected in improved working ability and productivity.
	Perceived Usefulness (Xu et al., 2014)	In the study of Xu et al. (2014), Perceived Usefulness is heavily associated with BIM functions (i.e. visualization and monitoring).
Ease of Operation and Maintenance	Perceived Ease of Use (Son et al., 2015)	Son et al. (2015) measures Perceived Ease of Use regarding technical complexity, and training sessions provided by the company.
	Perceived Ease of Use (Xu et al., 2014)	Perceived Ease of Use has been proved as one of the primary variables of BIM adoption in Chinese construction industry, regardless of specialities (Xu et al., 2014).
Down Time	Perceived Cost (Xu et al., 2014)	The large amount of staff number brings Chinses construction companies a significant financial concern in hardware upgrading (Xu et al., 2014).

3. RESEARCH METHOD

This study was employed face-to-face interview technique and designed a questionnaire to obtain quantitative and qualitative information. The questionnaire was prepared in two languages to collect data from two countries. To increase the reliability of the respondents and data, the questions were translated into Chinese and an external body was asked to translate back to English to make sure the translation is clear and correctly have been done. The questionnaire uses 7-point Likert scale to measure each manifest variable. Research participants were recruited from senior personnel by Chinese construction companies. The main criteria for select participants were their background regarding BIM experience or knowledge. A total number of 84 out of 90 valid responses were received. Respondents' backgrounds cover residential buildings, commercial buildings, and infrastructure projects. The respondent analyse shows that BIM was used for limited purposes such as quantity take-off, clash detection, and 3D visualisation are most frequently used BIM applications among respondents. Table 2 presents respondents' profiles.

Table 2 Respondent Profile

Item		Percent (%)
Respondent's Industry	Residential	35.71%
	Commercial	32.14%
	Infrastructure	32.14%
Period of Using BIM	Non-users	30.95%
	<12 months	13.09%
	1-2 years	26.19%
	> 2 years	29.76%
Position	Engineer	62.50%
	Design Personnel	16.07%
	Others (e.g. Estimator, Project Manager)	21.42%
Most Frequently Used BIM Applications	Quantity take-off	75.86%
	Clash detection	70.69%
	3D visualization	63.79%
	Cost estimation and cost planning	55.17%

This study was used Structural Equation Modelling to examine the model and for validation purposes. Anderson and Gerbing (1988) suggest a two-step approach in modelling to reduce the potential model misspecification. The first step is assessing data consistency and fitness of model structure. The second phase involves with testing hypotheses by using path analysis. As path analysis decomposes effects into direct, indirect and total effects (Alwin and Hauser, 1975), which gives a clear insight of connections among variables. Cronbach's α value is the consistency index used in this study (Cronbach, 1951). While the assessment of construct validate consists of convergent validity and discriminant validity (Campbell and Fiske, 1959). Convergent validity ensures that manifest variables measuring the same latent variable are demonstrating moderate inter-correlation; while an acceptable discriminant validity testing result requires independence among latent variables (Fornell and Larcker, 1981). Convergent validity may be assessed using the following indicators: factor loading, Composite Reliability, and Average Variance Extracted (Bagozzi and Yi, 1988). The most usual way to examine discriminant validity is comparing the AVE value of a certain latent variable with the squared values of correlations between that latent variable and others latent variables (Bagozzi and Yi, 1988).

4. RESULTS OF VALIDITY TESTS

Table 3 presents results of measurement model assessment, including reliability test and convergent validity. In this study, we use Cronbach's α value to evaluate data reliability; convergent validity was measured by factor loadings, composite reliability, and average variance extracted. Cronbach's α values range between 0.711 and 0.901, which are higher than the minimum acceptable threshold of 0.60 (Nunnally, 1978). Factor loadings of manifest variables to latent variables range from 0.536 to 0.998, composite reliability ranges from 0.708 to 0.903, and AVEs are between 0.379 and 0.720. The minimum acceptable threshold of these indicators is 0.5, 0.6, and 0.5, respectively (Hair et al., 1998).

Table 3 Reliability Test

Latent Variable	Manifest Variable	Factor Loading	Composite Reliability	Average Variance Extracted	Cronbach's α
Awareness	AW2	.813	.837	.720	.833
	AW3	.883			
Perceived Need	PN1	.704	.708	.379	.711
	PN2	.618			
	PN3	.591			
	PN4	.539			
Perceived Usefulness	PU1	.703	.826	.488	.851
	PU2	.771			
	PU3	.660			
	PU4	.663			
	PU5	.691			
Technical Condition	OS1	.810	.876	.643	.866
	OS2	.619			
	OS3	.926			
	OS4	.821			

Ease of Operation and Maintenance	EOM1	.699	.903	.609	.901
	EOM2	.820			
	EOM3	.770			
	EOM4	.827			
	EOM5	.817			
	EOM6	.766			
Down Time	DT1	.764	.841	.639	.839
	DT2	.854			
	DT3	.777			
Companies' Intention	OI1	.998	.822	.709	.779
	OI2	.634			

Table 4 shows results of the discriminant validity test. The values on the diagonal of the matrix are AVEs of each latent variable, while off-diagonal values are square values of correlations between the latent variable and other latent variables in its corresponding column. An acceptable level of discriminant validity requires AVEs greater than off-diagonal elements (Bagozzi and Yi, 1988).

Table 4 Discriminant Validity

	TC	PU	PN	AW	DT	EOM	OI
TC	.802						
PU	.291	.699					
PN	.666	.569	.616				
AW	.341	.390	.382	.849			
DT	.203	.118	.171	.003	.799		
EOM	.448	.032	.248	.009	.351	.780	
OI	.558	.423	.421	.425	.340	.167	.842

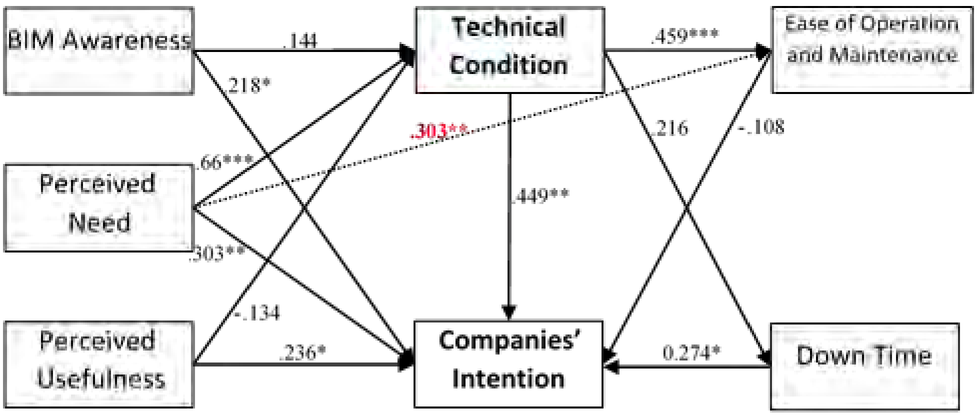
Another test should be performed before quantifying variables' correlations is model fit assessment, since a well-fitted model provides a solid foundation for hypothesises testing. The Goodness of Fit (GOF) indices provide an insight of how well-developed the structural equation models are. Table **5** presents the assessment results of model fitness, as well as the recommended values for each index (Bagozzi and Yi, 2012).

Table 5 Overall GOF statistics of confirmatory factor analyses performed

Indices	Measurement Model	Structural Model	Recommended Level
χ^2 / df	1.547	1.492	< 3.0
RMSEA	.081	.077	<0.1
CFI	.861	.871	>0.8
PNFI	.596	.608	>0.5

In this section, a summary of the standardized coefficients of research model is presented in Figure **2**. Seven out of eleven hypothesises were supported at $p<0.1$ significant level. Five factors have been identified as having critical influences to Companies Intention to Use BIM, which are BIM Awareness ($\beta=.218$, $p<0.1$), Perceived Need

($\beta=.303$, $p<0.01$), Perceived Usefulness ($\beta=.236$, $p<0.1$), Down Time ($\beta=.274$, $p<0.05$), and Technical Condition ($\beta=.449$, $p<0.05$). Moreover, an indirect effect from Perceived Need to Ease of Operation and Maintenance was detected ($\beta=.303$, $p<0.01$).



- *Figure 1 Direct Effects among Variab*

5. DISCUSSIONS

Results of the SEM analysis show that five factors including 'BIM Awareness', 'Perceived Need', 'Perceived Usefulness', 'Down Time', and 'Technical Condition' influence on 'Companies' intention' to implement BIM. The finding indicates that 'Down Time' is a major factor, but it has ignored in the literature. The results also echo the previous finding as it shows awareness, usefulness and technical infrastructure that an organization provided for BIM implementation is necessary for BIM adopters in China. The study of Ding et al. (2015) indicated that BIM capability and management support are critical to BIM adoption. Xu et al. (2014) found that interests in learning BIM and management support influence BIM adoption via perceived ease of use, while perceived usefulness affects BIM adoption directly.

Surprisingly 'Ease of Operation and Maintenance' is not identified as an essential factor by participants. Previous studies like Lee (2013) indicated that ease of use is one of the key factors affecting BIM acceptance in Korea. The emerged differences may come from cultural differences (i.e. working procedures) which may influence the process of technology adoption The participants explained that they employ specialist companies to operate BIM and its associated systems. Moreover, they would only use BIM under requests of clients (participants companies). In this case, participants have fewer concerns about how difficult is the BIM operation. This factor also covers ease of maintenance which evidently is not playing a critical role in BIM adoption decision making. However, it cannot be concluded that ease of maintenance is not important in BIM in all countries. The participants of the current study use BIM where they perceive a strong need such as contract requirements. In such circumstances, either operation difficulties or maintenance issues would not be major factors.

Another significant difference between the findings of this paper and previous studies is that they focus on technical challenges of BIM implementation, for example, technology complexity (Mutai, 2009), and interoperability issues in real practice (Sebastian et al., 2009). This paper presents a set of managerial factors such as companies support and needs and also technical factors such as importing/linking information from other sources. This technical factor has been investigated as a measure of perceived usefulness in the current paper. During the investigation in China, we found that two main BIM adoption barriers from participants' feedbacks, which are a lack of project collaboration with architects and software incompatible. The working procedure of construction projects in China leads to that contractors are undertaking responsibilities in modelling and creating BIM files, instead of architects.

Architects started their design with 2D CAD, not BIM. To them, BIM is only used in design plan optimisation, to attract client and buyers. This situation is caused by local committees who are with poor capabilities in reading and understanding BIM files. Thus documents in the schematic design phase and design development phase, which need approvals from local committees, are most likely in 2D formats. Deliverables from architects do not contain information that we need i.e. construction process and constructability. Therefore, even architects were delivering BIM files; we still need to devote lots of efforts in modifying models and adding information. To us, contractors, we do not have enough time in creating and remodelling BIM models. There is only a short time gap between the finish of tender and the start of construction.

6. CONCLUSION

The aim of this paper was to identify key factors influencing construction companies' decision to implement BIM. The BIM adoption model is developed based on six identified factors ('BIM Awareness', 'Perceived Need', 'Perceived Usefulness', 'Ease of Operation and Maintenance', 'Down Time' and 'Technical Condition'). The validated model provides an insight about which factors have influences to BIM adoption decision in a Chinese construction company. Meanwhile the quantitative feedbacks in this study provide more detailed information about BIM implementation barriers in Chinese construction companies. Previous studies mainly focus on modelling individuals' willingness of BIM adoption (Ding et al., 2015), and exploring BIM applications in real practice (Zhang, 2014). Few attentions have been placed in understanding key factors related to the companies' decision process. The results of this study indicate that 'Perceived Need' and 'Technical Condition' have most significant effects to BIM adoption decision, followed by 'BIM Awareness', 'Perceived Usefulness', and 'Down Time'. Moreover, 'Perceived Need', including competitiveness and contract requirements, is the most important initiator in driving construction companies to approach BIM. More importantly, 'Perceived Need' can effectively minimise challenges in BIM operation and maintenance through improving companies' technical conditions in BIM implementation. Furthermore, the quantitative information indicates that lack of collaborations between contractors and architects (e.g. BIM file delivery, exchanging digital information) is the main specific barrier of adopting BIM. Technical risks associated with BIM implementation (e.g. Down Time) were also identified as the main barrier to BIM adoption in the sample companies. The main limitation of this study is that research participants have been recruited among Chinese Grade A consturction companies. Therefore, the BIM awareness of respondents might be slightly higher than average level. Future study may investigate BIM adoption in various levels of construction companies.

REFERENCE

ADRIAANSE, A., VOORDIJK, H. & DEWULF, G. 2010. Adoption and use of interorganizational ICT in a construction project. *Journal of Construction Engineering and Management,* 136**,** 1003-1014.

AJZEN, I. & FISHBEIN, M. 1977. Attitude-behavior Relations: A Theoretical Analysis and Review of Empirical

Research. *Psychological Bulletin,* 84**,** 888.

ALWIN, D. F. & HAUSER, R. M. 1975. The decomposition of effects in path analysis. *American sociological review***,** 37-47.

ANDERSON, J. C. & GERBING, D. W. 1988. Structural equation modeling in practice: A review and recommended two-step approach. *Psychological bulletin,* 103**,** 411.

ASSOCIATEDGENERALCONTRACTORSOFAMERICA 2006. The Contractors' Guide to BIM.

AZHAR, S. 2011. Building information modeling (BIM): Trends, benefits, risks, and challenges for the AEC industry. *Leadership and Management in Engineering,* 11**,** 241-252.

BAGOZZI, R. P. & YI, Y. 1988. On the evaluation of structural equation models. *Journal of the academy of marketing science,* 16**,** 74-94.

BAGOZZI, R. P. & YI, Y. 2012. Specification, evaluation, and interpretation of structural equation models. *Journal of the academy of marketing science,* 40**,** 8-34.

CAMPBELL, D. T. & FISKE, D. W. 1959. Convergent and discriminant validation by the multitrait-multimethod matrix. *Psychological bulletin,* 56**,** 81.

CHEN, C., DIB, H. & LASKER, G. 2011. Benefits of implementing building information modeling for healthcare facility commissioning. *Computing in Civil Engineering (2011)***,** 578-585.

COOPER, J. R. 1998. A Multidimensional Approach to the Adoption of Innovation. *Management Decision,* 36**,** 493-502.

CRONBACH, L. J. 1951. Coefficient alpha and the internal structure of tests. *psychometrika,* 16**,** 297-334.

DAMANPOUR, F. & SCHNEIDER, M. 2006. Phases of the Adoption of Innovation in Organizations: Effects of Environment, Organization and Top Managers1. *British Journal of Management,* 17**,** 215-236.

DAVIS, F. D. 1989. Perceived usefulness, perceived ease of use, and user acceptance of information technology. *MIS quarterly***,** 319-340.

DAVIS, F. D., BAGOZZI, R. P. & WARSHAW, P. R. 1989. User Acceptance of Computer Technology: A Comparison of Two Theoretical Models. *Management Science,* 35**,** 982-1003.

DING, Z., ZUO, J., WU, J. & WANG, J. 2015. Key factors for the BIM adoption by architects: a China study. *Engineering, Construction and Architectural Management,* 22**,** 732-748.

DUBOIS, A. & GADDE, L.-E. 2002. The Construction Industry as a Loosely Coupled System: Implications for Productivity and Innovation. *Construction Management and Economics,* 20**,** 621-631.

FEATHERMAN, M. S. & PAVLOU, P. A. 2003. Predicting e-services adoption: a perceived risk facets perspective. *International journal of human-computer studies,* 59**,** 451-474.

FORNELL, C. & LARCKER, D. F. 1981. Evaluating structural equation models with unobservable variables and measurement error. *Journal of marketing research*, 39-50.

FRAMBACH, R. T. & SCHILLEWAERT, N. 2002. Organizational Innovation Adoption: A Multi-level Framework of Determinants and Opportunities for Future Research. *Journal of Business Research,* 55, 163-176.

GLEDSON, B., HENRY, D. & BLEANCH, P. 2012. Does size matter? Experiences and perspectives of BIM implementation from large and SME construction contractors.

HAIR, J. F., ANDERSON, R. E., TATHAM, R. L. & WILLIAM, C. 1998. Black (1998), Multivariate data analysis. Upper Saddle River, NJ: Prentice Hall.

HAMEED, M. A., COUNSELL, S. & SWIFT, S. 2012. A Conceptual Model for the Process of IT Innovation Adoption in Organizations. *Journal of Engineering and Technology Management,* 29, 358-390.

HANNA, A., BOODAI, F. & EL ASMAR, M. 2013. State of practice of building information modeling in mechanical and electrical construction industries. *Journal of Construction Engineering and Management,* 139, 04013009.

HARTMANN, W. R., MANCHANDA, P., NAIR, H., BOTHNER, M., DODDS, P., GODES, D., HOSANAGAR, K. & TUCKER, C. 2008. Modeling social interactions: Identification, empirical methods and policy implications. *Marketing Letters,* 19, 287-304.

HOWARD, J. A. & MOORE, W. L. 1988. Changes in Consumer Behavior over the Product Life Cycle. *Readings in the Management of Innovation* 2.

JIN, R., TANG, L. & FANG, K. 2015. Investigation Into The Current Stage Of BIM Application In China's AEC Industries. *WIT Transactions on The Built Environment,* 149, 493-503.

KOEBEL, C. T., HUDSON, E. & CAVELL, M. 2003. The Diffusion of Innovation in the Residential Building Industry. Blacksburg, VA: Virginia Polytechnic Institute.

LEE, S., YU, J. & JEONG, D. 2013. BIM acceptance model in construction organizations. *Journal of Management in Engineering*.

MANLEY, K. 2008. Against the odds: Small firms in Australia successfully introducing new technology on construction projects. *Research Policy,* 37, 1751-1764.

MCCOY, A. P., BADINELLI, R., KOEBEL, C. T. & THABET, W. 2010. Concurrent Commercialization and New-Product Adoption for Construction Products. *European Journal of Innovation Management,* 13, 222-243.

MIRCHANDANI, D. A., JOHNSON JR, J. H. & JOSHI, K. 2008. Perspectives of citizens towards e-government in Thailand and Indonesia: A multigroup analysis. *Information Systems Frontiers,* 10, 483-497.

MOTAMEDI, A. & HAMMAD, A. RFID-assisted lifecycle management of building components using BIM data.

Proceedings of the 26th international symposium on automation and robotics in construction (ISARC 2009), Austin, USA, 2009.

MUTAI, A. 2009. *Factors influencing the use of Building Information Modeling (BIM) within leading construction firms in the United States of America.* Indiana State University.

NEWTON, K. & CHILESHE, N. 2012. *Awareness, usage and benefits of building information modelling (BIM) adoption-The case of the South Australian construction organisations.* Association of Researchers in Construction Management.

NUNNALLY, J. 1978. Psychometric Theory (2nd eel.). *New York, Iv¥ cGrow-Hill*.

OZORHON, B., ABBOTT, C. & AOUAD, G. 2013. Integration and Leadership as Enablers of Innovation in Construction: A Case Study. *Journal of Management in Engineering*.

PARIDA, V., JOHANSSON, J., YLINENPÄÄ, H. & BAUNERHJELM, P. Barriers to information and communication technology adoption in small firms. 2010. Working paper, Swedish Entrepreneurship Forum.

PARK, Y., SON, H. & KIM, C. 2012. Investigating the Determinants of Construction Professionals' Acceptance of Wb-Bsed Training: An Extension of the Technology Acceptance Model. *Automation in Construction,* 22**,** 377-386.

POIRIER, E., STAUB-FRENCH, S. & FORGUES, D. 2015. Embedded contexts of innovation: BIM adoption and implementation for a specialty contracting SME. *Construction Innovation,* 15**,** 42-65.

RAMPERSAD, G., PLEWA, C. & TROSHANI, I. 2012. Investigating the Use of Information Technology in Managing Innovation: A Case Study from a University Technology Transfer Office. *Journal of Engineering and Technology Management,* 29**,** 3-21.

ROGERS, E. M. 1995. Diffusion of Innovations: modifications of a model for telecommunications. *Die Diffusion von Innovationen in der Telekommunikation.* Springer.

ROGERS, E. M. 2003. Elements of diffusion. *Diffusion of innovations,* 5**,** 1-38.

ROGERS, J., CHONG, H.-Y. & PREECE, C. 2015. Adoption of Building Information Modelling technology (BIM) Perspectives from Malaysian engineering consulting services firms. *Engineering, Construction and Architectural Management,* 22**,** 424-445.

SEBASTIAN, R., HAAK, W. & VOS, E. BIM application for integrated design and engineering in small-scale housing development: a pilot project in The Netherlands. International symposium CIB-W096 future trends in architectural management, 2009. 2-3.

SEXTON, M. & BARRETT, P. 2003. Appropriate innovation in small construction firms. *Construction management and economics,* 21**,** 623-633.

SON, H., LEE, S. & KIM, C. 2015. What drives the adoption of building information modeling in design organizations? An empirical investigation of the antecedents affecting architects' behavioral intentions. *Automation in Construction,* 49**,** 92-99.

STRAUB, E. T. 2009. Understanding Technology Adoption: Theory and Future Directions for Informal Learning. *Review of Educational Research,* 79**,** 625-649.

XU, H., FENG, J. & LI, S. 2014. Users-orientated evaluation of building information model in the Chinese construction industry. *Automation in Construction,* 39**,** 32-46.

YAN, H. & DAMIAN, P. Benefits and barriers of building information modelling. 12th International conference on computing in civil and building engineering, 2008.

ZHANG, M. Application of BIM Technology on Energy Efficiency Building Design. Applied Mechanics and Materials, 2014. Trans Tech Publ, 283-286.

EVOKING MALAYSIAN ARCHITECTURE CULTURAL IDENTITY THROUGH DEVELOPMENT OF PARAMETRIC BIM

Saifulnizam Suhaimi,

Department of Quantity Surveying, International Islamic University Malaysia

Puteri Shireen Jahnkassim

Department of Applied Art, International Islamic University Malaysia

Nashwan Dawood

University of Teeside

Maisarah Ali

Department of Civil Engineering, , International Islamic University Malaysia

ABSTRACT : *The aim of this paper is to discuss and highlight the potentials of BIM objects platforms with particular references to parametric modelling in creating a design process which involve the systematic abstracting of constructional elements learned from traditional architecture into systems of ratios, rules, proportion and hierarchy for urban typologies and applications. The paper focused on the constructional language from the design vocabulary of Malay vernacular architecture which is essentially timber-based and BIM tools is used to transmute elements of the vernacular into modern construction and typologies such as multistorey facades . 3D elements in a data base are mathematically studied through analysing the proportions of elements in elevation and programming such ratios and equation into the parametric modelling subprogram in BIM . With the aim of evoking identity in a densed city context, elements of the Malay vernacular can be reworked towards the transposition of identity in multistorey structures and applications to preserve the memory of cultural traditions in a densed city context. The capabilities of BIM is used to capture the essence of Malay identity into city scale urban typeform such as commercial and residential blocks through the capabilities of BIM . From an analysis of construction of Malay palace and villa architecture is studied interms of porportions and mathematical rules and engaging both the parametric rules and a library of profils and elements from the construction BIM database of Malay elements in architecture, a series of façade and formal templates can be generated and used as guidelines and elements to enhance the historical and visual character of a city.*

KEYWORDS: *Malay vernacular architecture, cultural identity, parametric modelling*

1. INTRODUCTION

All over the Asian context, including developing nations in the South East Asian region and cities, urbanisation are on the rapid rise while traditional zones, structures and identities are increasingly decimated in the face of rapid modernisation and progress. Particularly in certain parts of Asia such as Malaysia, Indonesia, Thailand, Cambodia and even China, traditional structures are essentially timber-based structures with their own tectonic language and vocabulary arising from unique constructional assemblies and connections. As development and urbanisation race through time and space, such structures gradually face extinction due to the nature of the material ephemerality. Architects and urbanists in the realisation of such gradual destruction has attempted to preserve the memory of their own cultures through various approaches. Basic principles of architecture, choice of materials and design details all are done sporadically and intuitively according to the professional's own initiative and effort. The segmented nature of these approaches are currently not working in parallel with the speed of modernisation where documentations are rarely transferable nor act as a 'living' information.

In Malaysia, although much has been documented on Malay architecture, the problem remains in the transposing of elements, rules and grammar into concrete and steel structures where a representative of Modern construction methods is present in a form of intuitive and generalised process. The current situation is that Malay architectural character is disappearing rapidly in the urban cities. One could walk within the city and yet find it hard to point to a specific identity of a Malay architecture. In the pursuit of documenting and preserving the fading identify of a Malay architecture, there must be a systematic method of documenting and retrieving building elements and essential rules to implement its character in urban building context. An analysis modeling and breakdown of 3D constructional elements is necessary is order for the knowledge of Malay architecture to be structured in such a way that the character of Malay architecture can be preserved and reconstructed for multistorey urban typologies.

In order for a Malay character and its systems be transformed into an objective set of rules and then be buildable, a feasible industrialized method of construction with its systems, details, components and proportions of Malay architecture must be derived from a Malay vernacular architecture study. The structured approach of documenting such effort requires specific platform that could record, integrate and operate all parametric data generated from the study. The capability of Building Information Modelling (BIM) as platform to document these study are seen having the potential to address issues concerning fading identity of Malay architecture. BIM is a building design and documentation methodology that provide a platform to characterized such Malay architectural elements. It coordinate and internally consistent at computing information about a building's construction elements and methods. Objects are defined as 'parameters', that relate to other objects. So if one related object changes, the other objects will automatically rebuild or reorganize themselves according to the rules attached with them. From these characterisations, the Malay character and 'Classical' building composition and its construction can be linked through BIM where it play a role as a technique to further build a knowledge-based architectural systems with information and semantics. The use of 3D BIM models organized as computational systems can provide not only tools for architects and urban designers to act as reference for the achievement of Malay character in an urban context, but also a powerful means of accessing, evaluating , using and understanding the principles of Malay architecture.

2. PROBLEM STATEMENT

Throughout the process of under standing the potential of documenting the Malay architecture vocabulary and integration it within the BIM environment, there are several questions that comes along the way which drive this effort. The following are some of the questions that are expected to lead the their way in realizing the objectives :

1) *What range of elements and rules throughout an analysis of the different variations in Malay house and palace architecture in the Malay states?*
2) *How can it be transpose into a BIM related 3D format and translated using modern structural systems, construction techniques and materials?*
3) *What are the variations in grammar, rules, proportion, extension, multiple rhythm, that can be set at a knowledge parametrized systems and so can align with the scale, size and measurements or various typologies of building found in a mixed development or in a city center?*
4) *What are modelling and parametric values based in IFC that can achieve compliances with proportions and ratios and yet achieve the essence of the Malay character?*

Smaller structures - such as houses, places of worship and schools - lend themselves more readily to an interpretation based on the traditional model.Traditional architecture however offers no clear models when it comes to ‘imported’ large building types such as multi-storey apartments, office buildings, airports and hospitals which have become part of a rapidly developing context. Due to rapid modernization, there was a need to develop a ‘regional’ architecture due to the increasingly hybrid nature of the tropical Asian cities. Powell and Ozkan (1983) has highlighted how such forms refer to a transformative’ regionalism which can be used to develop and guide the abstraction of forms and patterns from the traditional context and their re-articulation through the use of modern vocabulary and modern building materials. Architectural history is replete with examples of how a rescaled version of local architectural tradition results in the destruction of the essential proportions and balance in the larger version of a smaller traditional form.

3. LITERATURE REVIEW

The use of BIM digital representation of buidling assets and as documentation and management of architectural heritage sector has benefited from this technological innovation has been discussed by researcher such as Gaiani (1999). However it is increasingly realised that the applications of BIM in heritage is not just as a powerful modeling tool and database organiser, but the use of certain modelling capabilities within BIM such as parametric modelling has been explored by researchers in order to create potential industrialised methods to replicate traditional construction. This include the potentail to model such as semantic data pertaining to cultural, historical material and operational information. Therefore BIM is expected to rise in its role as a central objects library for cultural heritage. Currently various researcher have advocated the use of BIM to support comprehensive data input for lifecycle management, and where multiple data are collected, stored and retrieved for various efforts including facility management . The need to establish objects library has been discussed by researchers such as Koller, Frischer and Humphreys (2009) and Chevrier and Perrin (2009) that look into the parametric modelling of architectual components . Jim and Jeong (2012) in their effort to preserve the Han-ok structure in Korea, also utilise three dimensional object-based parametric modelling in which each element of an assembly of a vernacular structure can be defined through parametric modelling.

A study by Burhanuddin (1981) remains one of the few researcher who has attempted to analyse the Malay house as a systems of ratios and analyzed patterns of proportion and rules in the Malay house. He had ingenuously researched and documented on the proportionate systems of the Malay house according to elevations and spatial hierarchies in the vernacular house type. Yet more studies is needed towards a similar analysis other Malay architecture building such as palaces. Tajuddin et.al. (2005) provide a paradigm shift in exploring the typologies of the Malay architecture where focused are given on the essences of Malay houses and palaces, specifically on the unique spatial layout and spatial hierarchies. While there are various publications which have usefully documented the Malay vernacular, there is still a gap of drawing out rules from the deeper richness of palatial constructions and template. The essence of what is the Malay architecture heritage must include elevational analysis and mathematical related analysis and rules to be in parallel with the ever growing trends in architectural development.

3.1 **The context of the Malay vernacular**

The traditional Malay house is a basic form that is characterised by its local diversity as it differs from state to state in the Malaysian peninsula. There is a richness not in its overall form but more on its elevational characteristics and roof forms, as it tends to evolve according to different communities, beliefs and geographical regions. Malay houses can be almost singularly define as the post and beam type of tropical structure and are set apart by their roofs. Throughout the Malay states, a house's roof can vary in terms of shape, pitch, orientation and construction method, which inevitably results in localised characteristics. Roof ornaments include the gable finial (tunjuk langit), criss-crossed finials (silang gunting) and gable horns which are characteristic of traditional architecture of the archipelago. The most common type of traditional Malay house is the Rumah Bumbung Panjang (Figure 2), characterised by a gable roof with a long central ridge. Identified as the oldest type of Malay houses and arguably the simplest of the four predominant house forms in Peninsular Malaysia, many of these Rumah Bumbung Panjang are well over a hundred years old and still preserved in good condition. The most common material used for roofing is thatch or attap (from nipah fronds). Among other older houses in Perak is a type of long-roofed house, known as Rumah Kutai. It has a typical elongated roof, columns and a small opening for windows and an attic, but the most distinctive type has woven bamboo matting for the walls, expressed identically to a 'basket weave' pattern known as kelarai. The similarities that exist between all these components are derived from nature, specifically timber based material. The expansion of these timber components used in the the Malay architecture are extended to include detail construction joint system.

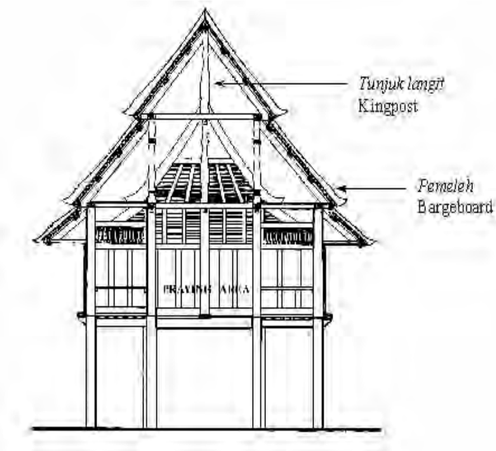


Fig.1 Tunjuk Langit (Source: Said, 2001)   Fig.2 Rumah Bumbung Panjang (Source: Ali, 2010)

3.2 The Malay Construction Systems

The construction tectonics and expertise essentially grow from timber carpentry yet one of the mosque unique elements identifiable to the Malay world is the method of ‘tanggam’ which refers to the discipline and rigors of a system of jointing and connecting the structural system and constructional framework of, specifically, timber. This method of jointing known as ‘tanggam’ is an important element and original principle of traditional Malay houses. Without this method, the construction system of Malay vernacular architecture would not have existed as we know it today. In the method of construction, tanggam refers to almost every method of connections known in Malay architecture. From a language viewpoint, the word tanggam revolved around an expression of the underlying construction of joints. For example, the Malays in Kelantan understood tanggam as the processes of connecting timber frameworks at explorative phases. They called it tanggam-menanggam. Tanggam also means ‘entering’ (masuk), or bringing close together, and many understood tanggam as the joints of a building (sendi bangunan) and the ‘clips’ (penyepit) of a building. Literally, tanggam refers to ‘the method of connecting timber elements in a wedge system (bertakuk-takuk) so as to connect them tightly and forcefully’.

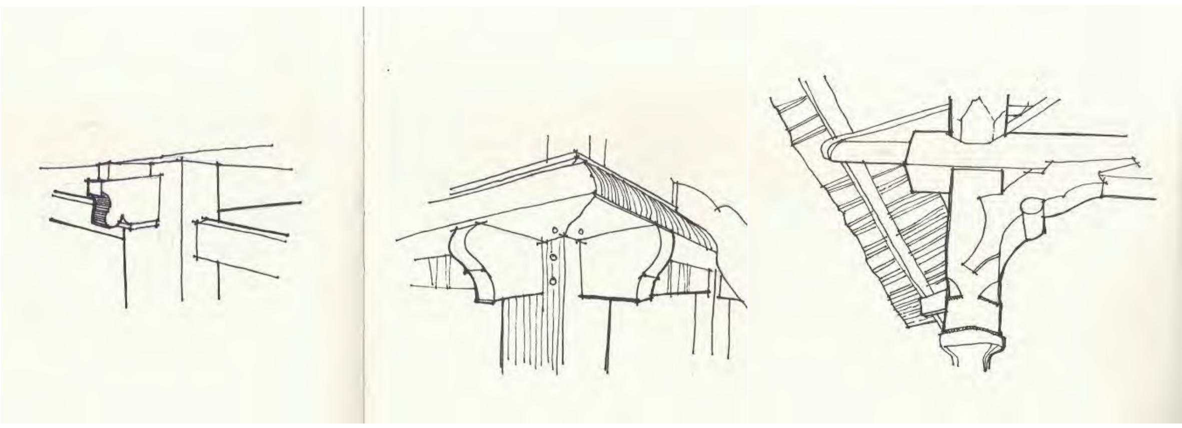


Fig.3 *Tanggam* from Malay Palace

In order to create a richer source of Malay form and varied elevational systems and structures, the Malay palace is a richer source of elements. Despite their grandeur, these palaces evolved from simple constructional technology and detail and thus their development also characterises the evolutionary path of Malay architecture. Form, style and grammar are differentiated from state to state, in a rich and diverse array of expressions and architectonics. In the palace typology discussed, the traditional rules of scale, technique and proportion of the vernacular house are essentially translated to a grander scale, and progressing towards towards a layering of lavish treatments. Malay palace architecture retains and refines the sense of proportion, scale and harmony which is characteristic of the traditional Malay-Nusantara vernacular. Both the Malay house and palace extoll a range of classical virtues such as proportion and order, but as a sophisticated prototype, the Malay palace manages to amalgamate diverse cultural influences while maintaining decorum through a varied system of proportionate rules.

In Sejarah Melayu, a seventeenth century text on the history of the Malays, there is a description of the original Malacca (a state in Malaysia) palace:

> *'...The palace consisted of twenty-seven partitions, each being three fathoms in breadth, [and] the wooden pillars which supported it were each the grasp of two arms in circumference. The roof consisted of seven stages with intermediate windows, the outer arches over them extending breadthwise and facades, including the bow windows and wings crossed each other, all of them being covered with fretwork. The peak was of red glass with a great diversity of ornament...'*
>
> *The Malay Annals, translated by John Leyden*

The palace has long ceased to exist and no visual representation survives. However, a model was constructed several decades ago by the state government of Malacca as a tourist attraction and it has been a popular choice for visitors ever since. This replica of the Royal Malacca Palace consists of a main building which represents the main portico and entrance of the palace. It is flanked by smaller proportioned buildings in a rhythmic succession. The reconstruction of the Royal Malacca Palace is guided by the generic proportions of the traditional Malacca architectural form. The doubletiered and double pitched roof is perhaps one of the most iconic features of the Malay vernacular. The roof can be read as several intersecting masses with a steeped pitch. In the essential Malacca roof, the dominating roof form is constituted by two gradients of the double-tiered roof – one at 60 degrees and the other at 30 degrees – typical of Malacca-style traditional houses as illustrated in Figure 4. The roof form recalls the layered characteristic of Malay cultural forms visible in architecture and clothing (such as the baju).

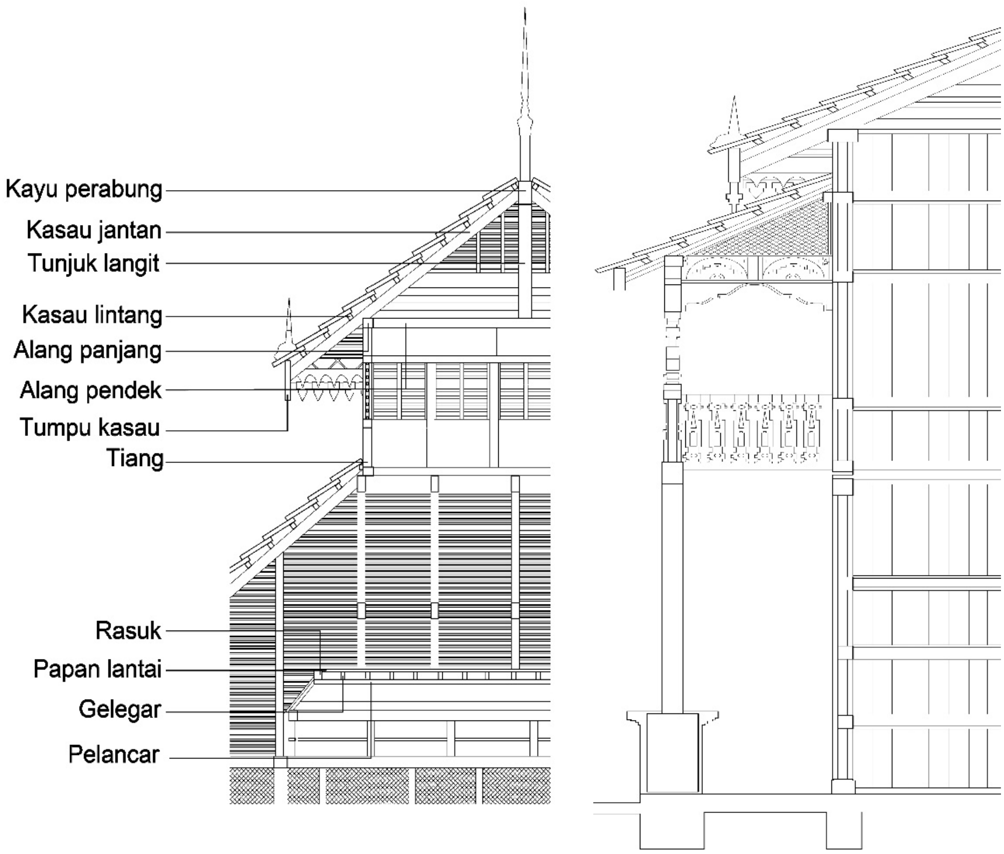


Fig.4 Cross-Section of a Traditional Malay Pitched Roof

Similar to the process of the ‘Palladianism’ of Greek antiquities in rules of a Classical architecture, proportions and orders can be developed as treatises and rules of Malay urban form and design which must be able to be universally applied and flexible enough to be used in a range of multistorey urban building types, functions and scenarios yet distilled and essential enough to evoke the Malay architectural characters. Using BIM, elements, ratios and grammar through Malay houses and palaces are studied, modeled and documented. Particularly through palatial archetypes and typologies, a study of its elements, mathematical proportion, can bring about a clear guidelines of its grammatical and mathematical rules which can be characterized and analyzed. The aim is to derive rules reminiscent of such roots, in which facades, grammar and proportions are abstracted and developed into a set of rules and grammar which can be transposed into multistory buildings, typologies and functions.

This project aimed at quantifying through analysis and abstraction, recognizable and distinctive principles, proportions and elements of Malay architectural lexicon and rules of grammar. Further extension of this study focussed on developing mathematical and content analysis of an extensive compilation and recongising essential features that can be adapted for use in urban buildings. Based on Malay architectural studies and books, parametric objects can be scripted using Geometric Descriptive Language (GDL) in ArchiCAD or Revit , and then mapped onto points cloud to automatically produce engineering drawings. Based on its ability to link 3D models with clear semantic description. In the past, the potential of BIM in facilitating the theoretical and historical application of architecture connectivity of elements to its origins in historical documents has been explored and highlighted by by Pauwels, Verstaeten, De Meyer and Van Campenhout J. (2008). Adopting from similar approach, this project attempt to place Malay architecture vocabulary within the BIM environment as platform.

4. ROLE OF BIM AND CULTURAL IDENTITY OF CITIES

Through a system and process akin with Palladio who manually record and proportionally remeasured Greek temple and traditional elements in order to derive relationship rules and ratio. Similarly such analysis in Malay palaces and traditional villa can give rise to similar values in ratios and proportions. Hence the consequent step is to utilise BIM to facilitate between the compositional and the constructional character of building. In this project, BIM will be potentially be used to create a parametric relationship that can automatically and seamlessly transform such relationship into a range of scales aligned with typologies in the city or in the urban context. BIM can further be used to breakdown components towards the sets of individual components of an essentially vernacular architectural language which is drived from Malay traditions and forms. In this way, the transmutation of Malay character will not longer be based on subjective assessment and intuitions , but components and parameters that can then be easily transmuted and fitted onto modern facade systems and modern building design compositions without essentially losing the sense of proportion , balance and character**.** The efforts are expected to be able to essentially preserve the character of the building tradition itself. From such compositions and rules , an Industry Foundation Class (IFC) with semantic database and content with its own metadata can be develop in BIM. It aim to break down elements into exact 3D construction components, knowledge and information that can be linked, including different design and construction procedures. Through BIM, a model can be divided into components and hierarchically organised, each part of the construction object to be connected to each other through set parametric rules or equations and a set of information. This can benefit users such as architects, builders and urban designers in transposing such element onto urban form. Massing 3D objects can be recovered easily and edited or varied to suit the programme of the design without losing the architectural character of the region or the community.

5. PROJECT AIMS

The aim is to select the appropriate standard to be used to capture the architectural components and then order and organize objects library of 3D models. The end product is as a collection of structural objects and systems where not only ‘shape’ is modeled but also information linked to historical documents, information enrichment construction and assembly methods.

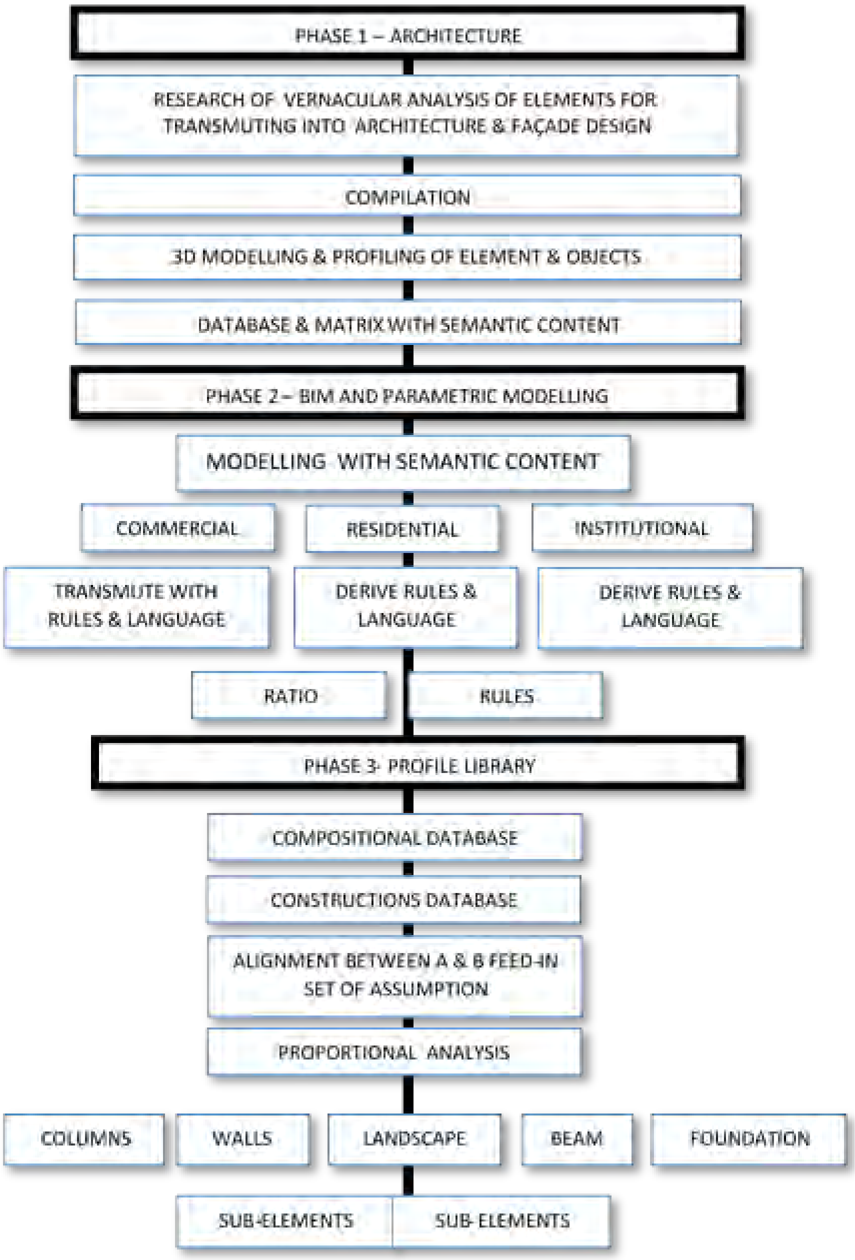
There are three (3) objectives of this project which are:

1) to develop an organized 3D model library derived from the compositional rules of Malay architecture as a means of the industrialization of building systems into BIM environment

2) to characterize Malay architectural components both geometric and semantic systems which can be translated into concrete and steel structures and components which characterize modular nature of the Malay architectural elements

3) to link objects library of families of similar elements from other global databases in terms of constructional procedures and identify standards that has been used to capture and code 3D models and meta data.

7. THE PROCESS



8. EXPECTED OUTCOMES AND IMPACT ON URBAN POLICY

The homogenization and modernization of the Malaysian urban landscape has invariably produced the soulless character of modern cities and urban life. In the race to modernize and progress, cities in the Malay Nusantara world have developed and mushroomed without a direction. The aim is not to delve into to remodel and regurtitate traditional vocabulary and construction but to highlight the potentials of BIM and its three dimensional parametric modelling in order to enact a method of transposing elements based on rules of the Malay architectural language and grammar. What seem to be disparate and complex patterns, forms and treatment can develop into objective relationships, orders or rules that can be used to differentiate the 'Malay language and grammar' from other stylistic grammar such as the Classical or the Modern style.

In Rennaisance architecture, using the templates of Classical architecture which has its roots in Greek and roman antiquity, the reinvigorated growth and development of the classical language began with the outline of common rules and orders, firstly observed by Vitruvius and later developed by Serlio, Bramante and Palladio. An order is the total assemblage of parts comprising of columns and its appropriate entablature. In the Classical orders, primary divisions of the column are base, shaft and capital; and the primary divisions of entablure are architrave, frieze and cornice. Through a rationally constructed study of Malay vernacular form through both house and palace, a similar system of orders can be derived.

The elements of the Malay palaces including their frontal elevation, wall panels, columns and roof extensions can be abstracted into rules of proportions, facade extensions and basic decorative elements present a significant potential for a recognizable style and language of the Malay world in terms of architecture. This can be coupled with grammar and vocabulary derived from salient elements of Malay architecture such as the 'awan lara't, 'tunjuk langit' and 'tebar layar'. The overall slenderness of the columns with its masonry base and then contrasted in terms of colors and the use of arcuate and 'weave-like' wall boards represent also essential and recognizable elements of a vocabulary.

There are many cases where grandiose variations of the essential typology destroy the overall harmony. Yet each Malay palace exudes a proportion that still instill a feeling of balance and repose. The problem is to systematically analyze and mathematically relate these elements and undertake an effort to analyze in terms of rules and elemental typology of its roots, which although derived from an essential timber-based construction tradition, contains a rich layering of aesthetic treatments. This is essentially due into a grander scale of the Malay palace, and as the typology evolves towards a more lavish treatment, yet throughout the Malay states, it never lost the sense of proportion, scale and harmony which essentially typifies the traditional Malay-Nusantara style.

The growth and development of the classical language had essentially begun with the common rules and orders, firstly observed by Vitruvius and later developed by Serlio, Bramante and Palladio. An order is the total assemblage of parts comprising of columns and its appropriate entablature. In the Classical orders, primary divisions of the column are base, shaft and capital; and the primary divisions of entablure are architrave, frieze and cornice. Through a rationally constructed study of Malay vernacular form through both house and palace, a similar system of orders can be derived. The elements of the Malay palaces including their frontal elevation, wall panels, columns and roof extensions can be abstracted into rules of proportions, facade extensions and basic decorative elements present a significant potential for a recognizable style and language of the Malay world in terms of architecture. This can be coupled with grammar and vocabulary derived from salient elements of Malay architecture such as the ‘awan larat’, ‘tunjuk langit’ and ‘tebar layar’. The overall slenderness of the columns with its masonry base and then contrasted in terms of colors and the use of arcuate and ‘weave-like’ wall boards represent also essential and recognizable elements of a vocabulary.

The architecture of the palaces in particular holds the possibility of such rules of flexibility and a grammar. The language of the palaces and house contain an openness towards change yet it manages to retain and capture the element of balance, as it undergoes influences and evolution with the other cultures without sacrificing its principles. For modern functions and multistory typologies, how can sizes of standard construction and structural elements such as columns, beams, joints and connectors be aligned to the rules of grammar and elements compiled and derived in objective (1) and (2).

Tajuddin et.al (2005) has provided a useful documentation and in depth discussion of the Malay traditions have been researches by various architects, theorists, historians and scholars. Historically the movement of people from the mainland Asia towards the peninsular and islands in the southern region of East Asia represented the movement that had been one of the important governing factors in deciding the architectural style of this region. The similarities are now seen on the surviving architectural heritage of the Muslim – Malay in the form of masjids, palaces, houses and etc. However, most discussion on the Malay architecture dwells mainly on the traditional houses with similar architecture of houses raised on stilts, which some historians called it “raise on pile”, to belong to the place of origin of those that came either to Java or stayed in the Angkor kingdom. However, due to the climatic conditions of the region, most of those buildings depicted had not survived to this date. Nevertheless, if some of those had survived, God willing, it may have lead us to gain some understanding on the origins of our Malay Architectural heritage. The aim is towards a common understanding with an open inquest the physical attributes of the true Malay architectural heritage, if any.

Andrea’s Palladio’s ‘The Four books of Architecture’ (Venezia, 1570) is seen as a good reference and represents a precedent that can guide such a process towards abstraction and rule. It has now become a historical and highly influential architectural testament, because in it not only did Palladio outline all elements of Classical architecture in terms of components and design details. But more importantly he outline the basic principles of the Classical Rennaisance, organized is such a way and with such a vocabulary and lexicon, so as to constitute an architect’s ,manual that is organized as a knowledge systems. Here the architectural orders are described not only in their choice of materials, but basic and mathematical proportions and through these, he formulated the classical design method in terms of a knowledge- based parametric system that began with his implementation in palaces and country villas, but later could be implemented in façade and forms of the commercial buildings on the time.

Through an understanding of the Malay palatial type which is crucial in identifying patterns and abstractions that can be developed into a language and grammar for modern large complexes and structures, rules of design and hierarchy are abstracted. The more complex typology of the palace lends itself more readily to the evolution of a language that can be used for multistory expression. Despite their grandeur, they had evolved from simple constructional technology and detail.

The aim is not only to characterize the rules of Malay architecture and its language, but the Malay palaces essentially contain more potential for such abstraction into essences of a language for large scale buildings. Palaces are essentially grander versions of the Malay house form, hence it reflects the same ethos and the same confluence between its essential functionalism, and a refined and elevated aesthetic. When combined with factors related environment, culture, climate, economy, and value of resources, they result in complexes that stylistically vary yet converge into one unique tradition. The palace, in the Malay context, is almost an elevated and refined form of its archetypical roots, the Malay house, while its variations and idiosyncrasies are related to essences found in variation of cultural traditions contained within the Malay states. The aim is towards the realisation of BIM potentials to create not only a stylized and rescaled architecture but a computerised method of transposition that ensures a process that will be far from, losing, the essential character, human-scale elements and proportions that mirrors the nature of the Malay culture.

9. REFERENCES

Azidah Ali (2010), Rumah Bumbung Panjang Negeri Sembilan, http://azidahali.blogspot.my/2010/04/rumah-bumbung-panjang-negeri-sembilan.html

Chevrier, C., Perrin J.P., (2009). Generation of architectural parametric components. In CAAD Future conferenc e proceddings, June 17-19, Montreal, Canada, Presses de l'Université de Montréal, pp. 105

De Luca L., Veron P., Florenzano M., (2005). Semantic-based modeling and representation of patrimony buildin gs, SVE Worksop towards Semantic Virtual Environments. EASTMAN C., (2009). What is BIM?, http://bim.a rch.gatech.edu/?id=402

Eastman C., Teicholz P., Sacks R., Liston K., (2007). BIM Handbook: A Guide to Building Information Modeli ng for Owners, Managers, Designers, Engineers and Contractors. John Wiley & Sons, New Jersey.

El-Hakim, S., Beraldin, J.A., (2002). Detailed 3D Reconstruction of Monuments Using Multiple Techniques, In Proceedings of the International Workshop for Cultural Heritage Recording, Corfu, Greece, pp. 58-64.

Fai S., Graham K., Duckworth T., Wood N., Attar R., (2011). Building information modeling and heritage docu mentation. In CIPA 2011 Conference Proceedings, XXIIIrd International CIPA Symposium, Prague, pp.8.

Gaiani M., (1999). Translating the architecture of the world into virtual reality and vice- versa: 7 years of experi mentation with “conservation and representation” at OFF. In Proceedings of Heritage Applications of 3D Digita l Imaging, NRC Ottawa.

Ismail Said (2001) *Art of Woodcarving in Timber Mosques of Peninsular Malaysia and Southern Thailand.* Jurnal Teknologi , Universiti Teknologi Malaysia (34). pp. 45-56.

Koller D., Frischer B., Humphreys G., (2009). Research Challenges for Digital Archives of 3D Cultural Heritag e Models. In Journal on computing and cultural heritage, vol. 2, n. 3 pp. 1-17.

Manferdini, A.M., Remondino, F., Baldissini, S., Gaiani, M., Benedetti, B., (2008). 3D Modeling and Semantic

Classification of Archaeological Finds for Management and Visualization in3D Archaeological Databases, In 14 th VSMM Proceedings, pp. 221–228.

Mitchell W.J., Mc Cullough M., (1995). Digital Design Media, (2nd edition) John Wiley&Sons, Inc., New York. MIRTSCHIN, J., (2011). Engaging Generative BIM Workflows. Collaborative Design of Lightweight Structur es - LSAA. Sidney, Australia.

Mohamad Tajuddin, Mohamad Rasdi (2000). The Architectural Heritage of the Malay World:The Traditional Masjid. Penerbit Universit Teknologi Malaysia, Skudai, Johor.

Mohamad Tajuddin, Mohamad Rasdi (2001). Identiti Senibina Malaysia: Kritikan Terhadap Pendekatan Reka Bentuk. Penerbit Universit Teknologi Malaysia, Skudai, Johor.

MURPHY M., MCGOVERNA E., PAVIA S.,(2011). Historical Building Information Modelling-Adding Intelli gence to Laser and Image based surveys. In 4th International Workshop 3D-ARCH 2011, pp. 7.

Norwina Mohd Nawawi and Noor Hanita Abdul Majid (2010). In Search of the Origins ofthe Malay Architectural Heritage. Proceeding of the at Malay Heritage in Cambodia, Laos and Vietnam International Seminar held in Phnom Penh, Cambodia from 24-26thJune 2010.

Norwina Mohd Nawawi (2009). Online lecture on "Islamic Influence on the Architecture ofthe Malay World" to Department of Architecture, Technical University of Crete,Greece. Lecture Input to “Beyond the Boundaries of the West. Journeys to Spatial Conception of the East” Course. 29th May 2009.

Palladio A., (1570). I Quattro Libri dell'Architettura. Venezia; (1965). The Four Books on Architecture translati on by Isaac Ware 1738, Dover Publications, New York.

Park H.J., (2007). Parametric variations of Palladio’s Villa Rotonda. In International Journal of Architectural Co mputing, vol. 06, n. 02, pp. 145-169.

Pauwels P., Verstaeten R., De Meyer R., Van Campenhout J., (2008).Architectural information modelling for virt ual heritage application. In Proceedings of the 14th International Conference on Virtual Systems and Multimedi a, pp. 18-23.

Wan Burhanuddin Helmi (1981), The malay house: Rationale and change. Unpublished Masters Thesis, Massachusetts Institute of Technology (MIT)

BIM: A DISRUPTIVE PROCESS TOWARDS TRADITIONAL PRACTICE

Ahmad Mohammad Ahmad., Mian Atif Hafeez.,

(Qatar University, Qatar)

Ahmad Muhammad Ahmad.,

(Abba Properties and Services, UK)

Abdullahi Adamu Aliyu.,

(Loughborough University, UK)

Sergio Rodriguez, Nashwan Dawood.

(Teesside University, UK)

ABSTRACT: *Most organizations will have to change in order to be competitive and reap the benefits of BIM. The adoption of BIM requires a shift/ change in the working process. However, change can result to disrupting organizational settings. Managing BIM disruption towards digitized practices will enable consultancies to adapt to BIM working processes. This paper is part of a project that focused on embedding BIM in UK construction organisations. The paper aims at identifying factors that facilitate BIM disruption in traditional practices and prescribes a strategy for managing disruption. Secondary and primary data were explored to achieve the aim of this paper. A focus group, survey and interviews were conducted sequentially at a UK consultancy. A key factor identified for managing disruption is (incremental BIM knowledge development) which is further categorised under four factors for managing BIM disruption. These factors include developing a BIM vision with short-term and long-term goals, while understanding company`s technical and financial capability; BIM implementation, BIM knowledge curve and BIM maturity. A sequential cycle node for managing BIM disruption is proposed. The findings of this paper could guide construction organisations on what to expect towards managing disruptions when implementing BIM.*

KEYWORDS: *BIM; management, traditional practice, BIM disruption*

1. INTRODUCTION

Traditional practice is considered as Level 0 BIM, which is described in PAS 1192-2: 2013. BIM push will change existing traditional technologies and processes within an organisation (Arayici, et al., (2009); Lu and Li, (2011); Grilo and Jardim-Goncalves, (2011)). Holzer, (2015) stated that digital innovations in technology facilitates organisational change. In this sense, Watson, (2010) stated that BIM could mean a significant disruptive technology. BIM could be disruptive as the combination of shifting in processes and technologies. Some BIM challenges include: data accuracy, data responsibility and information stewardship (Morlhon et al., 2014). However, it is important to understand that disruption can arise due to some challenges but all challenges do not lead to BIM disruption. Literature has presented many other challenges of implementing BIM. However, with appropriate planning, commitment, standards, policies, hardware and software in place; BIM can be fully implemented, but what are the isolated challenges that lead to BIM disruption? Organizational staff should be aware of these disruptions to know what to expect in order to acclimatize with the BIM trends. Disruption is defined by the English Oxford dictionary as a disturbance interrupting a process, while IGI Global described challenges as difficulty, barrier, problem, constraint or bottleneck. For the purpose of this paper, BIM is defined as a specific process (collaborative) for managing specific information (lifecycle) by specific people (stakeholders involved) using specific technology (agreed) which are guided by specific policies (standards/rules). Lindblad and Vass (2015) described their view of BIM as subdivided into three different areas: product (model and technical issues), organization (providing necessary resources) and process (work practices and processes). Succar, (2009:363) described BIM in three stages: These are BIM stage 1- Object-Based modelling; BIM stage 2- model-based collaboration; and BIM state 3- Network based integration. There is a sequence within the stages that moves from objects-models- network, while information within a project lifecycle is the common feature between the stages. However, in order to achieve the cohesion between the stages, the three pillars of BIM can be considered. These are process, policy and technology (Succar, 2009).

The problem statement for this paper revolves around BIM disruption experienced while implementing BIM within a consultancy. The disruption caused by BIM is not only centred on technology, but include social and economic factors. BIM comes with disruption due to the learning curve factor, such as defining time allocated for BIM training while non-BIM projects are on-going and the cost involved. However, more efficiency is undoubtedly registered with BIM projects. There is a need to prepare for the cultural shift. BIM readiness and adoption schemes could "*allow potential BIM users to identify the likely conflicts and risks*" that could arise due to change in work practice as "*BIM adoption would require a change in the existing work*" (Gu and London, 2010:998-999). They have identified technical (functioning requirements and needs) and non-technical (strategic factors) challenges to the adoption of BIM. Despite the challenges, BIM could evolve gradually. There are BIM Maturity Models that have clearly described the different requirements to attain the different BIM levels. However, there is a need to clearly define how the BIM levels can be achieved while managing existing UK construction challenges dragging the BIM push. Rooke et al., (2004) described some challenges of the UK construction industry which include reluctance to change, susceptible to conflict and opportunism.

2. INTRODUCTION

BIM disruption could affect various stakeholders in the construction industry, but which category within the adoption lifecycle will be affected the most still remains unanswered. Table 1 describes possible BIM disruptions to traditional practices. These disruptions are related to process, policy and technology factors. The concept of adoption is described in Figure 1. Arguably, late majority adopters (conservatives) and Laggards (skeptics) will find BIM less disruptive because they wait for standards to be available leading to an opportunity to get the knowledge/ technology in context readily available from prior adopters and possibly cheaper due to market availability and competition; this could facilitate a less disruptive BIM adoption. But, contrary to this, they lack the will to aggressively invest and explore new ways of doing things like the innovators, early adopters and majority. However, more risk is associated with early adoption (Moore, 1999). Figure 2 describes how disruption can be managed when related to risk involved in a given supply chain process.

Table 1: BIM Disruption

DISRUPTION CATEGORY	DISRUPTIONS	REFERENCE	DESCRIPTION
Stakeholder competency	Waiting for supply chain to attain required level of competences due to high cost of software purchase	Jung and Joo, (2011)	Supply chain might not be competent to make contributions towards the development of the model.
Risk	Organisations would have to deal with risks associated with product liability	Race, (2012)	Model changing to a product.
Existing processes	Organisations would have to manage existing cultural features.	Fellows et al., (1983)	Change involves aligning BIM process with existing processes.
Existing technology	Staff would have to leave some existing technology (CAD) and learn ones.	Ruikar et al., (2005)	Some staff resist the adoption of new technologies.
Recruitment policies	Organisations may need to recruit competent staff with BIM skills.	Arayici et al., (2009)	A BIM knowledge gap exists in the construction industry. Technical competence has impact on recruitment policy. There is a challenge of recruiting experience disciplines/ BIM specialist.
Integrated processes	Staff are disrupted with new ways of working.	Tulenheimo, (2015)	To work within a BIM project, every stakeholder has to adopt standardised collaboration and exchange protocols at an agreed level of BIM uptake.
Leadership	Leadership organizational structure will have to be redefined.	Deutch, (2011).	In order to change technology, process and delivery; leadership and senior management will also have to change and adopt new ways of working.

Financial policy	Need for BIM budget in an organisation.	Deutch, (2011).	Introduction of BIM has significant education, resources and training implications.

Figure 1: Technology Adoption Lifecycle (Moore, 1999).

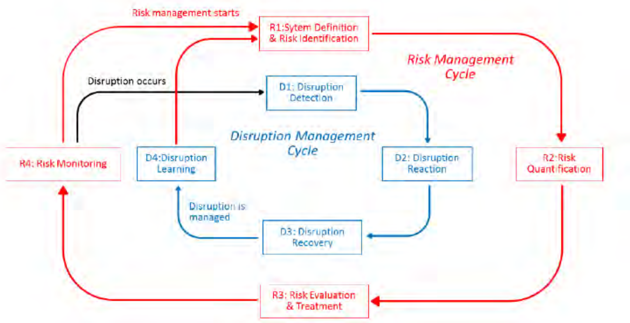


Figure 2: Framework to manage disruption in supply chain (Behdani et al., 2012)

3. RESEARCH METHODOLOGY

The methodology adopted for this paper include the sequential use of focus group, survey and interviews at consultancy X to identifying possible BIM disruptions and suggesting strategies for managing disruption. Consultancy X was chosen for case study for the following reasons. It is a large UK based design, engineering and project management consultancy with international experience. They are a multi-disciplinary consultancy with construction revenue of over £1 Billion pounds. There is an effort to implement BIM at the organisation, and primary data was available for collection.

3.1 Focus Group

There is a need to identify internal challenges that may exist. The focus group findings showed 11 possible disruptions or clashes that could arise when BIM is fully implemented. One member of each category was invited to take part in the focus group. These include: Project Management; Practice Management; Practice Staff - Engineer / Designer / Architect / Surveyor / Interior Designer, etc; Technical Management; and Technical Staff. Table 2 describe key challenges that could lead to BIM disruption as lack of management support, awareness of BIM and collaboration between different disciplines.

Table 2: Focus group findings

	FOCUS GROUP FINDINGS	DISRUPTION
1	Company is too big; not easy to implement strategies across different teams in other locations within UK and internationally.	There is disruption when different disciplines within the organisation are at different level of BIM understanding and are working together on a project.
2	There is a need for staff to collaborate with other team members.	There are many factors to consider but disruption of the collaboration process is vital.
3	There is doubt that management support for BIM implementation goes across the entire organisational hierarchy of the company (top to bottom).	Progress is made but full management support is not adequate which causes disruptions due to lack of support.
4	There is doubt in the general awareness and understanding of BIM implementation within the majority workforce.	Defining required or appropriate training is challenging. Moreover, the timing of implementing training when live projects are progressing is disruptive. The learning curve comes with disrupt process on the short-term.
5	Different stakeholders require different level of BIM training.	Management staff will require high level management training to support the technical teams while technical staff will require more detailed technical training.

3.2 Survey

The eleven possible BIM disruptions identified from the focus groups were presented in the Survey. Project management and technical management staff were targeted across consultancy X (UK offices). 100 staff were targeted and 30 percent response rate was recorded. Findings shown in Table 3 described lack of all stakeholders operating at the same BIM level as the highest ranking disruption.

Table 3: Possible BIM disruption towards traditional practices

POSSIBLE BIM DISRUPTION TO TRADITIONAL	MEAN	STD. DEVIATION	RANKING

	PRACTICE			
1	All stakeholders sharing information through the data sharing point would have to learn and adapt to the process (Learning).	4.00	0.68	1
2	More effort/cost/planning/collaboration is required at the early stages (Up-front contribution).	3.93	0.86	2
3	The industry has to work (Adapt and comply) with more standards (More standards).	3.88	0.85	3
4	Among many, architects will have to share their roles with other specialists at the early design stages (Working with others).	3.84	1.00	4
5	An information manager has to be introduced into the project team (New roles).	3.73	1.13	5
6	There are challenges when sharing "work in progress" with other project team members (Sharing with others).	3.68	0.94	6
7	There is a need to strategically manage the disruptions caused by BIM (Providing BIM support).	3.68	0.86	6
8	BIM will change the entire design process; change is the only certainty (Resisting change).	3.60	1.06	7
9	There is a high demand for accountability (Openness).	3.48	1.09	8
10	Staff could be put outside their comfort zone (Staff confidence).	3.45	1.15	9
11	Adhering to BIM culture is time consuming (Learning curve).	3.30	1.14	10

3.3 Interviews

Interviews were conducted with selected staff within consultancy X. Table 4 show participants to have three to 10 years of BIM awareness. The aim of the interviews was to identify how to manage possible BIM disruptions. Content analysis was conducted to achieve the aim of the paper. Five questions with sub-categories were presented to the interview participants. Themes were categorised to define the findings.

Table 4: Interview participant

CATEGORIES	PARTICIPANTS	AGE GROUP	BIM AWARENESS	BIM EXPERIENCE
Practice Management	P1	40s	3 Years	25
	P2	40s	3 Years	5
Practice Staff	P3	20s	3 Years	5
	P4	30s	5 Years	5
	P5	40s	10 Years	20

Technical Management	P6	50s	5 Years	5
Technical Staff	P7	30s	6 Years	5
	P8	40s	5 Years	20

Table 5: Interview participant`s view on selected questions

QUESTIONS	FINDINGS
How best would you suggest getting staff involved in your company`s change/ BIM schemes?	Senior management involvement (P2); Providing time and awareness for BIM (P3; P5; P6); Provide staff opportunities to explore BIM projects (P4); Informing BIM benefits (P7); Identify BIM leaders (P8).
How would you suggest fitting staff into your company`s BIM change programme?	Exploring on dummy BIM projects (P1); Identifying what is required to staff (P2); Training (P3); Clarifying BIM misconceptions (P4); Defining how existing roles will be affected at different levels (P5; P6; P7); BIM is project related, when a BIM project is available roles will be communicated (P8).
How would you prefer to get the minimum level of BIM understanding?	Through guides, training, videos and reference documents (P1; P2; P4; P5; P6; P8); Define BIM terminologies clearly (P3).
How would you prefer to provide and collect feedback on BIM level 2 clashes with traditional building process practices?	Repository for reporting (P1); Discipline BIM lead (P2; P3); Structured questions (frequent asked questions) and discussion report processes (P4); Selected BIM managers on projects (P6; P8); Searching documented through lessons learnt files (P7).
How adequately can management support be spread and improved from high level to bottom level technical staff?	Creating opportunities to interact between high level and low level staff through standardized portals (P1); Communication issues; knowing the right person to talk to about BIM (P2); Creating opportunities to present issues to management through meetings (P3); Management should listen and interact with staff. Reasons for not accepting proposals should be provided. Create a window for debate/discussions (P4); Middle management do not understand what is required and a times take regional approaches (P5); Management should be aware and committed. They should monitor progress and give leadership to enthusiastic members (P6); There should be standardized links to communicate with promised time frame for responses (P8).

The interview findings included the unilateral acceptance that BIM disruptions can be managed. *How can BIM disruption be managed*? Relevant patterns of interview findings between participants was identified using content analysis. The most named factors were categorised under *incremental BIM knowledge development*. Perhaps, gradual BIM progress can be achieved by identifying gaps, proposing short-term and long term BIM goals, identifying organisational capability and working towards long-term goals with organisational technical and financial capability in mind. The incremental BIM knowledge development theme was further categorised into four factors. These are: BIM vision, BIM implementation, BIM knowledge curve and BIM maturity. These factors are interrelated and can all be achieved incrementally within a defined planned strategy.

Managing change transition

Interviews conducted identified key factors that enable the successful transition of BIM change at consultancy X.

Different change management goals required different approaches depending on the goal in context. A number of factors that could be considered for transition include the following:

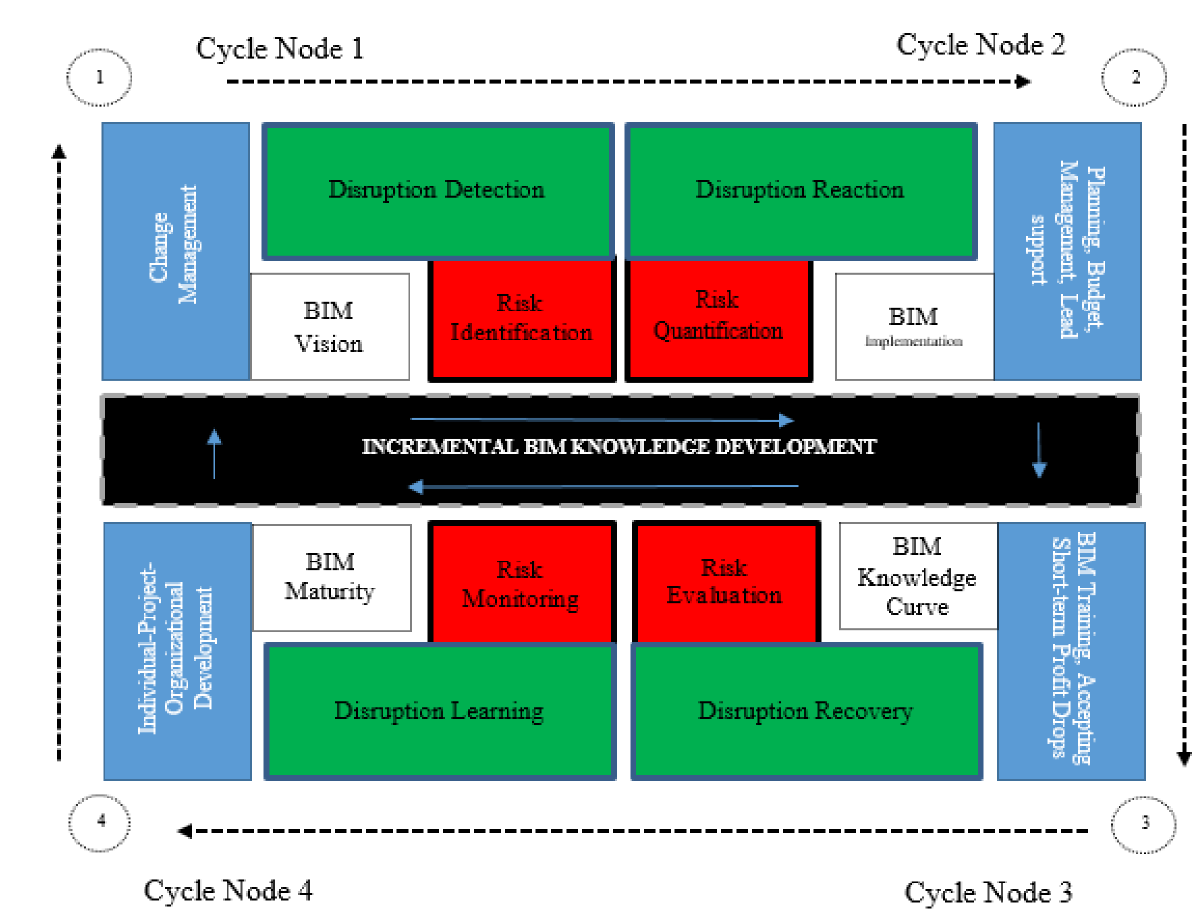
- leadership, policy and available resources are required to achieve successful transitions (P1);
- awareness, management support and successful communication (P3);
- getting people engage and on-board about the change and understanding the drive for change (P4);
- background studies and proper administration, communication and timing of change (P7);
- top-bottom management support, a sponsor, resources and the authority to make changes (P5);
- effective communication, engaging with staff on how and why change is happening (P2); and
- a clear planned structure enables transitions to take place (P8).

4. DISCUSSION

All participants agreed that there would be no serious possible disruption when adapting to level 2 BIM if all systems and requirements are provided. However, there are challenges associated with achieving BIM at consultancy X. These challenges are categorised as internal factors. These include: finding time to training staff while projects are on-going. Interview findings showed that on-the-job training will slow down the project pace due to the learning curve; standardised systems have to be updated regularly to avoid data loss when templates do not update; management not supporting the transition effectively at the lower levels will affect the BIM process. Some comments made by a number of interview participants regarding BIM change are stated as follows. P6 stated that "*appointment of technical staff at permanent positions should be based on ability to use software packages to support the transition. Organisations should assign right leaders with the right education at the right time*". P2 was of the view that much early work is required at the beginning of projects. P1 noted that it takes time to incorporate change, also stated that "*some of the challenges in the short-term, will slow us down and affect the quality of the model, and it could cause confusion to what we have to deliver. There is also potential to lose information at the early stages as this is the learning curve period*". P4 observed that it takes time to understand and set things up properly. Also stated that "*I will need someone at my own level to work with or someone that can quickly support me*". P7 described that training should be attached to projects. P8 noted that there is no structure or standardised templates across all disciplines within the organisation and it will cause some disruptions. Furthermore, interviewee P6 highlighted the challenge of appointing an information manager that "*Super Revit users should be the "information managers". When architects or engineers are assigned as the "information manager", they are not playing to their strengths*".

All participants stated that any possible BIM disruption can be managed effectively and efficiently. But to achieve this certain checks and balances have to be conducted. P4 stated that the organisational management have to provide "*time and right resources with leaders who know what they are doing and what is required*" to manage possible disruptions. Figure 3 presents a framework that can guide the management of BIM disruption inspired by Behdani et al., (2012).

The core strategy of managing disruption is to adapt BIM in an incremental development approach with the number of factors in mind such as organizational vision and capability. Knowledge increases as organisations move from *node* 1 to 4. Short-term and long-term goals can be defined and broken down into smaller packages that can be easily implemented and managed. For example BIM implementation can start with a small team by training selected individuals that form a defined project team which can later transfer experiences and learning knowledge to other projects teams and eventually develop an entire organization. The BIM disruption management cycle is developed in four different steps (cycle nodes). These are described as follows:



KEY

BOXES	DESCRIPTION
	Disruption Management Factors
	Features of Disruption Management Factors (not exhaustive lists)
	Disruption Cycle Nodes
	Risks Cycle Nodes
	Incremental Development across Disruption Management Factors

Figure 3: Disruption management framework

CYCLE NODE 1

BIM vision can define the magnitude and level of BIM implementation targeted by an organization. A vision can begin with change management, but as Rooke et al., (2004) described the construction industry is likely to resist change. When change management takes place possible disruptions occurs. These changes include the following:

Paper work: Traditional method requires exchange of hard copies at the end of a project. This leads to a large amount of printed document. Searching these documents is challenging. Nevertheless, different models are developed and federated within a BIM process; BIM requires digital exchange of information (electronic). However, both digital and hard copies are sometimes required by some contracts. Does this means paper work is still not optimised?

Document management: There is a need to fill-in many documents for competency, compliance purposes and so on. For example, during clash detection it is best practice to document all changes and approvals and standard documents used for implementing and auditing the clash detection process. Perhaps, an information manager will be required. An SME might struggle to employ an information manager for defined BIM projects.

Collaboration: Successive implementation of BIM requires interdisciplinary collaborative team working compared to non- BIM process. Communication, compliance and cooperation of all stakeholders involved are cornerstone to achieving collaboration. This culture has to be developed within an organization. The transition to a BIM collaborative working environment has a number of challenges.

Generational differences: There is a challenge posed towards older generation in the new digital age. Young graduate (young generation) are more open to new technologies. The same attitude is not common within the two generations. Older generation posed a greater challenge to adopt BIM technologies. Interviewee P4 stated that "*currently only technicians are trained who do not have the discipline experience*". As a result, possible disruption can be identified.

CYCLE NODE 2

BIM implementation requires a number of factors. These could include the following (non- exhaustive):

Planning: BIM vision can be defined into the organisation set-up. There is a need to respond to Employer`s Information Requirement (EIR) in the BIM execution plan. Planning is important towards achieving desired BIM goals; milestones are identified and considered in the early stages.

Management support: Management approves the budgets for projects to afford training, software, hardware and network systems required within a BIM enabled project. As a result, it is important to train management on what is required to adopt BIM within an organization.

Lead support: There should be a BIM lead that has the full support of the management. The BIM lead should be enthusiastic about BIM and be able to communicate effectively with others. As resistance to change is one of the challenges of a BIM shift.

Budget: A defined BIM budget is important towards the implementation of BIM and managing possible disruptions caused by middle management who fail to see benefit in adopting some BIM processes which require budgets. A define BIM budget can be used to adopt critical BIM processes supported by the BIM lead. As a result, some economic risk involved can be quantified based on the disruption detection and reaction observed within the implementation process.

CYCLE NODE 3

BIM knowledge curves will require training and expectancy of short-term profit drops. However, efficiency is undoubtedly expected in BIM enabled projects, but cost savings will vary project to project. People are core to the implementation of BIM. *People* use the *technology*, adopt defined *processes* with guided *policies*. One of the top disruptions is the need to train staff to adopt BIM processes.

Training is required due to the following:

Rapid changing technology: New technologies and newer versions are made available annually and quarterly in some software. Financial spending capability of an organization is put to question in order to remain competitive. Newer technology requires training and training cost money. Some organizations rather stick to tools and working formats they know rather than using applications that require training and bring about added cost. Interviewee P4 raised a concern that "*BIM Technicians could be driving the BIM initiative, focus should be given to both practice and technical staff, but requiring different training*".

Global flood of software: The availability of different software from different regions of the world is helpful and makes the market competitive. But organizations are challenged on making specific decisions on choosing appropriate software compatible with organization capability and project needs.

One of the challenging factors identified by the interview participants is defining the timing for BIM training when there are no on-going BIM projects available within a consultancy, it is challenging to train staff on pilot projects. Middle management are less likely to spend on training with only traditional projects at hand. However with BIM projects at hand, the need to train or hire BIM specialists is mandatory. Also when staff are trained to work on BIM projects and are left for months without a real live BIM projects, there is a likelihood that staff might need to be retrained (interviews). Starting up the learning curve is challenging especially for SME`s with lower financial capability. BIM training allows a smooth transition of CAD Managers to BIM Managers. Training is conducted over a defined period of time and can facilitate the recovery of defined disruptions. As a result, risk can be evaluated.

CYCLE NODE 4

BIM maturity is key to the incremental development strategy; it allows improvements at different levels. This can be achieved at an individual, project and organizational level. As the maturity increases, the less disruption should be expected. Disruption learning can be achieved within the disruption cycle. This occurs when a disruption is identified, risks is quantified towards the disruption reaction and the disruption is recovered through training. Risk can be monitored. Perhaps, the BIM vision can be revisited and the goals can pass through the disruption cycle as many times as required.

5. LIMITATIONS

The findings are representation from only one large and multi-disciplinary consultancy. Findings may not apply to other categories of organisations within the construction industry. However, there is an opportunity to learn from consultancy X.

6. CONCLUSION

This paper aimed to *identify and verify the drivers for managing BIM disruption within the UK consultancies. A case study was conducted at Consultancy X. Findings showed that.* BIM enabled projects are undoubtedly efficient. However, disruptions could occur which needs to be managed. This paper has clearly signified that not all BIM implementation challenges are disruptive (see Table 1). However there is tension between disruption and risks during the BIM implementation process. Primary data was collected from consultancy X which is a multidisciplinary organisation. Focus group findings identified 11 possible disruptions towards traditional practice. A survey was conducted, the 11 factors were explored through a statistical analogy. Interviews were conducted and findings demonstrated that BIM disruption can be managed through incremental BIM knowledge. Four factors are considered. These are BIM vision, BIM implementation, BIM learning curve and BIM maturity. The process of managing disruption was proposed in four sequential cycle nodes which can be repeated while revising the BIM vision of a consultancy. Node one introduces a BIM vision with comes with risk and disruption that can be identified. Node 2 is the implementation stage were disruption reaction takes place but can be managed through planning and management support. Node 3 is the stage were disruption is recovered through training as the BIM knowledge curve improves. Node 4 provides an opportunity to learn from the disruption through monitoring and conducting maturity assessments.

ACKNOWLEDGEMENT: This paper was made possible by NPRP grant [NPRP No.: 6 - 604 - 2 - 253.] from the Qatar National Research Fund (a member of Qatar Foundation). The statements made herein are solely the responsibility of the author[s].

7. REFERENCES

Arayici, Y., Khosrowshahi, F., Marshal Ponting, A. and Mihindu, S. (2009). Towards Implementation of Building Information Modelling in the Construction Industry. *Fifth International Conference on Construction in the 21st Century (CITC-V)* “Collaboration and Integration in Engineering, Management and Technology” May 20-22, Istanbul, Turkey.

Behdani, B., and Adhitya, A., and Lukszo, Z. and Srinivasan, R, (2012). *How to Handle Disruptions in Supply Chains: An Integrated Framework and a Review of Literature*.

Deutch, R. (2011). *BIM and Integrated Design: Strategies for Architectural Practices*. New Jersey: John Wiley and Sons.

Fellows, R., Langford, D., Newcombe, R. and Urry, S. (1983). *Construction Management in Practice*. 1st ed. Harlow, UK: Longman.

Gu, N. and London, K. (2010). Understanding and Facilitating BIM Adoption in the AEC Industry. *Automation in Construction,* Vol. 19, 988 – 999.

Grilo, A. and Jardim-Goncalves, R. (2011). Challenging Electronic Procurement in the AEC Sector: A BIM-Based Integrated Perspective". *Automation in Construction*, 20, 107 - 114.

Jung, Y. and Joo, M. (2011). Building Information Modelling (BIM) Framework for Practical Implementation, *Automation in Construction*, Vol.2, No. 20, 126-133.

Lindblad, H. and Vass, S. (2015). BIM Implementation and Organisational Change: A Case Study of a Large Swedish Public Client. *8th Nordic Conference on Construction Economics and Organisation*, Vol. 12, 178-184.

Lu, W. and Li, H. (2011). "Building Information Modeling and Changing Construction Practices. *Automation in Construction*. 20, 99-100.

Race, S. (2012). *BIM Demystified*. 1st (ed). London: RIBA Publishing, UK.

Moore, G. (1999). *Crossing the Chasm*. New York: Harper Business.

Morlhon, R.., Pellerin, R and Bourgault, M. (2014). Building Information Modeling Implementation through Maturity Evaluation and Critical Success Factors Management. *International Conference of Project Management*, 1126 – 1134.

Rooke, J., Seymour, D. and Fellows, R. (2004). Planning for Claims: An Ethnography of Industry Culture. *Construction Management and Economics*, Vol. 22, 655 – 662.

Succar, B. (2009). Building Information Modelling Framework: A Research and Delivery Foundation for Industry Stakeholders. *Automation in Construction* Vol. 3, No. 18, 357-375.

Tulenheimo, R. (2015). Challenges of Implementing New Technologies in the World of BIM: Case Study from Construction Engineering Industry in Finland. *8th Nordic Conference on Construction Economics and Organisation*, Vol. 21, pp. 469- 477.

Watson A. (2010). BIM- A Driver for Change. *13th International Conference on Computing in Civil and Building Engineering*. Nottingham, UK.

(2016). "Redpoint RTLS Technology Advantages." <https://www.redpointpositioning.com/rtls-technology/rtls-advantage/>. (Nov. 26, 2016).

Schilit, B. N., and Theimer, M. M. (1994). "Disseminating active map information to mobile hosts." *IEEE network*, 8(5), 22-32.

Schmidt, A., Beigl, M., and Gellersen, H.-W. (1999). "There is more to context than location." *Computers & Graphics*, 23(6), 893-901.

Shen, X., Chen, W., and Lu, M. (2008). "Wireless sensor networks for resources tracking at building construction sites." *Tsinghua Science & Technology*, 13, 78-83.

Smith, D. K. D. (2008). "Building Information Modeling (BIM)." <http://wbdg.org/bim/bim.php>. (June 3, 2010).

Wang, C., Wu, F., Shi, Z., and Zhang, D. (2016). "Indoor positioning technique by combining RFID and particleswarm optimization-based back propagation neural network." *Optik - International Journal for Light and Electron Optics*, 127(17), 6839–6849.

Yu-Chee, T., Shih-Lin, W., Wen-Hwa, L., and Chih-Min, C. (2001). "Location awareness in ad hoc wireless mobile networks." *Computer*, 34(6), 46-52.

Part II: BIM for Design, Manufacturing and FM

BIM FOR MANUFACTURING: A CASE STUDY DEMONSTRATING BENEFITS AND WORKFLOWS AND AN APPROACH FOR ENTERPRISE APPLICATION INTEGRATION (EAI)

Kin Ma, BIM System Integrator, KTP Associate, Hodgson Sayers & Teesside University,

kma@hodgson-sayers.co.uk

Nashwan Dawood, Professor, Technology Futures Institute, Teesside University

n.n.dawood@tees.ac.uk

Mohamad Kassem, Associate Professor, Northumbria University

Mohamad.kassem@northumbria.ac.uk

ABSTRACT: *Building Information Modelling (BIM) tools and workflows are now widely acknowledged as enablers for improved efficiencies across the lifecycle of construction projects. While BIM applications have been extensively researched in design and contractor organisations, there have been a dearth of investigations of BIM implementation within manufacturing. Research into BIM for manufacturing has been largely focussed on the topic of BIM objects and their graphical and non-graphical content. The knowledge gap within the 'BIM for Manufacturing' area is remarkable given the primary role of manufacturers in supplying building systems and components as well as the data for detailed design, construction and operation phases.*

The key areas that are under-scrutinised are: (a) BIM uses, benefits and workflows within manufacturer organisations, and (b) BIM link or integration with other business functions within either an 'Enterprise Application Integration' (EAI) or an 'Enterprise Resource Planning' (ERP) integration types. This paper aims to contribute to these two areas by (1) illustrating the application of BIM in design-for-manufacture (offsite fabrication) and design-for-site (installation), its benefits and workflow, and (2) discussing the ways for its integration with other business functions and proposing a suitable approach.

The results from the case study showed important tangible and latent benefits. The proposed approach for BIM integration showed potential links with several business functions within the manufacturing organisations including sales and estimation, procurement, production, construction management, and asset management.

KEYWORDS: *Building Information Modelling (BIM), Enterprise Resource Planning (ERP), Enterprise Application Integration (EAI).*

1. INTRODUCTION

BIM is now considered as the current expression of digital innovation within the construction industry (Succar and Kassem, 2015). It is affecting all phases involved in the delivery of built assets including planning, design, construction and operations either by facilitating and changing many of the functions and activities required across such phases or by introducing new capabilities. Reports and case studies from around the world have shown that BIM tools and workflows increases efficiency and reduces operating costs across all phases of a construction project (Bryde, Broquetas, and Volm, 2013). However, there is a dearth of studies investigating BIM implementation and applications within manufacturing organisations. In particular, there are no case studies that illustrate BIM uses, benefits and workflows within manufacturing organisations. There is also a gap in knowledge about the link or integration of BIM with other business functions within the manufacturing organisations. Manufacturing organisations have notoriously adopted approaches for integrating business functions - technology, resources and services - to achieve agility and flexibility in coping with rapid changes in both internal and external environments (Chung, Skibniewski, and Kwak, 2009). Two common approaches for integration are the ERP and EAI. The ERP approach integrates all functions and processes of a business and generate a comprehensive view of the entire company (Wilson, 2012). The EAI approach aims to modernise, consolidate and coordinate different enterprise applications (e.g. existing legacy application) while adding new applications that exploit new technologies (e.g. BIM, e-commerce, extranet) (Lee et al., 2003).

Using an organisation based in the UK as a case study, this paper aims to (a) illustrate the use of BIM in design-for-manufacture (offsite fabrication) and design-for-site (installation), its benefits and workflow and (b) discuss the approaches for BIM integration with other business functions and propose an adequate approach.

2. LITERATURE REVIEW

Studies investigating the different procedural and technological aspects of BIM and its implementation within projects, organisations and whole markets have proliferated over the last decade. Table 1 shows a non-exhaustive sample of BIM studies.

Ahn, Kwak, and Suk (2015) proposed a framework and organisational transformation strategies for BIM adoption by building contractors based on data collected from case study interviews. Arayici, Onyenobi, and Egbu (2012) investigated the influence of BIM on facility management using two expert semi-structured interviews. Azhar (2011) provided a summary of the benefits, risks and challenges affecting BIM implementation including a return on investment analysis. Bryde, Broquetas, and Volm (2013) also explored BIM benefits in construction projects and identified cost reduction and control through building and project lifecycle as the most frequently reported benefits. Love et al. (2013) discussed the benefits of BIM capital and operational expenditure for asset owners, if high level of detail (i.e. LOD 500) is adopted. They also argues that operational phase of buildings and the asset performance could be optimised, when integrated with an ERP. Ganah and John (2015) investigated the impact of BIM on health and safety in construction and concluded that the integration process of BIM and H&S was not possible with the technology and tools available at the time.

Table 1 includes only three studies that have addressed either BIM for manufacturing or BIM-ERP integration. Babič, Podbreznik, and Rebolj (2010) investigated the link between BIM and ERP information system to support design, manufacturing and construction processes through their integration with CAD tools and using Industry Foundation Classes (IFC) open standards. The proposed approach adopted a centralised BIM (model) and an ICT infrastructure that limited the integration with external stakeholders. Clevenger and Khan (2014) investigated the impact of BIM-enabled design-to-manufacture using two case studies. The identified benefits included time saving (early start of construction), cost reduction (liquidated damage) and increased accuracy of shop drawings. Palos, Kiviniemi, and Kuusisto (2014) qualitatively explored through interviews the potential to improve product data management (PDM) systematics and recommended future development needs to building product libraries for AEC organisations. Ghosh et al. (2011) examined the need to integrate BIM and ERP in relation to sustainability within small and medium construction organisations and proposed some general guidelines for project governance.

This summary shows there is still a general gap in knowledge in the area of BIM for manufacturing and particularly, there is a lack of both case studies demonstrating the benefits and approaches for BIM-ERP integration. This paper attempts to contribute to these gaps by adding case studies and proposing an approach for BIM-ERP integration.

2. BIM FOR MANUFACTURING

The two use cases were conducted within Hodgson Sayers, UK. It is a medium sized organisation involved in the construction supply chain as a manufacturer and installer of roofing and other building works such as fencing, security doors and metalwork on both new and renovation projects. The two use cases will illustrate how BIM was used to enable several business processes (design, production, outsourcing, installation) within the manufacturing organisation and discuss the benefits of its use.

2.1 Manufacturing and installation of louvres for a renovation project

This use case involved the design and replacement of security doors and louvres in a substation renovation project (Figure 1). This project entails offsite fabrication, which notoriously requires considerable planning and accurate design information. As a result site surveys are important in key site information such as measurements, materials and construction methods. A summary of the conducted survey is illustrated in Table 2. Due to the specific conditions of the site, the central louvre panels has to be fixed from the outside of the building which is different from the typical installation method by which the louvres are fixed from the inside. The intention is therefore to design and manufacture the side louvre panels for the standard installation procedure and the central panel for installation from the outside.

Table 1. Summary of literature review

	Concept/Schematic	Detailed Design	Manufacturing	Construction	Facilities	BIM Technology	BIM Integration with enterprise	Open Standards
Ahn, Kwak, and Suk (2015)	X	X		X		X		
Arayici, Onyenobi, and Egbu (2012)		X		X	X			X
Azhar (2011)	X	X		X	X	X		
Babič, Podbreznik, and Rebolj (2010)			X	X			X	X
Bryde, Broquetas, and Volm (2013)	X			X		X		
Clevenger and Khan (2014)		X	X	X		X		X

Ganah and John (2015)				X	X	X		X
Ghosh et al. (2011)	X	X		X		X	X	
Gilkinson et al. (2015)	X			X	X	X		X
Kassem et al. (2015)					X			
Liao et al. (2014)		X		X	X	X		X
Love et al. (2013)	X			X	X	X	X	
Olatunji (2014)	X			X	X	X		
Opitz, Windisch, and Scherer (2014)		X		X		X		X
Palos, Kiviniemi, and Kuusisto (2014)		X	X	X		X		X
Porwal and Hewage (2013)		X		X				
Steel, Drogemuller and Toth (2010)	X	X		X		X		X
Takim, Harris and Nawawi (2013)	X			X		X		
Travaglini, Radujkovic, Mancini (2014)				X	X			X
Volk, Stengel, Schultmann (2014)				X	X	X		X

Figure 1. The substation site for rennovation

Table 2. A site survey report conducted by the surveyor

	Market Street (New) Building Survey
Type and location:	This was a double emergency exit door with transom panel until I changed the hardware to give outside access
Current condition:	Poor
Overall size:	1280w x 2425h. Note: panel above the bulk head is lower on the outside
Frame section size:	100
Head section size:	50 with transom panel
Fixing centres:	RHS 110,650,1110 then two more holes to bolt in to the louvre (see photos) LHS space the fixing our evenly into concrete pillar
Fixing centre from front:	50

Additional notes:	All sizes are in mm unless otherwise stated. The asbestos does not come up to this frame There is a hardwood louvre to the right of this set from a ventilation duct. It is 3085w x 1155h including the thick hardwood cill sitting on the brickwork.

As this project represents a one-off situation, there were no standard procedures or processes provided for site managers or operatives. It requires the effective communication of design information between the client, contractors, metalwork managers, fabricators, site managers and operatives. The subsequent two sections will explain and compare the pre-BIM and post-BIM processes.

2.1.1 Pre-BIM Process:

Before the implementation of BIM tools and workflows, hand sketches made on site were used as an input to the design process and metalworking department or external suppliers (Figure 2). Based on these sketches, the external suppliers provide CAD drawings in circumstances where they might have issues or clarification about the product. Although the CAD drawings of external suppliers, used to express the design intent before they proceed with manufacturing, led to improvement, the process remained time consuming and cost intensive as the amount of request for information (RFI) and change orders were relatively high for both parties.

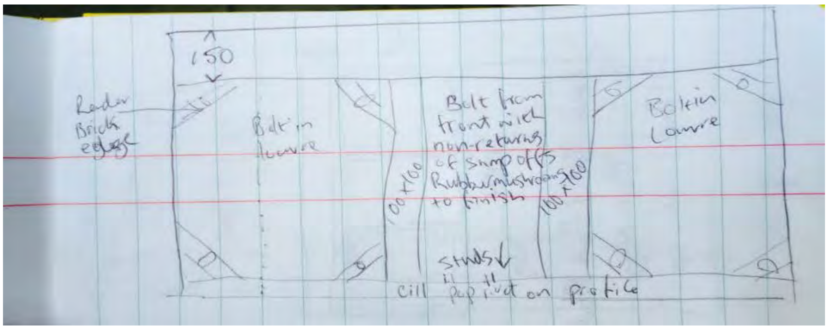


Figure 2. Hand sketches from site to inform design process.

2.1.2 Post-BIM Process

Based on the sketches provided, the designer was able to develop the detailed design for the louvres and security door using Autodesk Revit (Figure 3). This initial object-based model represented an opportunity to further discuss the design and reduce the impact of potential inaccuracies on fabrication and installation as discussed later. Figure 4 illustrates the early shop drawings following the initial design (Figure 3). These steps (site survey, design production, shop drawing production, manufacturing) can also be part the typical pre-BIM workflow and the subsequent steps would be to manufacture and install on site. However, given the particular condition of this project and the BIM ability of imposing or merging the designed products into the as-built model, it was decided to further check the design products. The louvres model was merged with the site as-built model and a clash detection test was performed. As a result of this operation, a design - installation issue was identified (Figure 5). The issue consisted of an obstruction by a wall which would prevent the site operatives from installing the side louvre from the back. This issue would not be capture without this BIM inherent ability used by the manufacturing organisation and the unfit-for-purpose side louvre would be detected only when it reaches site, hence, causing significant wastages of resources, time and money for both the client and manufacturer.

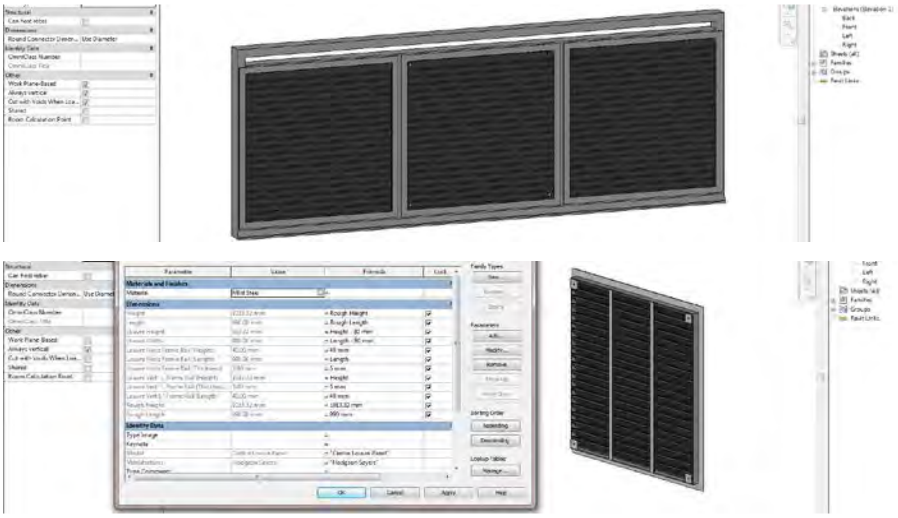


Figure 3. The design model for the louvre systems.

After the design error has been identified and resolved, the 2D shop drawings including installation methods were produced form the BIM (model) and sent to the suppliers for quotations (Figure 6). The supplier was able to accurately quote and fabricate the products. During this time, a significant reduction in RFIs was witnessed compared to the historical average with pre-BIM processes. The products were successfully delivered and installed on site. The project manager and the site operatives, using the BIM (model) and the installation instructions augmented with drawings extracted from the model, were capable to produce an improved method statement with reduced health and safety risks.

Following the successful BIM implementation on this use cases – as well as other use cases – a BIM workflow was set up as a protocol to follow in all future project (Table 3).

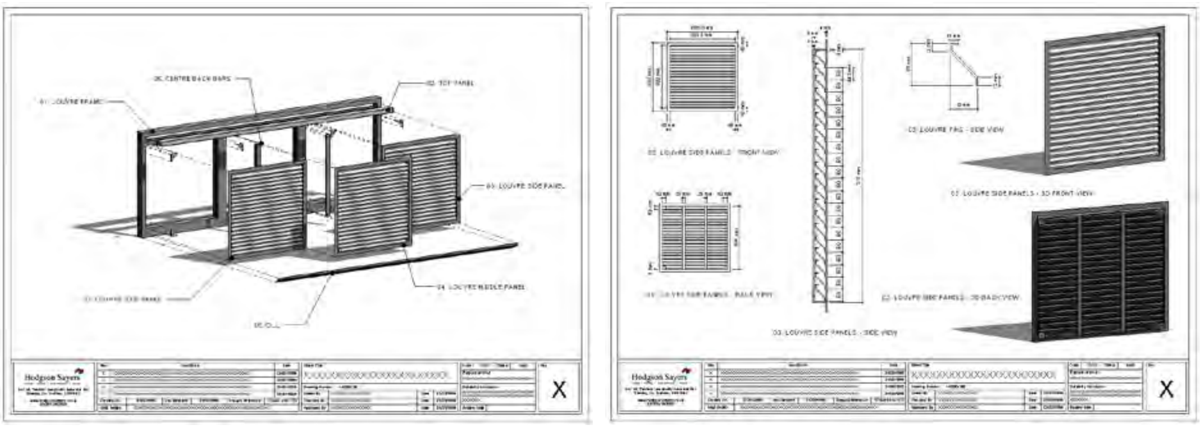


Figure 4. Screenshots of the shop drawing for the louvre panels.

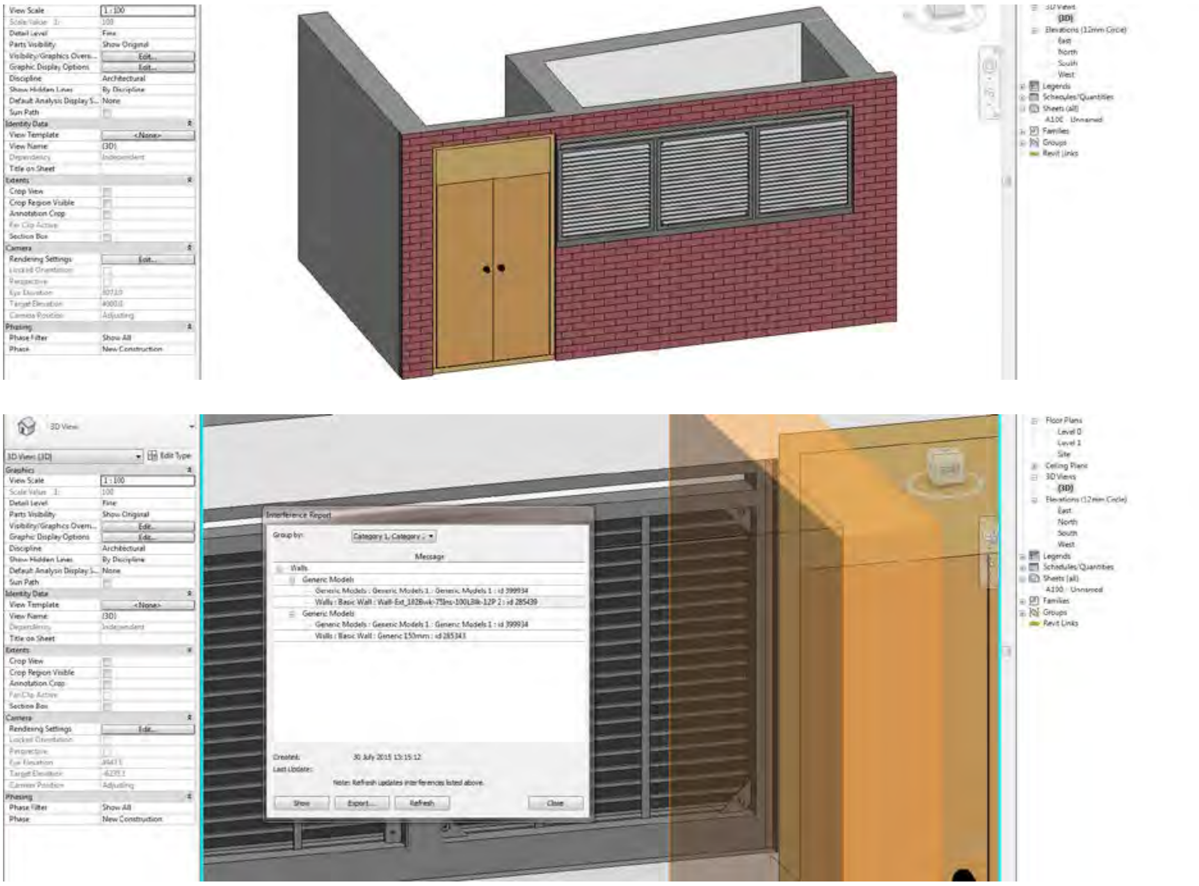
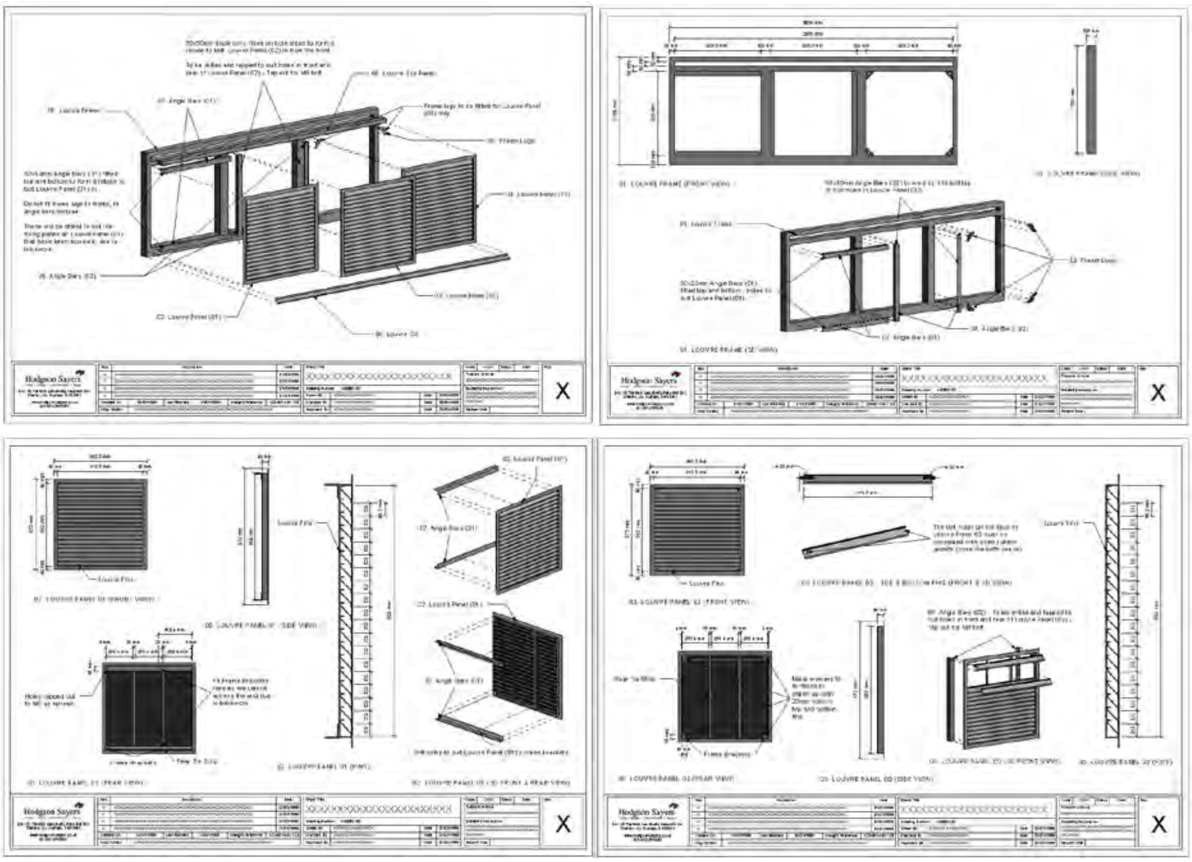


Figure 5. Identified installation issue spotted prior to fabrication and site.



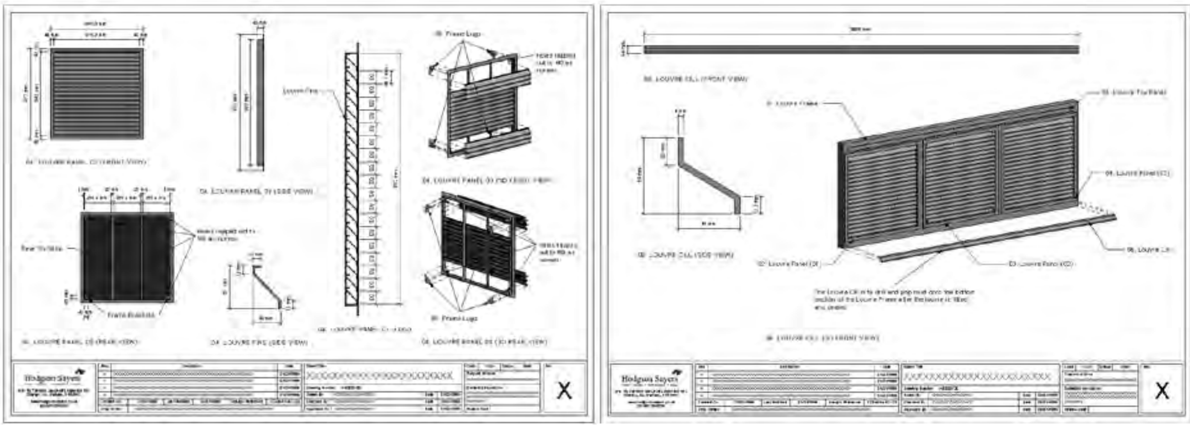


Figure 6. Sample of amended shop and installation drawings for the new louvre system shared with external suppliers for quotations

3. BIM-ERP Integration

Following the implementation of BIM alongside a number existing processes and technologies (Table 4) for specific organisational functions (sales, finance, procurement, etc.), there was a risk of creating information silos that could result in fragmentation and duplication. Concurrently, there was an opportunity to exploit the digital information of the BIM workflow to support several business functions and enabling an effective operation and project management. The two candidate approaches for achieving the integration are Enterprise Resource Planning (ERP) and Enterprise Application Integration (EAI). Table 5 summarises and compares the key technical, behavioural and risk factors of the two approaches. Follow the comparison of all factors included in Table 5 and the pre-existing decentralised business processes, the EAI approach was selected to integrate BIM as part of the overall enterprise integration of the organisation. However, to achieve such an integration a new system was required in addition to the pre-existing ones included in Table 4. The new system was required to avoid an approach, where integration is achieved through embedded interfaces and transformation between each pair of applications. Solutions with embedded interfaces are challenging to maintain over time due to the changes in data formats and the complexity of source and target applications. Figure 7 shows the position of the new application – called here as 'middleware' – among all existing systems including BIM. In addition to integrating the different systems, the 'middleware' has the paramount role of providing access to a single and most up-to-date source for each information and data item. Key principles of information sharing from the PAS 1192-2013 (BSI, 2013) were adapted to support this objective.

Table 3. Summary of activities within a BIM workflow for renovation projects.

Project Stage	Tasks	Responsible
Concept Design	1. Conduct building surveys and site analysis (output: site survey report)	CPM, S & O
	2. Extract design input (hand sketches) from site visit and survey. For complex project, conduct a laser scan of as-built conditions	CPM, S & O
	3. Conduct team review meetings to analyse and record potential risks and issues and plan next actions	PT
Developed Design	4. Create BIM (models) for the required project components	BM
	5. Create as built model for the site	
	6. Create and archive BIM objects with nested and shared parameters for the project's components for use on current project and future projects.	BM
	7. Merge the components' model with the site as-built model	BM
	8. Execute clash detection tests to diagnose potential issues with the design and installation procedures	BM
	8. Approve design? (Yes – Go to Task 9, No – Go to Task 2)	PT
Technical Design	9. Conduct a final review of the design alignment with job requirements and generate the request for quote (RFQ) to suppliers including shop drawings from BIM (model)	CPM
	10. External supplier receive and analyse enquiry	ES
	11. Issues to be raised? (Yes – Go to Task 12, No – Go to Task 14)	ES
	12. Raise RFI to Hodgson Sayers	ES
	13. Resolve RFI? (Yes – Go to Task 9, No – Go to Task 3)	CPM & BM
	14. Send quotations to Hodgson Sayers	ES
	15. Review quote? (Approved – Go to Task 16, Not approved – End or go back to Task 10)	CPM
Construction	16. Complete Job Quality Plans (JQPs), method statements, risk assessments, etc.	CPM
	17. Arrange for site installation, pick up and receive documents	O
	18. Install the products on site as per JQPs, method statements, as-built drawings, etc.	O
	19. Quality checks and prepare handover documents / digital BIM models to clients	CPM

Legend

C	Contract/Project Manager	S	Surveyor	O	Operative	PT	Project Team
BM	BIM Modeller	ES	External Supplier				

Table 4. Existing systems within the organisations.

Name	Scope
CRM Software	Manages the company's interaction with current and future customers and external suppliers.
Accounting Software	Automates and schedules financial reports, linking dynamically from Microsoft Excel.
Site App	Mobile App to electronically transfer site documents and reduce time and paperwork.

Autodesk Products	Revit, AutoCAD and Navisworks
Other	Google Earth, Microsoft Office suite.

The overall architecture of the integrated solution is illustrated in Figure 7. It shows the connected business functions and their corresponding exchange of data and information. The important role of BIM in such an integration is evident from the amount of interactions with other business functions that are either consuming its information or triggered by the completion of BIM deliverables. An example showing a specific BIM workflow and the interactions with other business functions is included in Figure 8.

Table 5. Approaches for enterprise integration.

		ERP	**EAI**
Behavioural	Degree of resistance	High	Low
	Business process	Centralised	Decentralised
	Implementation period	Long	Medium
	Required people readiness	High	Medium
Technical	Degree of Business Process Reengineering	High//Medium	Medium-low
	Integration method	Process Integration	Process Mapping
	Implementation Period	Long	Medium
	Programming requirement	Medium	Medium-low
	Complexity	High-medium	Medium-low
	Required technology readiness	High-medium	Medium-low
Overall Risk	Typical rating	High-medium	Medium-low
Overall Cost	Typical rating	High-medium	Medium-low

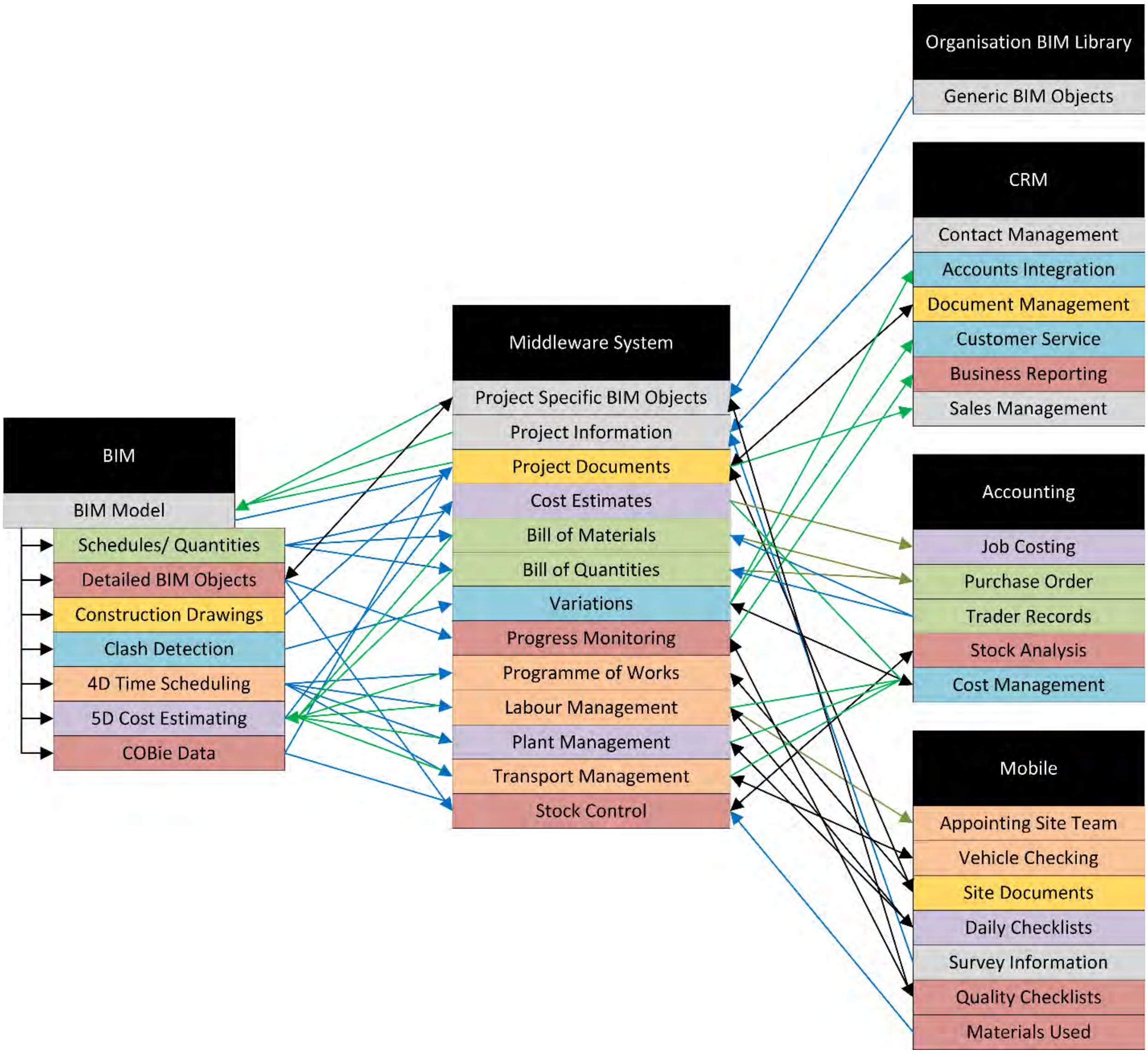


Figure 7. Dependencies and information flows within the proposed EAI solution

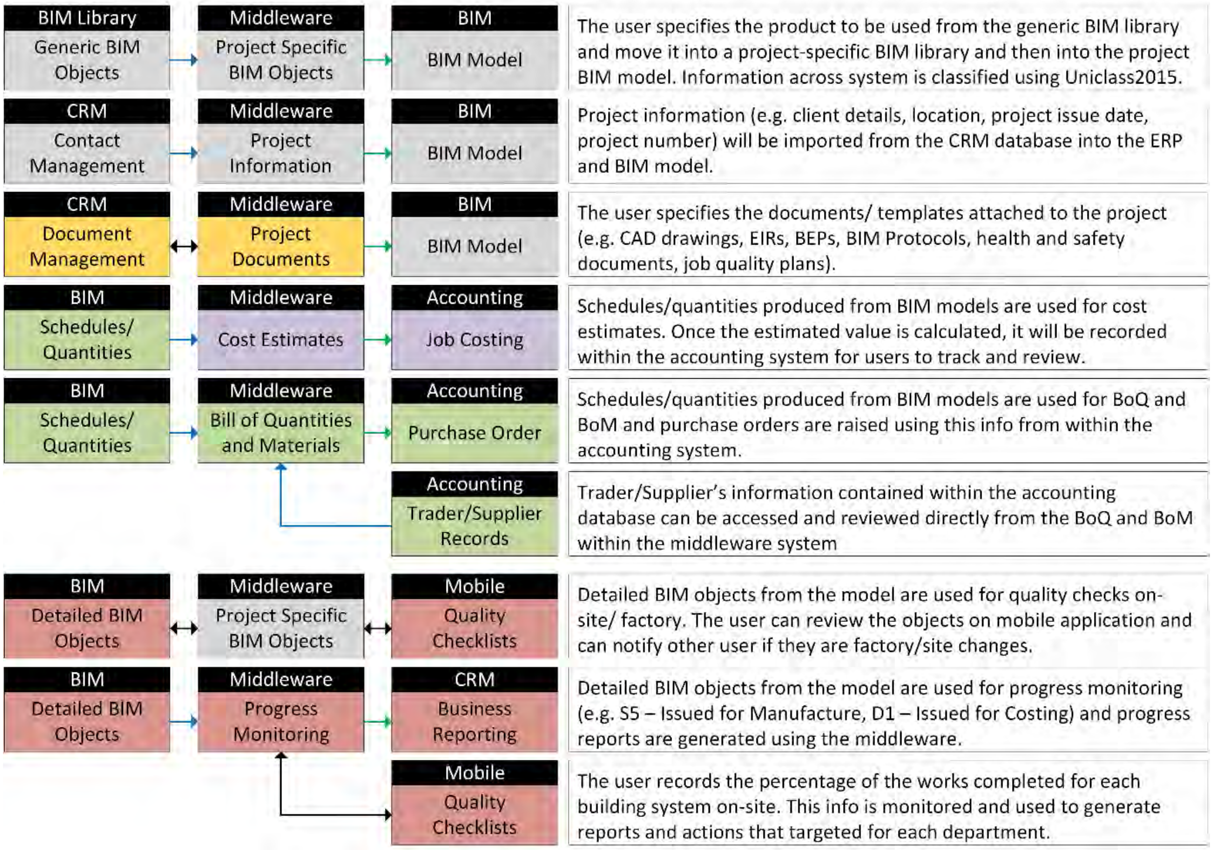


Figure 8. A use case scenario where BIM is part of the workflows of several business functions (design, finance, site, CRM, and project management)

4. Conclusion

BIM uses and integration with other enterprise systems are two primary implementation topics for BIM within manufacturing organisations that are still uncharted.

The first topic was addressed through the presentation of a case study of BIM applications within a manufacturing organisation, its benefits and workflows. The case study involved the use of BIM in design-for-manufacture (offsite fabrication) and design-for-site (installation) scenarios. Clear tangible benefits (i.e. reduction of wastages in material, time and cost; reduction of RFIs) were demonstrated as a direct result of implementing BIM workflows. These benefits were possible due to the early engagement between the manufacturer, contractor, external suppliers, surveyors and site operatives, which was supported by BIM workflows and technologies. It enabled the detection and elimination of design risks, the procurement of the right products and materials, and the definition of installation strategies and method statements.

The second aspect was addressed by proposing an outline approach for the integration of BIM with other business systems and functions using an Applied Enterprise Integration (AEI) methodology. The AEI was preferred over the ERP as a result of the decentralised pre-existing business processes and their supporting systems, and the overall lower business, technological and change management risks. To achieve the AEI, a 'middleware' system was implemented to fulfil the role of both integrating the business functions and systems (including BIM) and providing a centralised single source of truth for all business processes. The role of BIM within the integrated enterprise solution is evident from the several potential links with all other business functions including sales and estimation, procurement, production, construction management, and asset management. It is expected that the proposed AEI will reduce errors and decision latency and increase the visibility and traceability of information. The limitation of this research is in the ad-hoc nature of the proposed integration solution suitable for organisations who have several existing decentralised business processes and systems and are unwilling to accept the higher implementation risk and cost of integration through ERP.

References

Ahn, Y.H., Kwak, Y.H. and Suk, S.J. (2016) 'Contractors' transformation strategies for adopting building information modeling', *Journal of Management in Engineering*, 32(1), p. 05015005. http://doi.org/10.1061/(asce)me.1943-5479.0000390

Arayici, Y., Onyenobi, T. and Egbu, C. (2012) 'Building information Modelling (BIM) for facilities management (FM)', *International Journal of 3-D Information Modeling*, 1(1), pp. 55–73. http://doi.org/10.4018/ij3dim.2012010104

Azhar, S. (2011) 'Building information modeling (BIM): Trends, benefits, risks, and challenges for the AEC industry', Leadership and Management in Engineering, 11(3), pp. 241–252. http://doi.org/10.1061/(asce)lm.1943-5630.0000127

Babič, N.Č., Podbreznik, P. and Rebolj, D. (2010) 'Integrating resource production and construction using BIM', *Automation in Construction*, 19(5), pp. 539–543. http://doi.org/10.1016/j.autcon.2009.11.005

Bryde, D., Broquetas, M. and Volm, J.M. (2013) 'The project benefits of building information Modelling (BIM)', *International Journal of Project Management*, 31(7), pp. 971–980. http://doi.org/10.1016/j.ijproman.2012.12.001

Chung, B., Skibniewski, M.J. and Kwak, Y.H. (2009) 'Developing ERP systems success model for the construction industry', Journal of Construction Engineering and Management, 135(3), pp. 207–216. http://doi.org/10.1061/(asce)0733-9364(2009)135:3(207)

Clevenger, C.M. and Khan, R. (2014) 'Impact of BIM-Enabled design-to-fabrication on building delivery', *Practice Periodical on Structural Design and Construction*, 19(1), pp. 122–128. http://doi.org/10.1061/(asce)sc.1943-5576.0000176

Ganah, A. and John, G.A. (2015) 'Integrating building information modeling and health and safety for Onsite construction', *Safety and Health at Work*, 6(1), pp. 39–45. http://doi.org/10.1016/j.shaw.2014.10.002

Ghosh, S., Negahban, S., Kwak, Y.H. and Skibniewski, M.J. (2011) 'Impact of sustainability on integration and interoperability between BIM and ERP - A governance framework', First International Technology Management Conference, http://doi.org/10.1109/ITMC.2011.5995975

Gilkinson, N., Kiviniemi, A., Raju, P. and Chapman, C. (2015) 'Building information modelling: The tide is turning', *Proceedings of the ICE - Structures and Buildings*, 168(2), pp. 81–93. http://doi.org/10.1680/stbu.12.00045

Kassem, M., Kelly, K., Dawood, N., Serginson, M. and Lockley, S. (2015). BIM in facilities management applications: a case study of a large university complex. Built Environment Project and Asset Management, Vol. 5(3), pp. 261 – 277.

Lee, J., Siau, K., Hong, S., 2003. Enterprise Integration with ERP and EAI. Communications of the ACM, Vol. 46, No. 2, pp. 54-60 Linthicum, D.S., 1999. Enterprise Application Integration. Addison Wesley.

Liao, L., Teo, E.A.L., Li, L., Li, X. and Man, Q. (2014) 'Improving construction schedule and cost information feedback in building information modelling', *Proceedings of the ICE - Management, Procurement and Law*, 167(2), pp. 91–99. http://doi.org/10.1680/mpal.13.00016

Love, P.E.D., Simpson, I., Hill, A. and Standing, C. (2013) 'From justification to evaluation: Building information modeling for asset owners', *Automation in Construction*, 35, pp. 208–216. http://doi.org/10.1016/j.autcon.2013.05.008

Olatunji, O.A. (2014) 'Views on building information modelling, procurement and contract management', Proceedings of the ICE - *Management, Procurement and Law*, 167(3), pp. 117–126. http://doi.org/10.1680/mpal.13.00011

Opitz, F., Windisch, R. and Scherer, R.J. (2014) 'Integration of document- and model-based building information for project management support', *Procedia Engineering*, 85, pp. 403–411. http://doi.org/10.1016/j.proeng.2014.10.566

Palos, S., Kiviniemi, A. and Kuusisto, J. (2014) 'Future perspectives on product data management in building information modeling', *Construction Innovation: Information, Process, Management*, 14(1), pp. 52–68. http://doi.org/10.1108/ci-12-2011-0080

Porwal, A. and Hewage, K.N. (2013) 'Building information modeling (BIM) partnering framework for public construction projects', *Automation in Construction*, 31, pp. 204–214. http://doi.org/10.1016/j.autcon.2012.12.004

Steel, J., Drogemuller, R. and Toth, B. (2010) 'Model interoperability in building information modelling', *Software & Systems Modeling*, 11(1), pp. 99–109. http://doi.org/10.1007/s10270-010-0178-4

Succar, B. Saleeb, N. and Sher, W. (2016) 'Model uses: foundations for a modular requirements clarification language', Language, Australasian Universities Building Education (AUBEA2016), Cairns, Australia, July 6-8, 2016.

Succar, B., & Kassem, M. (2015). Automation in Construction Macro-BIM adoption : Conceptual structures. Automation in Construction, 57, 64–79. http://doi.org/10.1016/j.autcon.2015.04.018

Takim, R., Harris, M. and Nawawi, A.H. (2013) 'Building information modeling (BIM): A new paradigm for quality of life within architectural, engineering and construction (AEC) industry', *Procedia - Social and*

Behavioral Sciences, 101, pp. 23–32. http://doi.org/10.1016/j.sbspro.2013.07.175

Travaglini, A., Radujkovic, M. and Mancini, M. (2014) ‘Building information Modelling (BIM) and project management: A Stakeholders perspective’, *Organization, technology and management in construction: An international journal*, 6(2). http://doi.org/10.5592/otmcj.2014.2.8

Volk, R., Stengel, J. and Schultmann, F. (2014) ‘Building information modeling (BIM) for existing buildings — literature review and future needs’, *Automation in Construction*, 38, pp. 109–127. http://doi.org/10.1016/j.autcon.2013.10.023

Wilson, C.V., 2012. Post implementation Planning and Organizational Structure of Enterprise Resource Planning Systems. PhD. Thesis, Walden University, College of Management and Technology, USA.

SUPPORTING BUILDING OWNERS AND FACILITY MANAGERS IN THE VISUALISATION OF AN INTEGRATED ASSET INFORMATION MODEL (AIM) BASED ON OPEN STANDARDS

Joao Patacas, PhD Researcher, Teesside University

J.Patacas@tees.ac.uk

Nashwan Dawood, Professor, Technology Futures Institute, Teesside University

n.n.dawood@tees.ac.uk

Mohamad Kassem, Associate Professor, Northumbria University

Mohamad.Kassem@northumbria.ac.uk

ABSTRACT: *Clients and facility managers require accurate and trusted data and information about their assets at the handover stage. In current practices the data required for asset management can be found in several different sources, systems and formats. Research addressing the management of data for the use phase of buildings using open standards is still in its infancy. This study proposes a method for the development and visualisation of asset data (i.e., graphical, non-graphical and documentation) in the form of an integrated Asset Information Model (AIM) – data model that contains the digital data required to operate an asset or portfolio of assets. Industry Foundation Classes (IFC) and Construction Operations Building Information Exchange (COBie) are used for the graphical and non-graphical data requirements. The definition of content models based on Content Management Interoperability Services (CMIS) is adopted for the AIM documentation data requirements. A method is proposed to enable the integration and visualisation of the different sources of asset data in a virtual environment. The proposed method was successfully evaluated in a use case focussed on building maintenance. Future work will focus on the evaluation of the proposed method and tool with building owners and facility managers in real world projects, and the inclusion of additional data sources for further FM use cases.*

KEYWORDS: Asset Information Model, Asset Information Requirements, BIM, CMIS, COBie, IFC, open standards

1. INTRODUCTION

Over half of the total lifecycle costs occur during the use phase of buildings (Becerik-Gerber et al. 2012). However, project stakeholders in the construction sector remain largely focused on the minimisation of capital costs (Becerik-Gerber et al. 2012). Investigations into data and information management methodologies from the early development stages of construction projects are much needed to improve the performance of both the information handover activities and the use phase of buildings. Within this context, this research provides methods and tools that enable the structured definition and the checking of owners and Facilities Management (FM) information requirements against project deliverables.

Building Information Modelling (BIM) is providing new capabilities to exchange information across the lifecycle of buildings. Its implementation at the design and construction stages is providing proven benefits, particularly in the management of design, construction schedules and corresponding costs (Eastman et al. 2011, Love et al. 2014). However, these benefits are relatively small when compared with the overall lifecycle cost of an asset. With the e increasing adoption of BIM within the construction sector, investigating the theme of whole life cycle performance (e.g. lifecycle costing, lifecycle impact analysis, lifecycle management of information flows, etc.) have been reinvigorated. This has been witnessed not only in research but also in the national BIM initiatives and mandates of countries. For example in the UK, the need to support the owner's requirements in the definition of asset information models has been recognized in PAS 1192-3:2014, which specifies an information management methodology for the operational phase of building assets based on open BIM standards - IFC and COBie (BSI 2014). Information in building models should satisfy the owner's requirements so that at the handover stage it concurs to form the owner's Asset Information Model (AIM) – a data model that contains all digital data required to operate an asset or portfolio of assets.

While Publicly Available Specification such as the PAS1192-3:2014 (BSI 2014) broadly recommends the structured definition and consideration of the owner's requirements in building and infrastructure projects, a methodology to support the definition and compliance checking of the owner's requirements throughout the lifecycle of a building is missing. This research hypothesises that BIM and its open standards could provide the opportunity for structuring these information requirements and supporting their change management including verification throughout the building lifecycle. Within this context, this research investigates the role of BIM and open standards in enabling a methodology for the structure definition and compliance checking of client's requirements throughout the lifecycle of a building.

In this paper, a method is proposed for the definition and visualisation of Asset Information Models (AIM), considering graphical, non-graphical and documentation data sources, which can be stored in disparate models and databases. The proposed method utilises open standards including IFC, COBie and CMIS for the different data types involved in the AIM. The AIM graphical model and its non-graphical and documentation data can be displayed and interrogated within a game engine environment.

2. RESEARCH METHODOLOGY

This research aims to provide building owners and facility managers with methods and tools for the verification and visualisation of Asset Information Models including its graphical, non-graphical and documentation data from disparate models and databases. A literature review was conducted to explore how asset management data requirements could be fulfilled by open standards such as IFC, COBie and CMIS, and by concepts such as the Asset Information Models. Current research in VR and serious games approaches in AEC/FM was also reviewed. Based on findings from the literature, a method is proposed to allow the visualisation of AIM data - graphical, non-graphical and documentation data sources - in a virtual environment using a game engine. The proposed method is applied to a case study of an existing building to demonstrate how the owner and FM team can access the AIM data from several sources from within the virtual environment. Finally, a discussion is carried out to clarify the significance of the results and to outline future development.

3. LITERATURE REVIEW

3.1 Asset Information Model (AIM)

The importance and impact of managing owner requirements in the construction industry has been the subject of numerous studies. For example, Kamara et al. (2000) proposed a framework to convey the information in client requirements to downstream stakeholders in design and construction. Love et al. (2014) proposed a framework to assist asset owners in generating value from investing in BIM. Achieving tangible value for clients and owners depends on the definition of their requirements in a structured way (Love et al. 2014). However, in current practice there is still a lack of clarity in the definition of clients' project briefs and a limited engagement of the client in the briefing process (Yu et al. 2010).

Potential benefits that building owners can gain by using BIM for requirements checking include (Eastman et al. 2011): increased building energy performance; reduced financial risks through earlier and more reliable cost estimates; shortening of project schedules by using BIM models for coordination; assuring program compliance through the analysis of the BIM model against owner and local code requirements; and optimised facility management and maintenance through the definition of the relevant information for Asset Information Models (AIMs).

PAS 1192-3:2014 vaguely outlines an information management methodology for the operational phase of buildings. It proposes the definition of the Asset Information Model (AIM), Asset Information Requirements (AIR), and Organizational Information Requirements (OIR). The AIM consists of graphical, non-graphical and documentation data components about assets in order to support an organization's asset management system (BSI, 2014). The AIM can relate to a single asset, a system of assets, or the entire asset portfolio of an organization. The AIM is initially composed of data coming from the Project Information Model (PIM) which will subsequently require update during the operational lifecycle of assets. The AIM should provide the function of a data repository and also provide means for accessing and receiving information. The AIM can be managed as a single model, including all the information needed to manage building assets, or as a collection of models linked to existing enterprise information systems (BSI, 2014; Talamo & Bonanomi 2015). Asset Information Requirements (AIR) specify the owner's data requirements for the AIM. AIRs are generated based on the owner's Organizational Information Requirements (OIRs), which specify the objectives of the organisations from attaining the required data and information (BSI 2014).

Five key areas of AIR have been outlined in the PAS 1192-3:2014: legal, commercial, financial, technical and managerial. Some of the main requirement topics in each of these areas are detailed in Table 1.

Table 1. – Asset Information Requirements proposed in PAS 1192-3 (BSI 2014; Talamo & Bonanomi 2015)

Legal	Commercial	Financial	Technical	Managerial
Ownership	Asset description and function	Original purchase/leasing cost	Design parameters	Identification number
Contractual information	Vendor data	Current replacement costs	Asset dependencies / interdependencies	Asset location
Property boundaries	KPIs		Commissioning dates and data	Spatial data (e.g. room/pavement area)
Work instructions	Condition / performance targets		Performance data	Warranties description and duration
Legal obligations (H&S, etc.)	Criteria of non-conformance			Work schedules and task details
	Spares information			Hazardous content/ waste
				Asset end of life data

IFC and COBie have been proposed in PAS1192-3:2014 as data sources for structuring graphical and non-graphical data for the PIM and the AIM. IFC and COBie can be used for the definition of the AIMs and for the interface between AIMs and existing enterprise systems (BSI 2014). IFC is an open source BIM data format published by buildingSMART to support information exchanges throughout the lifecycle of buildings. It is currently registered with ISO as ISO16739 (ISO 2010). COBie is a subset of the IFC model, based on the Facilities Handover model view definition, which can be used to define the owner/client's requirements and handover the information for FM tasks (East 2014). COBie is the method of information exchange adopted by the UK government centrally procured projects on which BIM is mandated.

Talamo & Bonanomi (2015) analysed the COBie schema against the Asset Information Requirements as proposed in PAS 1192-3:2014 and concluded that COBie can fulfil most of the data requirements. Some limitations were found regarding data in the commercial category, including the lack of support of data about the condition and performance targets of assets, key performance indicators (KPIs) and criteria for non-conformance of assets. A previous analysis of IFC and COBie support for asset register information requirements defined in BS 8210 (BSI, 2012) also revealed the lack of support of some of these requirements for the use phase of buildings (Patacas et al. 2014). An analysis of the IFC schema for information and data requirements for the O&M phase also revealed that the current IFC standard does not include all the required properties and relationships required in the O&M phase (Motamedi et al., 2014). Examples of such properties include: operational statuses (e.g., decommissioned, broken, inactive), downtime information, failure classes, and physical/ operational conditions. While it is possible to add additional data fields to IFC and COBie using custom property sets, this can result in models that are heavy, non-efficient and difficult to use. It is therefore necessary to identify and/or define complementary schemas that are suitable to support AIM data that is out of the scope of IFC/COBie. It is also necessary to provide a methodology that can support the use of this data in an integrated fashion for the purpose of FM areas such as the planning and execution of maintenance tasks.

3.2 Virtual Reality (VR) and serious games in AEC/FM

Research efforts in Virtual Reality (VR) have been mostly focused on supporting collaboration throughout the design process and the health & safety training for construction workers. VR Research addressing design collaboration, design decisions and evaluation of design alternatives, has identified advantages from the use of VR and related technologies (Gu et al., 2011; Rüppel and Schatz, 2011; Ku and Mahabaleshwarkar, 2011; Ayer et al., 2013). The use of web-based virtual environments enable synchronous collaboration with remotely located designers (Gu et al. 2011, Ku and Mahabaleshwarkar, 2011). VR and serious games in H&S applications provide effective ways to train health and safety construction trainees, in a realistic and risk-free environment (Lin et al., 2011; Addison et al., 2013). Training using VR can consider the outcomes of workers' actions, which can contribute to diminishing human-error based accidents in construction sites. Several game-based learning approaches have focused on the use of serious games and AR for hazard identification purposes (Chen et al., 2013; Chi et al., 2013, Dawood et al. 2014). Hazard identification is the focus of many H&S training programs and the visual capabilities of VR effective help trainees in this task (Chi et al., 2013).

Some investigations are proposing game-based learning and training for FM tasks. PlayFM proposed a serious games and game-based learning methodologies for FM knowledge transfer. PlayFM incorporates several FM processes to allow Facility Managers to simulate typical FM activities (May et al. 2012). The Total Facilities Management Solutions project is aiming to provide training to facility management students, focusing on the maintenance of HVAC systems (Chang 2015).

Current challenges in the adoption of VR and serious games technologies in the AEC/FM domain are related to the lack of interoperability with BIM tools (Ku and Mahabaleshwarkar, 2011; Rüppel and Schatz, 2011; Kim et al. 2013, Dawood et al. 2014). Other challenges also affect the embedding of and access to non-graphical data from BIM models in virtual environments. Despite the proliferation of studies on VR and serious games application in the construction industry, only two of the reviewed approaches focus on FM (May et al. 2012, Chang 2015). This paper aims to contribute to the identified challenges by investigating approaches for integration of graphical, non-graphical and documentation data in virtual environments.

4. PROPOSED METHOD

4.1 AIM definition

The AIMs include graphical, non-graphical and documentation data, and must fulfil the AIRs defined by the owner with the input from designers and facility managers (BSI, 2014). The proposed approach in this study uses the open standards listed in Table 2 to support the data requirements of AIMs. Graphical and non-graphical data requirements are conveyed through IFC and COBie, respectively. However, not all data requirements for asset management are directly supported by the default IFC and COBie entities and property sets. Some requirements can be satisfied by defining custom property sets in the IFC Schema and the COBie specification. In this research, asset criticality data was defined according to BS 8544:2013 as an IFC property and was used as criteria to identify critical assets (BSI, 2013).

The Content Management Interoperability Services (CMIS) standard has been identified to represent document data requirements. CMIS is an open standard that enables interoperability between different content management systems (e.g. Alfresco Community Enterprise Content Management, Microsoft Sharepoint). It allows the definition of folder structures for documents and the definition of specific properties of documents and folders as metadata. CMIS support of interoperability allows the reusability of content models across various content management systems (OASIS 2016).

The AIM documentation data requirements were defined in a content model witin a CMIS compliant content repository – Alfresco. Alfresco provides an implementation of the CMIS bindings, including the mapping of the Alfresco content metamodel to the CMIS domain model. This allows content models defined in Alfresco to be exposed and manipulated via CMIS. Alfresco content models are defined as XML documents, which must comply with the content metamodel XSD schema provided by the Alfresco content repository (Alfresco Software 2016).

The content model metadata was defined based on generic requirements identified in Product Data Templates (PDTs) (CIBSE 2016) and embedded into the Alfresco Community Enterprise Content Management with the Eclipse Mars.1 IDE using the bootstrap approach. The IFC GUID property was included in the content model to enable the linking of documentation metadata to game objects in the virtual environment. The Alfresco content model schema is represented in Fig. 1. The definition of custom properties to support the AIM is described in Table 3.

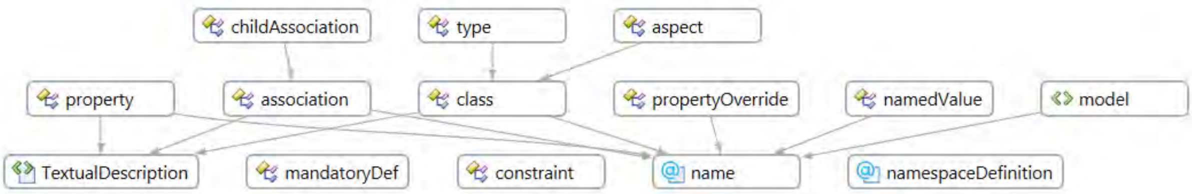


Fig. 1 – Alfresco content model XML schema definition (XSD) (Alfresco Software 2016)

Table 2. Identification of open standards to support Asset Information Model (AIM) data sources

Asset Information Model (AIM) data sources	Supporting standards
Graphical Model	IFC
Non-graphical data	IFC and COBie
Documents	CMIS

Table 3. Alfresco content model properties for the Asset Information Model

Property	CMIS property name	Property Type
IFC GUID	bim:IFCGUID	Text
Manufacturer name	bim:Manufacturer	Text
Manufacturer website	bim:ManufacturerWebsite	Text
Product Model Number	bim:ProductModelNumber	Text
CE Approval	bim:CEApproval	Text
O&M Manual	bim:OMManual	Text

4.2 AIM visualisation

The Unity game engine was selected to perform the visualisation of AIM data in an integrated virtual environment. Since Unity only supports the direct import of geometric data (in the form of FBX files), a method was developed to allow for the import of non-geometric and documentation data to support the requirements of the AIM. The method requires importing geometric data into the Unity game engine, and attaching non-graphical and documents data to the corresponding game objects as metadata using the elements' IFC Global Unique ID (GUID). For this reason, IFC GUID has been added as a property to the CMIS content model metadata (Table 3).

The method used for the visualisation of integrated AIM data consisted of the following steps, which are summarised in Fig. 2:

1. Export geometry of BIM model as an FBX file from the design application (e.g. Autodesk Revit).
2. Export BIM model as an IFC file from the design application.
3. Import FBX file in 3DS Max software.
4. Assignment of materials and textures in 3DS Max to the geometric model for accurate rendering of the model in game engine, according to design or as-built specifications.
5. Export geometric model as an FBX file from 3DS Max. The model should be exported as separate geometric objects (as opposed to a single mesh) to allow for the mapping of non-graphical and documents data.
6. Set up a new scene in the Unity game engine and import the FBX file. At this stage it is possible to assign mesh colliders to the model's game objects. Depending on the size of the model, individual colliders might have to be simplified to improve performance.
7. Checking and fixing import errors. Errors that were experienced by the authors included errors in material

assignments and in the geometry of the model.

8. Convert the IFC model to COBie using the open source Bimserver environment.

9. Export data from CMIS compliant EDMS (e.g. Alfresco).

10. Retrieve building maintenance data from FM database.

11. Attach COBie, CMIS, and building maintenance data to game objects as metadata through the definition of scripts in Unity.

Access to CMIS-compliant content repositories is provided through several APIs, including a .Net API – DotCMIS, which has the minimum requirement of .Net framework version 3.5 (Apache 2015). Since the Unity game engine runs on .Net framework version 2.0, it was not possible to directly access CMIS repository data from the game engine. For this reason, a separate .Net application was developed to access the CMIS-compliant repository - Alfresco - and export the metadata from the AIM content model. The application connects to Alfresco through the AtomPub 1.0 service interface and retrieves the metadata from the AIM documents as .csv files. A class diagram of the application is depicted in Fig. 3. The Openmaint environment (Tecnoteca 2016) is used to support the AIM maintenance data requirements. The NPGsql framework (Npgsql 2016) is used to access Openmaint's underlying PostgreSQL database and retrieve the relevant maintenance data to be displayed in the virtual environment.

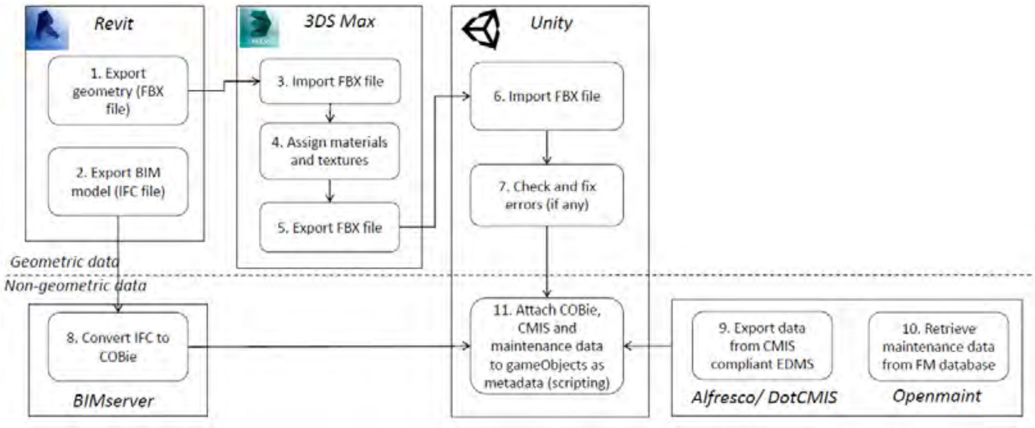


Fig. 2 –Workflow for visualisation of the AIM in the Unity game engine

Fig. 3 - Class diagram for the application to export documentation metadata from Alfresco

5. RESULTS

To demonstrate the visualisation of the integrated AIM within the game engine, a case study of an existing Teesside University's building (Centre House) was performed. It is a two-storey building with an internal gross area of approx. 275 m^2. An as-built Revit model of the building was provided by the Teesside University Estates Department. The model included non-graphical data which was used to demonstrate the proposed method. Following the steps described in section 4.2, an empty scene was set up in Unity, where the geometric model (FBX file) with texture and material definitions was imported. The First Person Controller package is imported into the project and added to the scene to enable navigation through the model. Upon import of the geometric model, errors were apparent. Some of the game objects lost the material assignments and there were also errors in the geometry of the stairs (Fig. 4). While material assignments can be easily rectified in Unity, the stairs required remodelling in 3DS Max and re-importing into Unity.

Fig. 4 – Loss of material assignment (left); Coordinates mismatch and loss of material assignment (right)

Non-graphical data from COBie can be imported into the game engine and attached to the model's game objects. The project was exported as an IFC model from Revit and converted to COBie using the Cobielite xml-based COBie format (Bogen & East 2016) and open source Bimserver (bimserver.org). Finally, it was imported into the Unity project as a project asset. COBie data can be included in the model as metadata of game objects. Following the method proposed by Boeykens (2016), two scripts were defined in the Unity project and are initialised when the game starts: 1) a script that adds metadata to game objects, and 2) a script that parses the Cobielite file using LINQ queries.

To display on-screen information about the building, scripts can be defined to react to users' interactions with the game objects. This functionality can be achieved through the definition of colliders and their association with the game objects. This allows the information to appear on-screen when the user walks through a Space defined in COBie, or when the user clicks on a game object that contains COBie data (Fig. 6). For this purpose, it is important to identify the key assets (critical assets) which require the display of their data and information. In this research, the asset criticality methodology proposed in BS 8544:2013 is adopted for the classification of critical assets that require the display of data (BSI 2013).

Asset data from a CMIS-compliant repository (e.g. Alfresco) can be attached to game objects in a similar way. An application connects to the repository and exports the data as a csv file, which is then imported into the project Assets folder in Unity. A script that parses the csv file is defined and initialised at the start of the game. The metadata script defined previously adds the documents metadata to the corresponding game objects. By clicking on the game objects the user can access the asset's COBie and CMIS metadata, and the attached documents through a link to the repository. Fig. 5 shows COBie space data can be displayed when the user walks through a space with a defined collider and the asset data that is available when the user clicks on an object with attached data. Fig. 6 shows the collider definitions for the display of data.

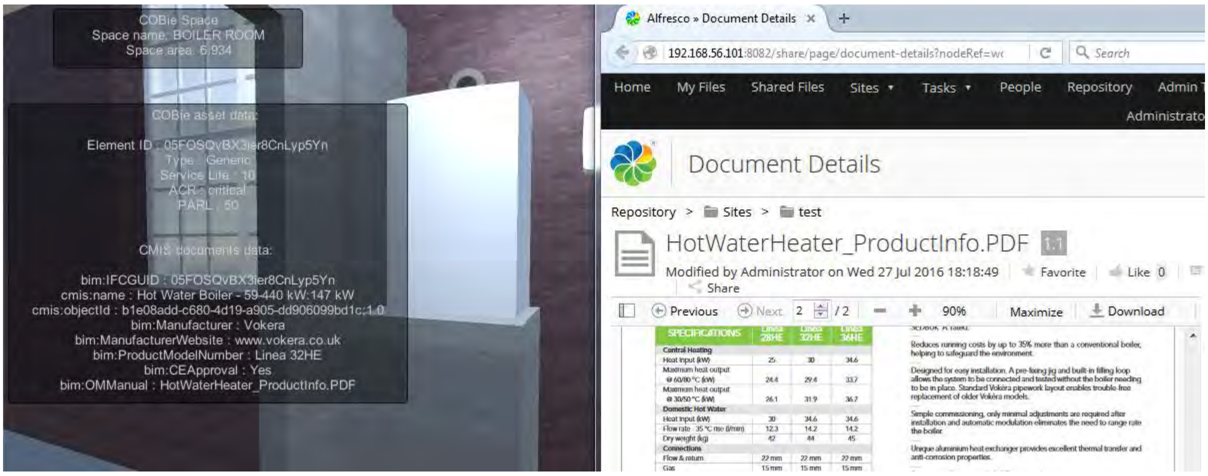


Fig. 5 – Displaying COBie space data and COBie documentation asset data in Unity

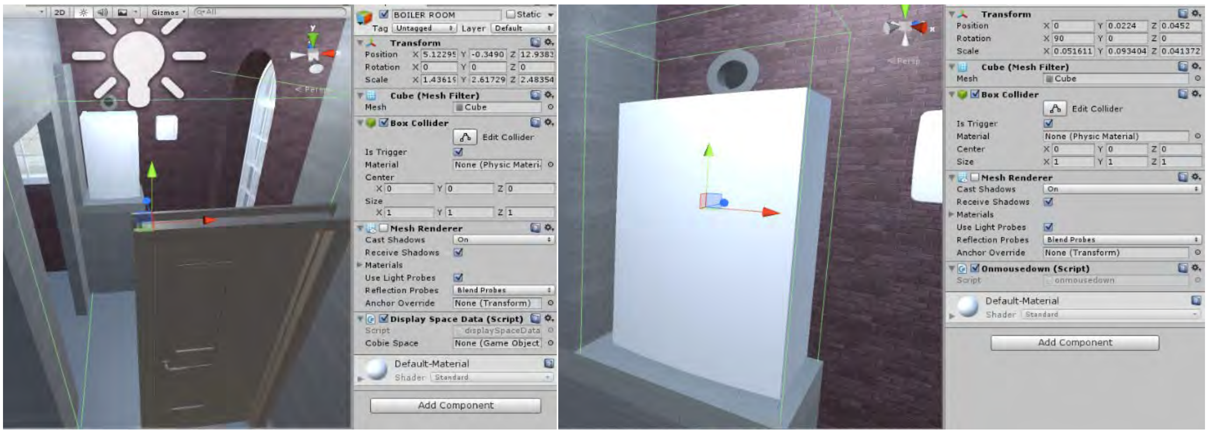


Fig. 6 – Definition of colliders in Unity to allow the display of COBie space data and COBie documentation asset data

6. DISCUSSION

This research proposed a method to deliver an integrated AIM that combines the graphical, non-graphical and documentation data coming from disparate sources while using open standards. The proposed approach, tested in a case study, revealed a number of challenges: 1) issues in the import of geometric models, particularly models with complex geometry (e.g. stairs) and 2) limitations on the use of external APIs due to the version of the .Net framework used in the Unity engine (version 2.0). Geometric errors can be rectified through the editing of the model in the design applications but this process would require a demanding inspection of the models, particularly in the case of large models. BIM models typically contain overly complex geometry that is not suited for use in game engines. This challenge did not cause significant performance issues within the proposed case study. However, mesh optimisation methods have to be performed to enable running the game in less powerful machines, particularly in mobile platforms. Such methods include, but are not limited to, the mesh optimisation capabilities of 3DS Max (on export) and Unity (on import). Regarding the integration of documentation data, it was not possible to establish a direct connection between the Unity environment and the Alfresco repository. We overcame this limitation by exporting the asset documentation metadata from Alfresco through the implementation of a separate application, and importing this data into Unity. The established direct link is beneficial for both performance purpose and data integrity. The non-graphical and documentation data, which is parsed and added to the model during the initialisation of the game – due to performance issues –, will be reliable if the data in the Alfresco repository is kept up to date and in compliance with the owner's requirements.

The adoption of the proposed approach is expected to provide building owners and facility managers with effective means for the planning of maintenance tasks. Maintenance personnel can use the virtual model to locate assets and their associated data and documents before going to site or reaching the intervention space. This is also essential in minimising the downtime of the building while work is being performed on assets. The asset criticality methodology proposed in BS 8544:2013 was successfully adopted to select which game objects should have non-graphical and documentation asset data displayed (BSI 2013). The approach also provides an enhanced walkthrough experience to the user, when compared to the walkthrough capabilities provided by design applications, allowing for the interaction with the model and associated objects and documentation data. Finally, it is possible to deploy the game on several platforms including mobile devices thus, providing the owner and FM team access to the model and data on site.

7. CONCLUSIONS

The study proposed a method to improve asset management tasks (e.g. maintenance tasks) through the integration and visualisation of the graphical, non-graphical and documentation data sources of AIMs. This aim was achieved through the identification and utilisation of open standard schemas, specifications and technologies that fulfil the information requirements of the AIM. The integration of the different AIM data types was demonstrated using open technologies and standards within a use case which was focussed on building maintenance. Some of the asset data requirements (e.g., asset criticality) required in the AIM for this maintenance use case could not be supported by the default IFC and COBie and required to be defined using custom property sets. Some of the unsupported required such as the 'asset criticality' were considered important for the presented use case (i.e., maintenance) as they were used in the game engine to identify the objects that require the display of non-graphical and documentation data. This is necessary to avoid overloading the game with unnecessary information which can affect its performance. The current limitations in implementing the proposed approach are related to the lack of interoperability between 3D design applications and the Unity game engine. Future development will validate the proposed method with owners and facility managers; consider additional external data sources that can make part of asset data requirements (e.g. data related to energy management and other FM application areas), and optimise the virtual environment for deployment on mobile platforms.

8. REFERENCES

Addison, A., O'Hare, W.T., Kassem, M. and Dawood, N. (2013) 'The importance of engaging engineering and construction learners in virtual worlds and serious games', *CONVR 2013*. London, UK, 30-31 October. , pp. 448-457.

Alfresco Software (2016) *Alfresco Documentation*. Available at: http://docs.alfresco.com/ (Accessed: 30/06/2016).

Apache (2015) *Apache Chemistry DotCMIS*. Available at: http://chemistry.apache.org/dotnet/dotcmis.html (Accessed: 30/06/2016).

Ayer, S., Messner, J. and Anumba, C. (2013) 'ecoCampus: A new approach to sustainable design education', *CONVR 2013*. London, 30-31 October.

Becerik-Gerber, B., Jazizadeh, F., Li, N. and Calis, G. 2012, "Application Areas and Data Requirements for BIM-Enabled Facilities Management", *Journal of Construction Engineering and Management*, vol. 138, no. 3, pp. 431-442.

Boeykens, S. (2016) *Getting BIM data into Unity*. Available at: http://cad-3d.blogspot.co.uk/2016/03/getting-bim-data-into-unity-part-5.html (Accessed: 30/06/2016).

Bogen, C. & East, W.E. (2016) *COBieLite: A lightweight XML format for COBie data*. Available at: https://www.nibs.org/?page=bsa_cobielite (Accessed: 30/06/2016).

BSI 2012, *BS 8210:2012: Guide to facilities maintenance management,* BSI Standards Limited.

BSI 2013, *BS 8544:2013: Guide for life cycle costing of maintenance during the in use phases of buildings*, BSI Standards Limited.

BSI 2014, *PAS 1192-3:2014: Specification for information management for the operational phase of assets using building information modelling*, BSI Standards Limited.

Chang, D. (2015) *Total Facilities Management Simulations*. Available at: http://www.tribe-studios.com/blog/total_facilities_management_simulations (Accessed: 30/06/2016).

Chen, A., Golparvar-Fard, M. and Kleiner, B. (2013) 'SAVES: A safety training augmented virtuality environment for construction hazard recognition and severity identification', *CONVR 2013*. London, October 30-31.

Chi, H., Kang, S. and Wang, X. (2013) 'Research trends and opportunities of augmented reality applications in architecture, engineering, and construction', *Automation in Construction*, 33(0), pp. 116-122.

CIBSE (2016) *Product Data Templates*. Available at: http://www.cibse.org/knowledge/bim-building-information-modelling/product-data-templates (Accessed: 30/06/2016).

CIC 2012, *Building Information Modeling Planning Guide for Facility Owners.*

Dawood N, Miller G, Patacas J, Kassem M (2014) Construction health and safety training: the utilisation of 4D enabled serious games, *ITcon* Vol. 19, Special Issue BIM Cloud-Based Technology in the AEC Sector: Present Status and Future Trends , pg. 326-335, http://www.itcon.org/2014/19

East, W.E. 2014, *Construction-Operations Building Information Exchange (COBie)*. Available: http://www.wbdg.org/resources/cobie.php. [Accessed 17 July 2014]

Eastman, C., Teicholz, P., Sacks, R. and Kaner, I. (2011). *BIM handbook : A guide to building information modeling for owners, managers, designers, engineers and contractors.* John Wiley & Sons, Inc.

Gu, N., Kim, M.J. and Maher, M.L. (2011) 'Technological advancements in synchronous collaboration: The effect of 3D virtual worlds and tangible user interfaces on architectural design', *Automation in Construction*, 20(3), pp. 270-278.

ISO (2010), *ISO 29481-1: Building information modelling – Information delivery manual – Part 1: Methodology and format*, International Organization for Standardization, Geneva, Switzerland.

Kim, M.J., Wang, X., Love, P.E., Li, H. and Kang, S. (2013) 'Virtual reality for the built environment: a critical review of recent advances', *ITCon,* 18, pp. 279-305.

Ku, K. and Mahabaleshwarkar, P.S. (2011) 'Building interactive modeling for construction education in virtual worlds', *ITCon,* 16(Special Issue Use of virtual world technology in architecture, engineering and construction), pp. 189-208.

Lin, K., Son, J.W. and Rojas, E.M. (2011) 'A pilot study of a 3D game environment for construction safety education', *ITCon*, 16(Special Issue Use of Gaming Technology in Architecture, Engineering and Construction), pp. 69-84.

Love, P.E.D., Matthews, J., Simpson, I., Hill, A. and Olatunji, O.A. (2014). A benefits realization management building information modeling framework for asset owners, *Automation in Construction,* 37(0), pp. 1-10.

Kamara, J.M., Anumba, C.J., and Evbuomwan, N.F.O. (2000). Process model for client requirements processing in construction, *Business Process Mgmt Journal*, 6(3), pp. 251-279.

May, M., Holzer, F. and Otto, F. (2012) 'eLearning in Facility Management by Serious Games', *Proceedings of the 7th International Conference on eLearning.* The Chinese University of Hong Kong, 21-22 June 2012. , pp. 294-304.

Motamedi, A., Hammad, A. and Asen, Y. 2014, "Knowledge-assisted BIM-based visual analytics for failure root cause detection in facilities management", *Automation in Construction*, vol. 43, pp. 73-83.

OASIS (2016) *OASIS Content Management Interoperability Services (CMIS) TC.* Available at: https://www.oasis-open.org/committees/tc_home.php?wg_abbrev=cmis (Accessed: 30/06/2016).

Patacas, J., Dawood, N. and Kassem, M. (2014). Evaluation of IFC and COBie as data sources for asset register creation and service life planning, *14th International Conference on Construction Applications of Virtual Reality in Construction and conference on Islamic Architecture*. Sharjah, UAE, 16-18 November 2014.

Talamo, C. and Bonanomi, M. (2015) 'Methodological Experimentation: Proposal of a Datasheet Template for FM Activities in the BIM Environment', in 'Methodological Experimentation: Proposal of a Datasheet Template for FM Activities in the BIM Environment' *Knowledge Management and Information Tools for Building Maintenance and Facility Management.* Switzerland: Springer International Publishing, pp. 179-196.

Rüppel, U. and Schatz, K. (2011) 'Designing a BIM-based serious game for fire safety evacuation simulations', *Advanced Engineering Informatics*, 25(4), pp. 600-611.

Yu, Ann T.W., Chan, Edwin H.W., Chan, Daniel W.M., Lam, Patrick T.I. and Tang, Peony W.L. (2010). Management of client requirements for design and build projects in the construction industry of Hong Kong, *Facilities*, 28(13), pp. 657-672.

STRATEGIC DAYLIGHT VISUALIZATION FOR THE GREEN BUILDING PROCESS: INTEGRATING OPTIMIZATION INTO AN AIRPORT TERMINAL DESIGN WITH SKYLIGHTS

Siti Norzaini Zainal Abidin, Faculty of Design and Built Environment, First City University College

Puteri Shireen Jahnkassim, Kuliyyah of Architecture and Environmental Design, Department of Architecture, International Islamic University Malaysia

ABSTRACT: *Visualisation through daylight simulation are now increasingly used to achieve performance-based green building targets, both in terms of daylight penetration and energy savings strategies . Green buildings require an emphasis on both daylight and passive design to achieve energy related points and strategic inputs in the design process are as important as the outcome. The paper reports on how the process of integrated design in which daylight visualisation is used to strategically guide design and construction (commissioning) processes under a tropical climate. This study investigates the effectiveness and success of the process in terms of the outcomes of measured and monitored data during occupancy as captured by the building monthly energy, working plane lux distribution and accuracy of simulation tools, of a large international airport terminal. A range of accuracy errors of the tool is also identified and discussed through a series of verification studies. As daylight suffers from excessive accompanied heat gain throughout the day, and large buildings with skylights are particularly vulnerable, the aim is to maximize daylight admission while controlling heat gains at the same time. Particularly in long span roof dominated building typologies, skylights represent a significant potential to save lighting energy. The paper presents the strategic process in terms of inputs and steps in an integrated design process and how such process had significantly achieved the initial intended energy and daylight targets of green building performance.*

KEYWORDS: *daylight design process, visualization, green building, airport terminal design, optimization*

1. INTRODUCTION

The central problem of daylight design in airport terminals is meeting the stringent requirement of international green building rating systems in terms of both daylight levels and energy efficiency. The key issue is also to ensure that the main occupied areas of an international airport terminal building such as main terminal halls receive the required amount of daylight - its magnitude and distribution – hence the use of skylights. Since an airport terminal structures mainly comprises of main terminal hall and concourse spaces, due to the fact that main terminal halls are large open plan spaces, the other the other key problem IN skylight design is the specific conflicts and conditions in hot climates including tropical climates ie, to achieve daylight performance without comprising extent of maximum energy savings through passive design particularly a control of cooling loads and incoming solar heat gains. The parametric elements and methods conducting simulation study of skylight design and are discussed. The effect on roof thermal and energy performance is reviewed. A preliminary strategic design decision for daylighting design through skylight is identified to achieve the energy used in airport terminal buildings. This is more critical in the tropical climate where conflicting issues, constraints and requirements for daylighting design through skylight are also evaluated. The tropical climate, unlike the temperate climate, suffers from conflicting conditions in daylighting and the crucial need to balance daylight and heat gain through the roof. In a design process of large energy intensive structure and space, simulation methods play a significant role in assessing the balance between different thermal and skylights yet such processes must be integrated and inserted at strategic phases or points during the design and construction processes in order to achieve the balance between daylight and heat gain to achieve the optimized level of the energy performance of an airport terminal building.

1.1 Previous studies

Various researchers have studied the parameters which govern the amount of light entering sky-lighted spaces are the skylight to roof ratio (SRR), visible transmittance (VT) and the skylight well factor. At times, these factors were combined into one lumped parameter (SRR x VT x WF) which is called the effective aperture (Ae). They conduct a range of analysis of different configurations each with different SRR and VT x WF, but using the same effective aperture demonstrates that this simplification facilitates interruption of results without loss of accuracy. Arasteh et,,al (1985) combined factors into one parameter, (Ae); Arasteh et al. (1985) mentioned that even though they examined the (Ae)'s between 0 and 0.04, an (Ae) of 0.04 can correspond to any skylight configurations from an SRR of 5%, VT of 0.80 to an SRR of 10% and VT of 0.57 (Refer to Figure 1). Base on the use of diffusing skylights with these two skylight areas, they found out that the annual percent of lighting savings are identical.

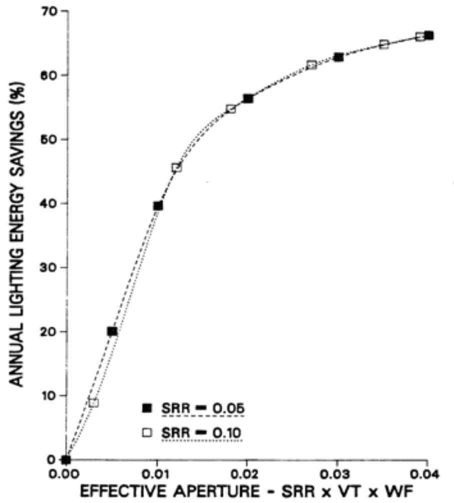


Figure 1: Graph Annual Lighting Vs Effective Aperture

1.2 Parametric Studies with Glazing Area as the Constraining Parameter (Tropical Climate)

Studies focusing on the element of 'window area' as a constraining parameter in optimising façade systems have been undertaken for both temperate and tropical climates (Johnson et.al., 1984, Zain-Ahmed, 2000, Jahnkassim & Ip, 2006). For example, Arasteh et.al. (1985) significantly found that: *There is a climate-dependent optimum window area for minimising peak load and that this optimum is a function of shading coefficient, visible transmittance and installed lighting power density*. Zain-Ahmed (2000) using, measured daylight data in Malaysia, found that the optimum WWR under the Malaysian climate is 0.25. She added that the model year climate, global solar irradiation data were used as the basic input parameter for the modelling of the diffuse and beam irradiation. Another study by (Jahn Kassim and Ip 2006) used the optimisation of daylight and heat gain in bioclimatic highrise forms and found the optimum WWR of 0.3 under the Malaysian climate. This 'optimum' level indicates the window area where the balance between the positive impact of daylight and heat gain is achieved. Supported by another study (Mahdavi & Inangda 2013) discovered the best WRR of 0.25 under the context the overcast sky through an optimisation of high-rise office building in Kuala Lumpur, Malaysia; in agreement with past studies including Kandar et al., (2011) and Zain-Ahmed et al., (2002). Arasteh et al (1985) concluded in their study that the control of solar gains is vital in the tropics if daylighting are to provide net cooling energy savings. To ensure that daylight is 'cooler' source of light than electric lights, the designer need to ensure:

1. A fenestration system with high daylight transmittance and a relatively low solar heat gain transmittance by using daylight oriented glazing and/or appropriate shading systems;
2. Design strategies that improve the uniformity of daylight distribution within space and;
3. Moderate or large apertures are used, to be able to actively control the glazing transmission when transmitted daylight and solar gain level are excessive.

1.3 The Malaysian Climate

The climate of Malaysia referring to Yuan, (1987) can be classified as warm humid equatorial, characterised by high temperatures and humidity. Air temperature averages within 22 and 32 degree Celsius with small annual and diurnal ranges. It is continually near but seldom exceeds normal skin temperature. Kuala Lumpur located at 3.1° deg U has an equatorial climate with year-round variation and rainfall that excesses than 2000mm per year. Most days have cloud cover which cuts off a substantial amount of sunshine thus solar radiation resulting in about 6 hours sunshine per day in average with long hours of sunshine throughout the entire year in addition to the enormous daylight luminous in Malaysia (Mahdavi and Inangda, 2013).

2. INTEGRATED DESIGN PROCESS (IDP) WITH DAYLIGHT

Building Information Modeling (BIM) does not merely involve the use of BIM software and tools, but more importantly, a strategic design process which allow strategic input of visualization studies and analytical data in order to significantly influence the outcome of passive design after construction particularly on critical goals such as energy savings. To achieve this under the tropical climate, a control of heat gain vs daylight is necessary yet the daylight level and distribution must be adequate enough to achieve green targets such as LEED which require 75 percent of the 250 lux (or more) on the working plane. This paper reports on the outcome of a long-term research which documents the processes of a BIM –IDP stages using daylight in an actual design project which proves the crucial role of integrated passive design with visualization in order to achieve stringent energy savings and standards in terms of balancing costs and impact. The overall contribution is focused on the developing a process which highlights the role of daylight simulation in an integrated design process of a green building in order to achieve a balance with heat and lighting energy use. The process is verified under the context of an actual case study with actual monitored data and parameters.

3. THE METHODOLOGY AND FLOW

Using an actual case study of an international terminal being, with a supporting case study of an airport of similar function complexity and capacity, the approach is to conduct a series of daylight simulation during the design process of the new terminal, but to use an existing airport as a means of verifying and measuring the accuracy of the daylight software tool within the specific framework of this typology and this climate. Hence once the tool is verified (by comparing simulation vs monitored data), it is then used to predict the outcome of design options and used as a tool to inform design decisions of the new terminal. The process is then documented and the outcomes are measured again after construction completion and occupancy. This overall method also capitalises on the opportunity that the location which the researcher is based, Malaysia was in the midst of planning, designing and constructing a green airport. Implementation through integrated design process was identified with parametric study on daylighting strategies through series of simulation exercise. Integration into the design process and sensitivity analysis on passive design strategies and its impact on energy efficiencies compares the different scenarios with daylight while a post occupancy Study through comparison of field and measurement study with daylight simulation was performed in order to verify the accuracy or error of the simulation tool.

The summary of the implementation through a parametric study on daylighting strategies through simulation exercise integrated into the design process and sensitivity analysis on passive design strategies and its impact on energy efficiencies comparing to daylight, is as per flow chart in Figure 2. This is followed by Daylight Monitoring of the case study. This is continued by comparing the results and analytical discussion to determine the framework and documentation of the optimisation process,

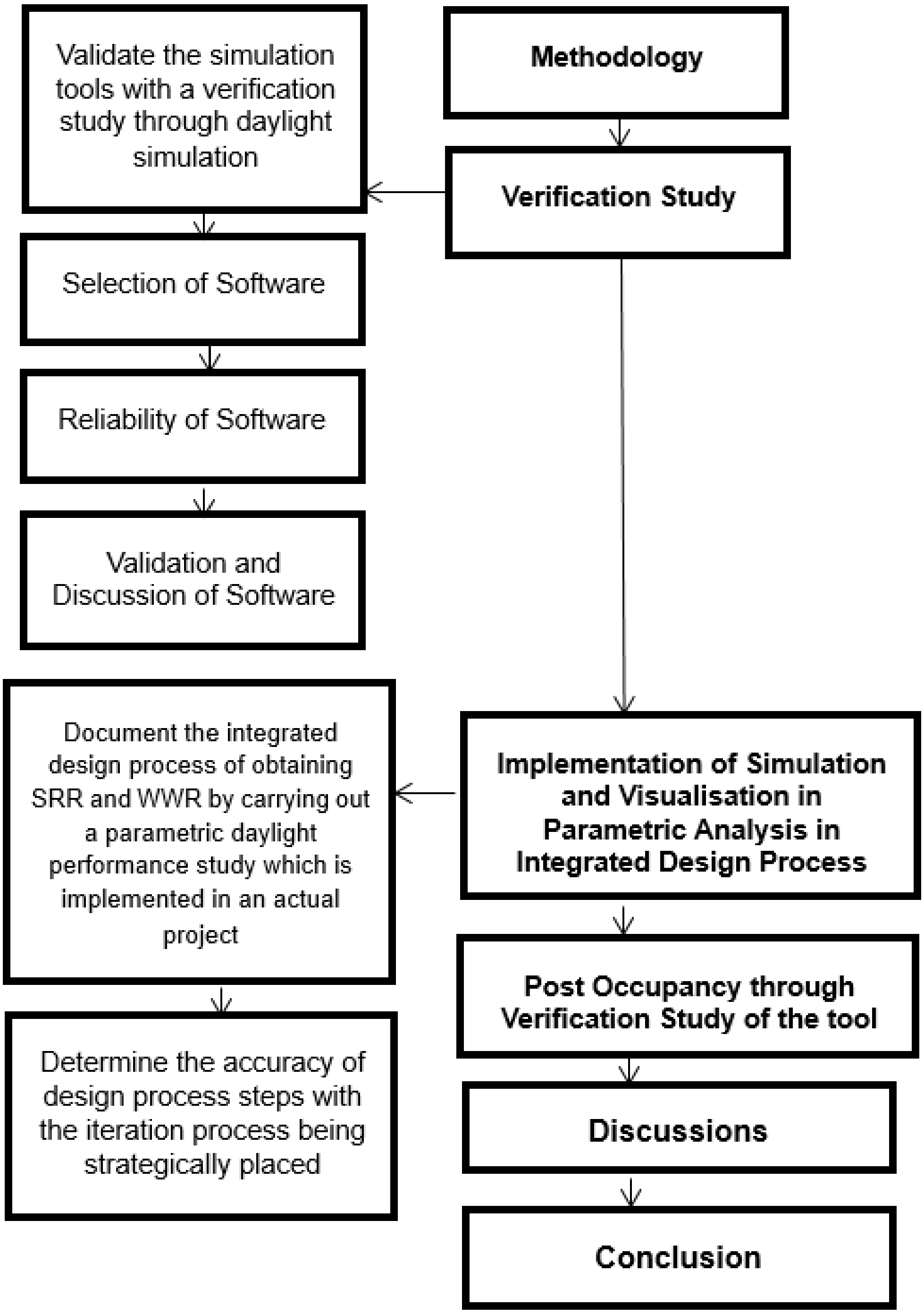


Figure 2: General Flow of Methodology

The software used in measuring the daylighting performance is RADIANCE in IES<VE>. Roof solution with skylight becomes an essential part of the design of these buildings for both their lighting and visual performance with three main areas namely 1) Simulation study of the daylighting performance, 2) Field study measurement and 3) Comfort assessment study (Figure 3). The comparison between simulation and measured performance allows the estimations of the extent of errors from the prediction tools.

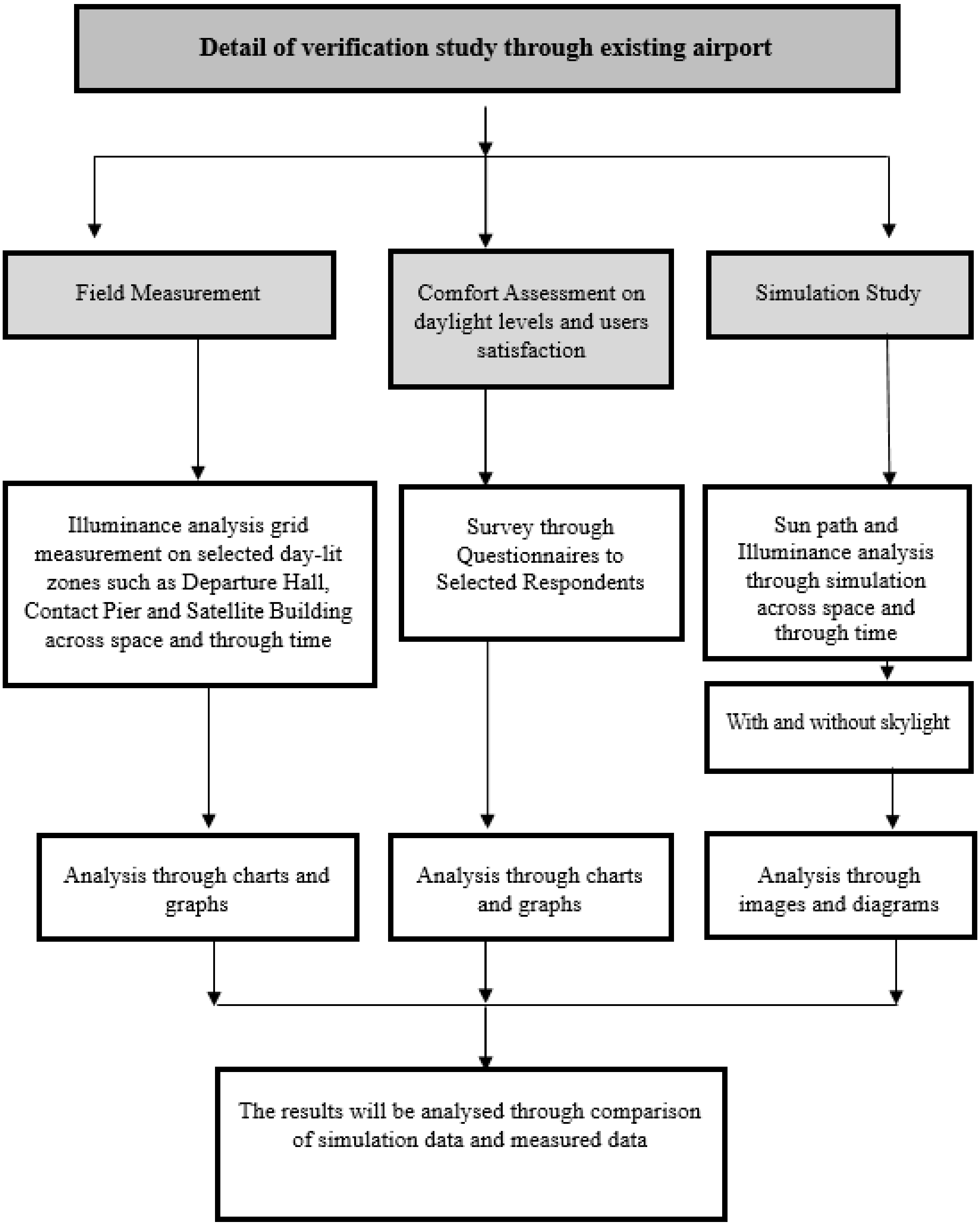


Figure 3: General Flow of Verification Study

An optimisation method involving a parametric study to find the actual balance of daylight and heat gain. To define roof skylight parameters that can balance the benefits of daylighting and control of heat gain, a series of simulation were undertaken to test a range of values represent daylight related impacts and these become parameters that fine-tune the form from schematic to design development phase. The main outcome of this simulation is to determine the capacity every simulated parametric factor with variation in sizing, sky conditions, and window to wall ratio (WWR).

1. The optimisation techniques that are involved much earlier in the design process, right at the

conceptual stages to guide the development of the implementation of the fenestration strategy (skylight and façade openings).

2. The optimum size and spacing of the skylight glazing in relation to SRR or WWR that look into heat gain and daylighting performance,

3. To have an estimation in terms of a balance between these preliminary parameters on balancing the lighting energy needed and heat gain due to the size of the skylight; and roof ratio that will be applied in the final design stage.

This simulation data of the main case study airport will be evaluated on:-

1. The optimum size and spacing of skylight glazing in relation to SRR or WWR

2. The optimum SRR or WWR in relation to heat gain and daylighting performance.

The simulation evaluates the daylight admittance under standard 10K CIE overcast sky through calculation of interior lighting distribution (illumination levels) based on the geometry and massing of the verification case study airport with regards to the sun, building orientation and daylight admittance in order to understand the sun irradiation and heat gain. Radiance in IES VE was used to quantify the daylighting within space. The outcome is assessed against the recommended illumination levels for spaces in airport and transportation hubs as recommended by the IESNA Handbook of Lighting Standards 2000 (Table 1).

Table 1: Recommended illumination levels for spaces in the airport: The IESNA lighting handbook: (Source, Mark S.Rea, 9th Edition, and New York, NY: Illuminating Engineering Society of North America, 2000. Chapter 10, pg 13 and Chapter 17, pg 16).

Transportation Terminals	**Illuminance Horizontal (lux)**	**Illuminance Vertical (lux)**
Waiting Room and Lounge	50 lux	30 lux
Ticket counters	500 lux	300 lux
Baggage Checking	300 lux	50 lux
Rest Rooms	50 lux	500 lux
Concourse	30 lux	30 lux
Boarding Area	50 lux	50 lux

4. THE PARAMETRIC MODELLING

The main reiteration in the simulation process aims is to achieve the optimum sizing of the skylight, the balance of the lighting energy and heat gain from the sizing of the skylight which decrease with the increase of sizing of the skylight while finding the correct balance to achieve the lux levels and distribution area of daylight. Hence the aim of visualisation is to achieve through analysis, the optimum balance of solar heat gain and daylighting through a series of parametric studies on the skylight areas of the long span roof airport terminal design under the Malaysian climate.

4.1 Sample of Visualisation output

4.1.1 Schematic Design Phase

In the schematic design phase, the modelling of the building focuses on the geometrical form of the building as shown in Figure 4 and Figure 5. This involves building dimensions of floor height and area of departure hall in terminal building. The opening sizes and its positions for glazing are done with Model IT.

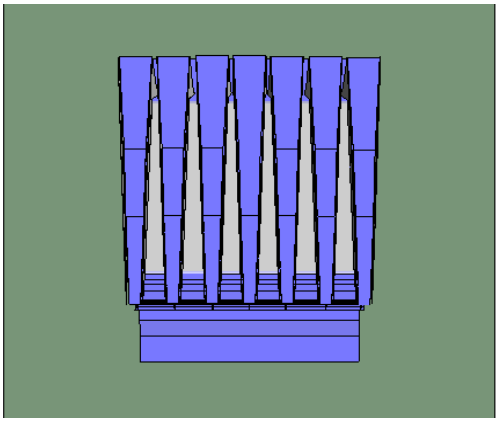


Figure 4: The preliminary simulation model showing top view of the case study model

Consequently, the schematic design phase showed a very high daylight distribution with more than 350 lux covering 93.5% of the floor area of departure hall. This scenario increases the need for cooling load due to the solar heat gain based on the 50% of skylight of the roof design. With the analysis being obtained from this design particularly, application of the skylight area outweighs the lighting energy benefits as heat gains increased with the size of skylights. As daylighting measures tend to be portrayed as being universally positive, a more controlled daylight always improves the daylight quality of space and saves energy at the same time.

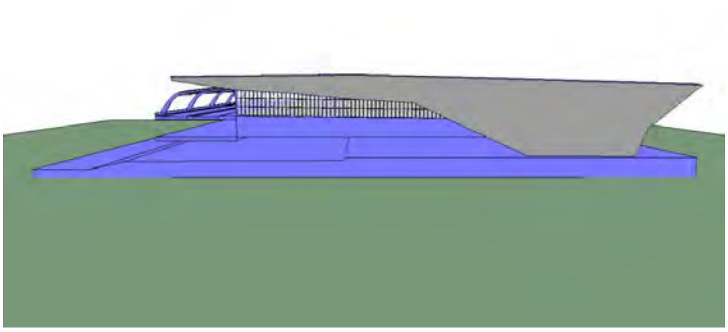


Figure 5: The side facade of the preliminary simulation model of Main Terminal Building of case study

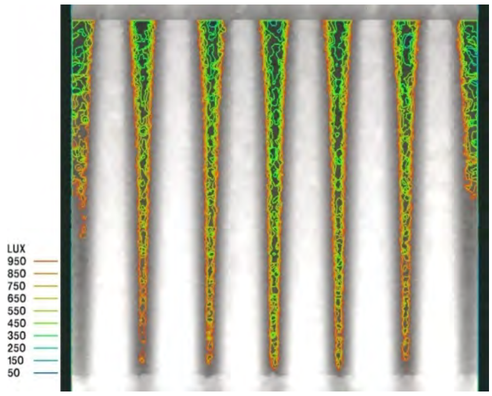


Figure 6: The distribution of lux contour (plan view) of Main Terminal Building with the application of initial SRR (50%)

The schematic design phase showed a very high daylight distribution with more than 250 lux covering 70% of the floor area of departure hall. The daylit core zone area presented a high incidence of daylight into the concourse and major consideration to control heat gain and cooling load. Hence, the skylight area needs to be reviewed (Figure 6).

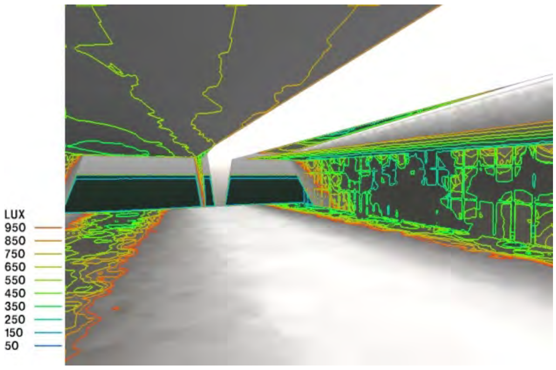


Figure 7: The distribution of lux contour-perspective view (near the east facade) of Main Terminal Building with initial SRR (50%)

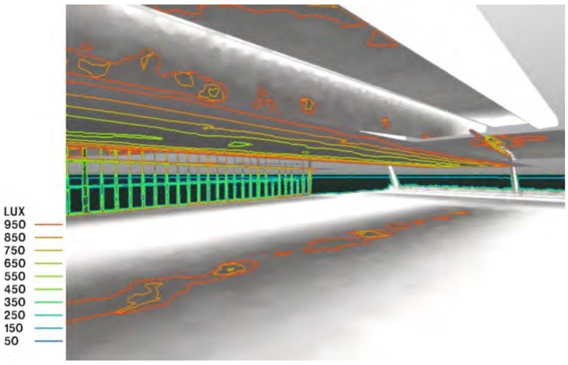


Figure 8: The distribution of lux contour-perspective view (near west facade) of Main Terminal Building with initial SRR (50%)

Based on the series of daylight simulations (Figure 7- 8) as per the results shown, that there is a high incidence of daylight and insufficient consideration of controlling heat gain from the application of skylight opening of the original roof design of main case study. During the schematic design phase, it is started by calculating the heat gain impact, daylight and simple modelling considering the simple generic form of an airport terminal which only testing on the sizing of the skylight (6%, 8%,10%), based on the information of a proposal of an airport terminal such as the figure below (Figure 9). The contribution of daylight impact of skylights to energy savings is representative of among of floor area where lighting energy is necessary through the working day i.e the floor areas below 250 lux. The contributed heat gain impact to skylights is represented by a combination of solar and conduction gains through the roof as a result of the increase in skylight aperture area. From the following results, it can be seen as an optimum skylight to roof ratio of 6-8% (Figure 9).

With reference to the above figure, approximately 8%-9% of the skylight to roof ratio (SRR) is estimated to achieve the optimum balance of the lighting energy needed and total heat gain per day (solar and building surface-wall and roof). As the skylight sizing increase, the percentage of lighting energy needed decreases while the total heat gain increase in parallel with the sizing of the skylight. Hence, at approximately 8%-9% of the SRR demonstrated, the intersection gave an estimation of balance between these preliminary parameters on balancing the lighting energy needed and heat gain due to the size of the skylight and roof ratio. Increasing SRR would increase in both total and cooling energy use. However, reducing SRR to the lowest means will reduce the energy usage. An estimation of SRR and total heat gain can be extracted from the graph above, the estimated heat gain with SRR 10% is approximately 7400kW per day, followed with estimation without skylight is approximately 6500kW per day and estimated heat gain with skylight and daylight control is approximately 7104kW per day.

The simulation was then generated with the three different percentage of the skylight to roof ratios (6%, 8% and 10%) with the application of surface properties as shown in the Table 2. When applying the surface properties, construction data was provided and applied as shown in Table 2, showing the thickness, which were used for the walls, windows and roof. This data was used to recreate simulation model in ModelIT, with the given construction details by the architect.

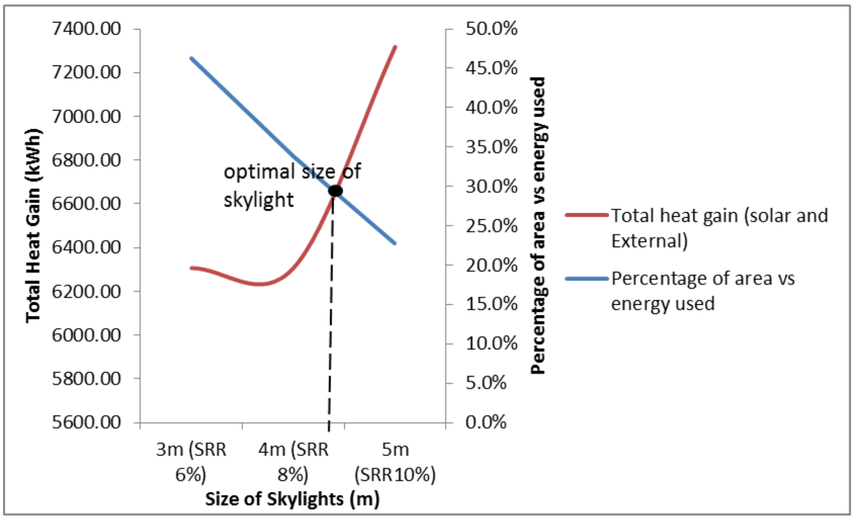


Figure 9: The intersection of the total heat gain and percentage of lighting energy needed

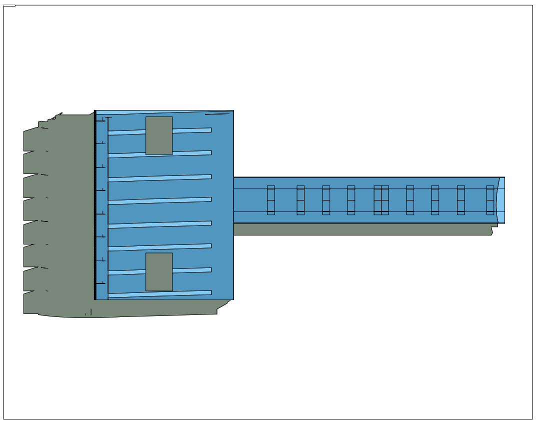


Figure 10: Skylight to roof ratio value 6%, 8% and 10% was studied through daylight simulation studies

Models in this simulation exercises used are simplified with basic perimeter form of the real situations. Most importantly, these computer models able to assist the architect and professionals involved in this project to realise the impact of the skylight area in contributing the uniformity and distribution of daylit areas while reducing heat gain into the terminal building.

Referring to the above Figure 10, a model with a generic pier rectangle terminal form integrated with skylight openings parallel with a linear connecting pier was simulated. Daylight distribution of 6%-10% of SRR was simulated with the simulation input shown in the Table 2 below.

Table 2: Table showing the reflectance and transmittance values of elements used during the Radiance simulation studies

No.	Elements	Colour	Reflectance Value
1.	Floor	Grey	0.250
2.	Wall	Brown	0.371
3.	Ceiling	White	0.9
4.	Furniture	-	-

No.	Glazing Elements	Colour	Transmittance

1.	External Glazing	Clear	0.250	Pilkington K 6mm
2.	Internal Glazing	Clear	0.190	Clear Float 12mm

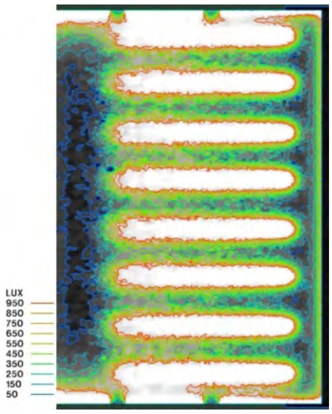


Figure 11: Daylight distribution of 8% SRR Departure Hall

By applying 10% of SRR as it is found that the daylit area is more than 70% and the contour demonstrates approximately 70% of the daylit area achieve more than 900 lux. Following that, by applying 8% of SRR as the figure above (Figure 11), it is found that the daylit area is more than 60% and the contour demonstrates approximately 60% of the daylit area achieve more than 900 lux. This is considerably high for an airport terminal and will contribute to heat gain, higher cooling load energy and visual discomfort.

It is realised that by applying 6% of SRR, it is found that the daylit area is more than 50% and the contour demonstrates approximately 50% of the daylit area achieve more than 900 lux. The bigger the ratio of the skylight to the roof, the higher daylight area was obtained. This will also lead to the increase of total heat gain and higher energy needed for example cooling loads and lighting energy. Through a preliminary study of skylight area at differing percentages, the aim is to see the approximate total floor area which would be adequately lit by daylight.

4.1.2 Design Development Phase

The results above have given us the opportunity to generate an improved model with the improvement on the design and skylight to roof ratio values of from 5% to 10% that were studied. The improved model was tested with the additional perimeters with the consideration of the façade of the terminal building - Window to Wall Ratio (WWR) and again the sizing of skylights.

Based on the results from the schematic design phase (SRR-8%-9%), the skylight was redesigned to find a solution that would fulfil 75% of the threshold for daylight with a minimal value of 250 lux. This is also because the simulation results of the schematic design phase only deal with an opening from the skylight of the terminal building's roof. Each simulation exercise with façade daylight contribution was reanalysed during the design development phase to aim at achieving 75% of the threshold for daylight minimal value of 250 lux.

A study on four different skylight options (1m, 1.5m, 2m and 2.5m) was simulated to determine the threshold percentage of the skylight, which distributed a diffusing 250 lux illumination level throughout the designated spacing of sidelight glazing on the positioned skylights. This parametric exercise aims to fulfil 75% of the threshold for daylight minimal value of 250 lux. The model was built without partitions in order to minimise the effect of sidewalls as well as to generally look into the varying distribution of daylight through the façade and skylight. It also aims to find a balance between the daylight availability and heat gain reduction, which occurs at 8%-9%-SRR and resulted from the schematic design phase.

4.1.3 Simulation with Façade Contribution

i. **Option 1**

The simulation was carried out with three options of testing the size of the skylight. In option 1, the model was tested and the size of skylight of 1m x 140m with a 40% glazing of the façade with daylight hours from 8 is – 6 pm. (Figure 12). The simulations were carried out for the period of 9 am, 12 pm and 3 pm for comparison of validating the method and procedure. The illuminance distributions were quite consistent during this period of time and most daylit core areas were above 250 lux.

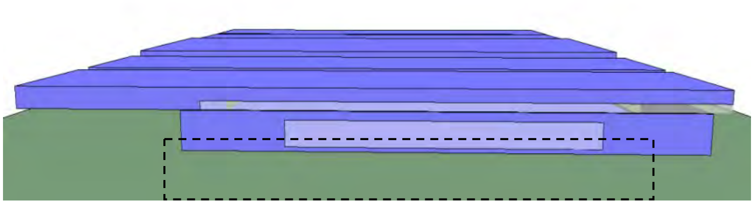


Figure 12: The model showing the size of skylight with 1m x 140m with a 40% glazing of the façade with daylight hours from 8 am – 6 pm

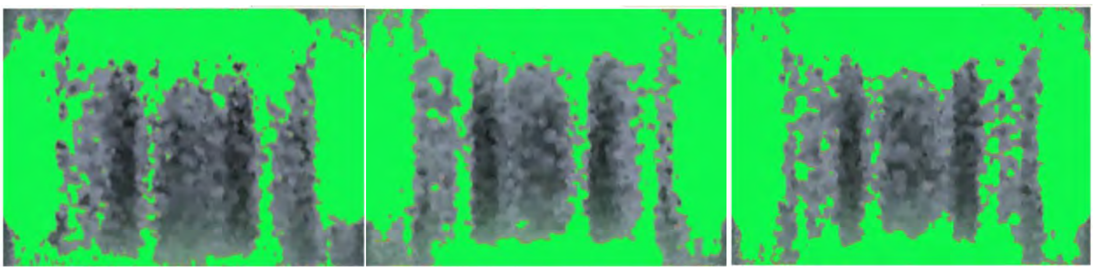


Figure 13: The distribution of lux with skylight area of 1m x 140m with daylight hours at 9.00am, 12.00pm and 3.00pm

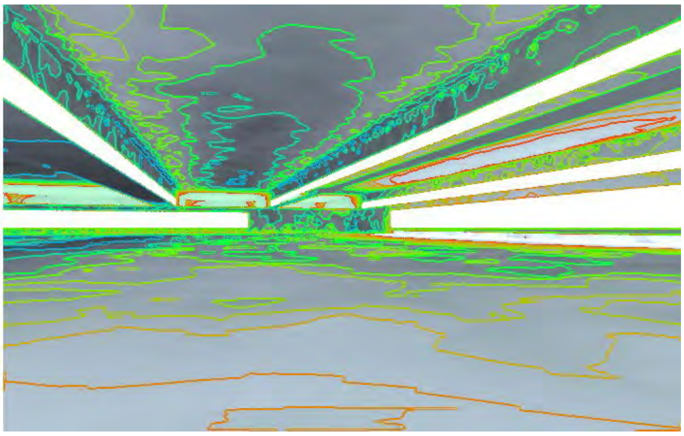


Figure 14: The distribution of lux contour with skylight area of 1m x140m with daylight hours at 12.00pm

For the illuminance analysis, it was shown that the diffuse distribution of daylight of the main terminal building through the above condition of glazing and 10K overcast sky condition, at 9 am, the incidence of light penetrating the overall space which occurs more than 250 lux, achieved 51.06%. While, at 12 p.m., it achieved 58.38% and at 3 p.m., it achieved 54.24% (Figure 13-14). It shows a consistent pattern of distribution of diffused illuminance. The incidence of light that achieves more than 250 lux covers deeper area during 12 p.m. and 3 p.m. and this contribute to a more diffuse distribution of daylight which allow for less usage of artificial lights in the concourse terminal area. The light penetration to the overall space covers approximately 20m on the north, 13m on the east and west, and 6m on the south.

ii. Option 2

In option 2, the computer model was simulated with skylight dimension of 1.5m x 12m and 40% of façade glazing with daylight hours from 8 am – 6 pm. As shown in Figure 15.

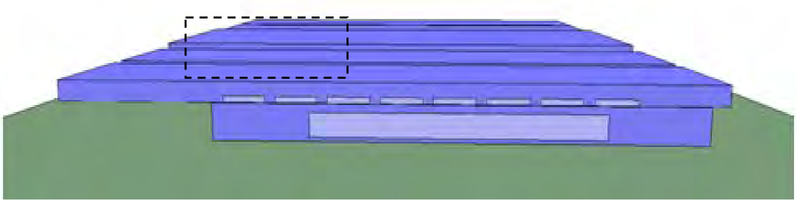


Figure 14: The model showing the size of skylight with 1.5m x 12m with a 40% glazing of the façade with daylight hours from 8 am – 6 pm.

Table 3: Summary of parameter' input in the parametric modeling

Parameters	Constant	Variables
SHGC	0.4	
Visible Transmittance	0.8	
Skylight Shading Coefficient	0.8	
Glazing	6mm thick, grey tinted with Low E on external Side 13mm thick, grey tinted on internal Side and 12mm airspace Gap	
Skylight to Roof Ratio (SRR)		From 6%-10%
Window to Wall Ratio (WWR)		20:80, 30:70, 40:60
Skylight Size		1.0m, 1.5m, 2.0m, 2.5m

At this stage, the glazing type, area, shading coefficient, visible transmittance is determined and finalised to accommodate the later stage model as requested and discussion with the architect of the case study (Table 3). Finally, the input of the interior spaces such as ticketing counters, service rooms, retail outlets, etc., is considered and constructed in the later stage model. This will definitely generate an impact to the required daylight provision of the spaces. Finally, a later stage model will be modelled to demonstrate the achievable desired illumination levels which comply with IESNA standards as well as to show the comparisons of simulation model with skylight and without skylight which justify the significance of skylight which contributes on achieving the desired illuminance level.

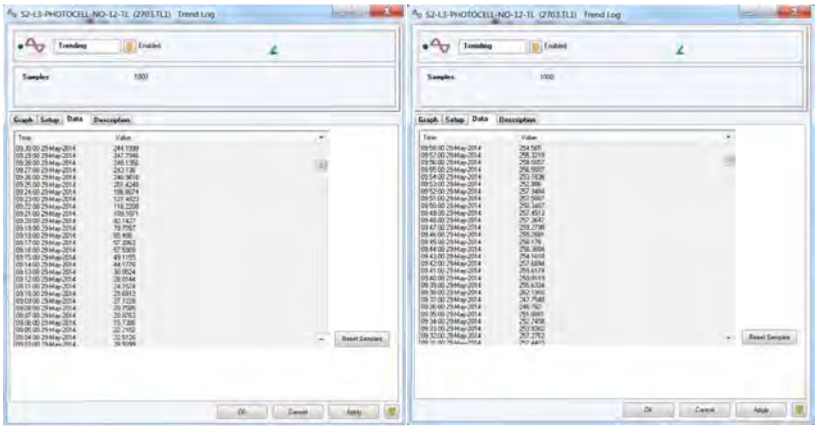


Figure 16: Trend Log of Daylight Sensor at S2 L3 Departure Hall, KLIA2

Referring to Figure 16, the Trend Log of Daylight Sensor at S2 L3 Departure Hall above, lux level at sensor increased from around 25 lux (9.00am) to 250 lux (9.30am) and stabilized at 250 lux. This information demonstrates and confirms that all systems are programmed and operating correctly as predicted. This data verifies that automatic daylighting controls are installed and functioning properly. The above process suggests the importance of integrating passive strategies in each design process in order to obtain a more critical satisfactory results technical analysis with regards to the impact of daylighting to energy savings. The following framework presents a procedure in strategic integration of design process as this could possibly suggests a framework of modeling process to bridge the gap in research issue on performance and prediction as discussed by Jahn Kassim et al (2015), (refer Figure 17).

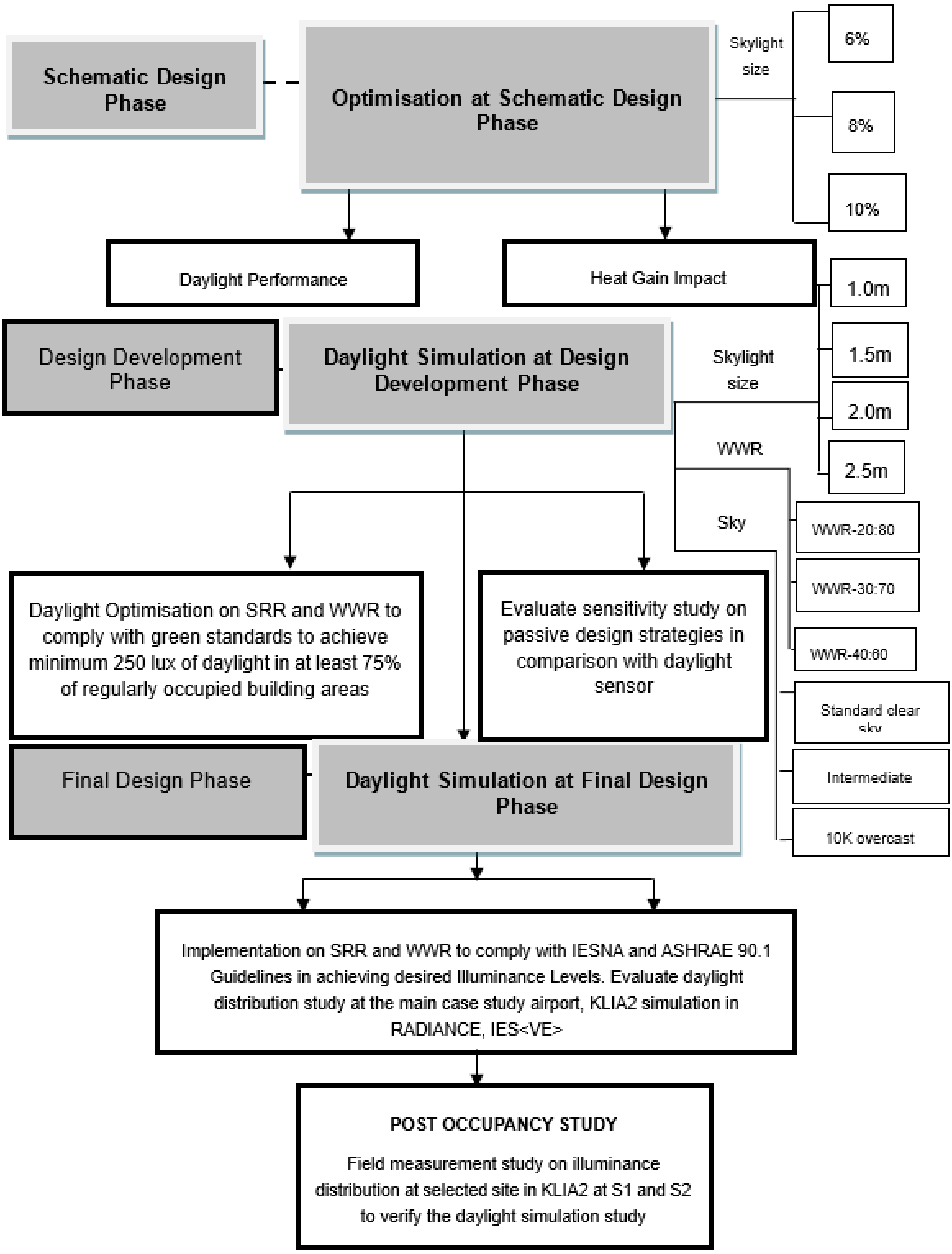


Figure 17: Framework of Simulation Modelling in Integrated Design Process

5. CONCLUSIONS

Parametric or reiterative simulation is a necessary part of sustainable design decision making yet most of the present studies discusses these processes outside of the actual design process. This paper brings reiterate and parametric modeling into the very boundaries and constraints of the design. It then reports on the specific outcomes which were a result of discussion with consultants and what can be done within the time constraint of the project. This case study method is created in an actual context of work and establishes the link between analysis and geometric form. It gave the role of visualisation in terms of a successful case study and outline the processes that could link design and application through a series of parametric studies which being tested through variables such as sizing, Skylight to Roof Ratio (SRR), Window to Wall Ratio (WWR), sky conditions and finding the optimum solution; all of which would benefit energy efficiency in a more focused and tightly defined scale of problems such as balancing heat gain and obtaining the optimum illuminance distribution throughout the selected space and its adjoining areas. This paper focuses, through a specific case study in outlining an optimisation process involving the use of daylighting simulation processes to achieve strategic targets in skylight design and situations under the critical conditions of the tropical climate in particular. It is analysed and discussed in relation to passive design building targets in an actual project. The obtained results from the simulation processes are preceded by a comparison to measured data to investigate the degree of accuracy of the software itself. The software selected able to assess the link between the skylight design and the overall pattern, distribution and range of standard IESNA illuminance levels to the terminal space in the tropics. The research found that the outcome is accurate as the tool itself was used as a daylight-heat gain optimisation strategy in early stages rather than merely as a daylight modelling tool. It points to further research to find the level of error with other standard skies such as CIE intermediate sky and daylight simulation which look into the time series programing of daylight into the BIM-IDP process for exact level of error and uncertainties.

6. REFERENCES

Arasteh, D., Johnson, R., and Selkowitz, S. (1985b). The effects of skylight parameters on Daylighting, Energy Savings, Windows and Daylighting Group, Lawrence Berkeley Laboratory, University of California, Berkeley, California.

Jahnkassim, P.S., and Ip, K. (2006). Linking bioclimatic theory and environmental performance in its climatic and cultural context – an analysis into the tropical high rises of Ken Yeang, *PLEA 2006 - The 23rd Conference on Passive and Low Energy Architecture*, Geneva, Switzerland, 6-8 September.

Jahnkassim, P. S., Has Yun Hashim, K. S., Hussein, Z. and Riduan, B. (2015). An Integrated Carbon and Sustainability Index from Green Buildings in the Tropics, *CIBSE Technical Symposium*, London, UK 16-17 April.

Johnson, R., Sullivan, R., Selkowitz, S., Nozaki, S., Conner, C., and Arasteh, D. (1984). Glazing energy performance and design optimisation with daylighting, *Energy and Buildings*, no.6.

Kandar, M. Z., Sulaiman, M. S., Rashid, Y. R., Ossen, D. R., Abdullah, A. M., Wah, L. Y., and Nikpour, M. (2011). Investigating Daylight Quality in Malaysian Government Office Buildings through Daylight Factor and Surface Luminance, *Engineering and Technology* 59.

Mahdavi, A., Rao, S.P., and Inangda, N. (2013). Parametric Studies on Window-To-Wall Ratio for Daylighting Optimisation in High-Rise Office Buildings in Kuala Lumpur, Malaysia, *Journal of Design and Built Environment*

Vol.12, June.

Mark, S. R. (2000). The IESNA lighting handbook: reference and Application, *Illuminating Engineering Society of North America*, 9th Edition. New York.

Yuan, L. J. (1987). The Malay House: Rediscovering Malaysia's indigenous shelter system, Penang. Institute Masyarakat, Malaysia.

Zain-Ahmed, A. (2000), Daylighting and Shading for Thermal Comfort in Malaysia Buildings, Unpublished PhD Thesis, University of Hertfordshire.

Zain-Ahmed, A, Sopian, K., Zainol Abidin, Z., and Othman, M. Y. H. (2002). The availability of daylight from tropical skies-a case study of Malaysia, Pergamon-Energy Conversion and Management, *Elsevier Science L*td.

CAN EXPERIENCE OVERCOME THE COGNITIVE CHALLENGES IN DRAWING-BASED DESIGN REVIEW? — DESIGN REVIEW EXPERIMENTS

Ghang Lee*, Jaehyuk Park[γ], Jongsung Won[≠], Harrison Kwangho Park[γ], Miyoung Uhm* &Yunho Lee[€]

[*]Department of Architectural Engineering, Yonsei University, Seoul, Korea

[γ]GS Engineering & Construction, Korea

[≠]Korea National University of Transportation

[€]Daesung Industrial Engineering & Construction, Korea

ABSTRACT: *Despite the widespread use of building information modeling (BIM)—including BIM-based design review, which is known as an early step of BIM adoption—many regions and small companies struggle with using BIM effectively. Many existing studies have provided industry- and project-level statistical data on the impact of design errors in construction, as well as an industry-level statistical analysis of the effectiveness of BIM-based design review, but such studies are often challenged by professionals who strongly believe in the effectiveness of drawing-based design review. This study conducted four design review experiments with eight experienced professionals to provide an inherent personal-level cognitive limitation of drawing-based review. The experiments reveal that due to an overwhelming number of potential errors to review, drawing-based design review only allows professionals to deploy a targeted search strategy, which might be an effective information search method within a given or predefined search space but is limited in finding unanticipated design errors. As a result, experienced professionals could not even detect 5% of known errors on drawings during the experiments. The result confirmed that experience cannot overcome such cognitive challenges in drawing-based design review.*

KEYWORDS: *building information modeling (BIM), drawing, error, design review, experienced professionals, expert study, search strategy*

1. INTRODUCTION

The 737 airplane is composed of approximately 367,000 parts. The number of objects (parts) of a large building exceeds this number, which makes it very challenging to review a design. Despite the expectation and proven records about Building information modeling (BIM) as an effective means for design review, many regions and small companies are still suffering in their efforts to adopt BIM. Among the many uses of BIM, this paper focuses on BIM-based design review, which is known as an early step of BIM adoption and as the most effective way of using BIM. Many existing studies have provided industry- or project-level statistical data on the impact of design errors in construction and industry level statistical analysis of the effectiveness of BIM-based design review, but such studies are often challenged by those who believe that experience can overcome challenges in drawing-based design review.

This paper refutes the belief that experience can overcome challenges in drawing-based design review by reporting an experiment and a case study and discussing the causes of the differences between drawing-based and BIM-based design review. This paper consists of three parts. First, it discusses why this study is necessary when many are aware of the problems of drawing-based design review by reviewing previous studies on design errors and obstacles to BIM adoption in practice. Then, it explains a design review experiment with four teams of highly experienced practitioners to investigate how well experienced and skilled designers and engineers can detect design errors using the traditional drawing-based design review method. Third, a case study is conducted to trace a design review process of a 30-story building construction project in Seoul, South Korea, which had a unique case of deploying a drawing-based design review method and then a BIM-based design review method to resolve endlessly occurring design errors to investigate the difference in types of the design errors that can be easily detected by drawing- and BIM-based design review methods.

2. PREVIOUS STUDIES & BACKGROUND

Some may question the need to study the drawing-based design review capabilities of experienced practitioners when many are aware of the problems of drawing-based design review that led to the adoption of BIM. Various surveys show that the belief that the drawing-based design method is better than BIM is still one of the most prevalent obstacles to the adoption of BIM (Lee et al. 2012a; Nikkie BP Consulting Inc. 2011). This widespread belief leads to a passive and sometimes antagonistic participation in BIM activities during projects (SPAR Point Group staff 2014).

Many believe that enough evidence exists to show the ineffectiveness of the drawing-based design review capabilities of experienced practitioners. Contrary to the general perception, evidence that can refute the belief in the effectiveness of the drawing-based design review capabilities of experienced practitioners is rare despite the large number of studies on design errors. Previous studies on design errors are conducted mostly in five areas: 1) classification of errors (Atkinson 1998; Burati et al 1992; Ellirtgwood 1987; Lopez et al. 2010); 2) causes (Busby 2001; Ellirtgwood 1987; Lopez et al. 2010; Love et al. 2012a; Mahalingam and Levitt 2007; Melchers 1989; Taylor 2007a; Taylor 2007b); 3) cost and schedule impacts (Han et al. 2013; Hwang et al. 2009; Lee et al. 2012b; Lopez and Love 2012; Love et al. 2012a; Love et al. 2013); 4) case reports (Acharya et al. 2006; Haydl and Nikiel 2000); and 5) error avoidance strategies (Busby 2001; Le May and Deckker 2009; Lee et al. 2003; Love et al. 2012b; Love et al. 2011a; Love et al. 2011b; Palaneeswaran et al. 2013; Sacks et al. 2003; Sweeney 1998). Many of these studies indirectly demonstrate the problems of drawing-based design review through the analysis of the potential impact of design errors on cost and schedule. However, none of these studies directly deal with the drawing-based design review capabilities of experienced practitioners and their limitations.

Another misconception is that such problems of resistance towards adopting BIM exist only in BIM-developing countries because we mostly hear only successful stories. But countries that are perceived as BIM-advanced countries, such as North American countries, northern European countries, the United Kingdom, South Korea, Japan, and Singapore, still face challenges that must be overcome before BIM-based design review becomes a general practice. For example, a longitudinal study that has been conducted from the late 1990s to date of IT adoption in the Swedish building sector reports that the use of 3D computer-aided drafting (CAD) and BIM is becoming common, but the use of BIM is still limited mostly to geometric data (e.g., rendering and 3D visualization) and object data is rarely deployed (Samuelson and Björk 2014). Similarly, a recent international survey reports that over 40% of BIM users in the UK, Canada, Denmark, and Japan perceive BIM either as BIM software or as a synonym for 3D CAD drawings (NBS 2016).

As discussed above, many regions and trades are still challenged by a strong belief in the effectiveness of drawing-based design review and the overconfidence in practitioner experience. This study conducts a controlled experiment with eight experienced practitioners and a case study to review the drawing-based design review capabilities of experienced practitioners to find evidence to refute the misbelief.

3. DESIGN REVIEW STUDIES

This section is composed of three subsections. First, we discuss the qualifications for experienced practitioners. Second, we report the results from four drawing-based design experiments and discuss possible causes for the results. In the third subsection, we continue the discussion and report which types of errors can or cannot be easily detected when a drawing-based design review method is adopted.

3.1 Qualifications for experienced practitioners

Since this study evaluates the design review capabilities of experienced practitioners in the architecture, engineering, and construction (AEC) industry, it will be important to define the qualifications for experienced practitioners first.

In construction, professional is a common term to denote an expert. Practitioner is commonly used as a synonym for professional. We use the two terms interchangeably in this paper. A professional is a person with specialized skills and knowledge in a profession. Some professionals require an academic degree or a license—a Professional Engineer license (PE) is required for construction engineers (US Legal 2015) and an Architectural Institute of America license is required for architects (AIA 2015)—but some professionals in construction, such as detailers or schedulers, may not require a license. These licenses are the minimum requirement for a licensed professional and do not necessarily signify high levels of expertise.

Years of experience, therefore, is more generally used across various industries as a criterion for determining the level of expertise of professionals than a license, academic degree, or other measures. The Korea International Cooperation Agency classifies a professional with over 20 years of experience as a first-tier professional, 15-20 years as a second-tier professional, 10-14 years as a third-tier professional, 7-9 years as a fourth-tier professional, and a professional with under 7 years of experience as a fifth-tier professional (KOICA 2013). PayScale, a website featuring salary data of various professionals in the US, classifies the level of PEs by 1 year, 5 years, 10 years, and over 20 years (PayScale 2015). Although these two references do not clearly define entry-level professionals versus experienced professionals, a person with more than three years of experience is not regarded as entry-level in a typical job market.

Based on these standard practices, this study categorizes professionals with less than 3 years of experience as entry-level, professionals with 3-7 years of experience as experienced, professionals with 7-20 years of experience as very experienced, and professionals with over 20 years of experience as extraordinarily experienced.

3.2 Experiment: How many errors can experienced practitioners find in two to three hours?

3.2.1 A survey on the perceived design review capabilities of experienced practitioners

Separate from the design review experiments, we conducted a survey with 54 practitioners in the AEC industry to understand the practitioners' perceptions about the current drawing-based design review practice and to analyze the gap between the perceived and actual design review capabilities of experienced practitioners. The respondents of the survey had 10 to 35 years of experience (average: 18.6 years, standard deviation: 4.6 years). The 54 respondents included 27 architects, 14 contractors, and 13 engineers. The question simply asked what percentage of design errors would practitioners with over 20 years of experience be able to detect related to a specific floor within two to three hours using the traditional drawing-based review method. The respondents believed that practitioners with over 20 years of experience would be able to detect 30-50% of errors related to a specific floor within two to three hours using the traditional drawing-based review method.

3.2.2 Setup of design review experiments

To validate this perception of experienced practitioners' proficiency in identifying design errors, a total of four experiments were conducted at two different construction sites (two experiments per site). We referred to the first project as Project A and to the second project as Project B. Project A was an office building and Project B was a large hospital project.

A total of eight professionals with six types of different backgrounds were invited to the experiments since professionals with different backgrounds may have different levels of design review capabilities. The six types of backgrounds were a design manager, a field engineer, an office engineer, a cost estimator, a MEP coordinator, and a detailer (draftsman). All these professional types were recommended a candidate for whom could find the most number of errors during a design review process by the other practitioners.

The first and second teams were asked to find errors and clashes in the architectural and structural drawings of the first basement floor of an 84,214.96 m^2 office-building complex. The first team was composed of a design manager with 21 years of experience and a field engineer with 16 years of experience. The second team was composed of an office engineer with 15 years of experience and a cost estimator with 14 years of experience. Because no mechanical engineering expert was involved in the first set of experiments, the scope was intentionally limited to architectural and structural drawings; mechanical-electrical-plumbing (MEP) drawings were excluded.

The third and fourth teams were each composed of a senior MEP coordinator and a detailer since they worked together as a team in practice. A detailer is also known as a draftsman. The third team was composed of a senior

MEP coordinator with 15 years of experience and a detailer with 7 years of experience. The fourth team was composed of a senior MEP coordinator with 32 years of experience and a detailer with 3 years of experience.

The experiments were conducted based on the following guidelines:

- Each experiment was conducted with a team of two professionals. The team members were allowed to talk to each other to discuss problems and find errors more effectively and accurately than if they were working alone.
- We recommended that each experiment be conducted for two hours. However, subjects were allowed to take more time if they desired.
- All subjects were asked to analyze the drawings from their own projects so that they would not need extra time and effort to familiarize themselves with the projects. Furthermore, the subjects had been working on their projects for periods ranging from several months to a year and a half before the experiments and had therefore had sufficient time to comprehend their projects.
- Subjects had seen earlier versions of drawings of the given floor, but had not reviewed the given version of the drawings.
- The scope of the experiments was limited to a floor area of approximately 3000 m^2, which was the floor area of designs on a single shop drawing.

In case of Project A, a single floor of one building was approximately 3,000 m^2 (2,946 m^2) and thus the design was reviewed by floor. Project B was divided into 18 sectors and reviewed by sector (2,800-3,000 m^2) rather than by floor since a single floor of Project B's hospital buildings was very large (approximately 12,000 m^2).

In the case of Project A, even after excluding MEP drawings, a total of 34 architectural drawings, 25 structural drawings, and 6 schedules including beams, columns, windows, and other schedules were given to the participants. In the case of Project B, participants were asked to review 1 architectural plan, 6 structural plans (concrete body plans), and 12 combined service drawings, which included MEP designs of the given floor. The given floor was composed of four sectors, and drawings of three other sectors around the target sector were also given to the third and fourth teams to provide a context.

The accuracy and recall (hit rate) of each team's results were measured using the following definitions:

$$\text{accuracy} = \frac{\text{number of true positives} + \text{number of true negative}}{\text{total population}} \qquad \dots \text{Eq. 1}$$

$$\text{Recall (hit rate)} = \frac{\text{number of true positives}}{(\text{number of true positives} + \text{number of false negatives})} \qquad \dots \text{Eq. 2}$$

- True positives: reported errors that were confirmed to be actual errors.
- True negatives: reported non-errors that were confirmed not to be errors.

- False positives (Type I error): cases that were identified as errors but were confirmed not to be actual errors.

- False negatives (Type II error): actual errors that were not reported by an experiment.

Design review did not track any true negative (non-error or correctly designed) cases. Thus, instead of accuracy, recall (hit rate) was used as a measurement to quantify the error detection performance of the subjects. The definition of recall is the number of true positives divided by the total number of correctly reported (true positive) and non-reported (false negative) errors.

To establish a basis for evaluating the drawing review capabilities of the participants, the drawings used in four experiments were reviewed through a BIM-based design review process. Through the BIM-based design review process, the BIM teams found 194 design errors from the Project A drawings reviewed by the first and second teams and 416 errors from the Project B drawings reviewed by the third and fourth teams. These errors were confirmed by the other engineers participating in the project. This review process took less than an hour.

3.2.3 Experiment Results

The results of the experiment with all four teams showed extreme inaccuracy. The first and second teams gave up in the middle of the experiments without finding any errors. The first team participated in the experiment for only 80 minutes. The team scanned through the 65 drawings for about 15 to 20 minutes to set up a review strategy. The team members decided to review drawings independently, expecting to find more errors than when working together. After a while, one of them tried to find discrepancies between drawings by crosschecking drawings and schedules, but the participant’s effort was in vain. After 80 minutes, the team members agreed to stop the session without finding any errors even though they were asked to take as much time as they needed.

A similar pattern was observed for the second team; members of this team decided to stop the experiment in the middle of the experiment without finding any errors. The second team participated in the experiment for 40 minutes and decided to stop the experiment without finding any errors.

The third and fourth teams performed slightly better than the first and the second teams and found 25 and 10 errors, respectively, stopping after two hours (Fig. 1) even though they were allowed to use more time if they wanted to.

The third and fourth teams had similar error-detection strategies to one another, but very different approaches from those used by the first and second teams. Both the third and fourth teams used a calculator to calculate the elevation of each MEP element. They seemed to focus solely on physical clashes between MEP elements and physical clashes between MEP and other building elements. They mentally stacked MEP elements to check whether the MEP parts could fit into the given plenum space. They also tried to obtain mental visualizations of the MEP runs by using their fingers as a makeshift three-dimensional representation of ducts and pipes to check whether MEP elements conflicted with other elements. They sometimes put their heads below their finger as if they were looking up at the MEP elements from the bottom of a ceiling.

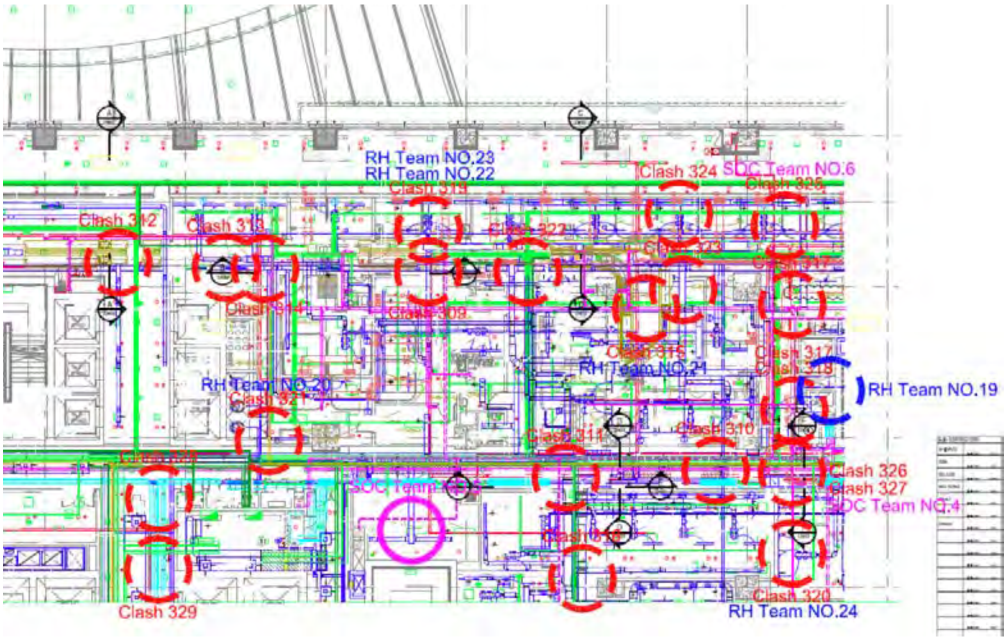


Fig. 1: Errors identified by Teams C and D, marked on a drawing for result analysis

We reviewed the errors detected by the third and fourth teams to check whether they were actual errors. Of the 25 errors that the third team detected, 6 were confirmed to not be errors (false positives) and only 19 errors were actual errors (true positives). The number of errors we detected through BIM-based design review for the same area was 416, and all of the valid 19 and 10 errors (true positives) detected by the third and fourth teams respectively were included in the 416. Thus, the total number of undetected errors for the third team was 397 (excluding the invalid 6 errors) and the total number of undetected errors for the fourth team was 406. The recall (hit rate) of the third team was 4.6% (=19/(19+397)). The recall of the fourth team was 2.4% (=10/(10+406)). Table 1 summarizes the results.

Table 1: Experimental results.

Team type	**Actual errors (True positive)**	**Unreported errors (False negative)**	**False errors (False positive)**	**Recall (Hit rate)**
Team A	0	194	0	0/(0+194) = 0%
Team B	0	194	0	0/(0+194) = 0%
Team C	19	397	6	19/(19+397) = 4.6%
Team D	10	406	0	10/(10+406) = 2.4%

3.2.4 Discussions on design review experiments

Although the third and fourth teams performed slightly better than the first and second teams, the values of the detected errors—4.6% and 2.4% respectively—are still very low. When the results are compared to the survey results (30-50%) on the perceived design capabilities of experienced practitioners, we can conclude that the experiment clearly confirms how challenging error detection is—even for experienced professionals and regardless of their professions—when attempting to examine and detect errors by relying on drawings. The results might have slightly varied if the experiments were conducted in different settings with different groups of practitioners. However, it is doubtful that experienced practitioners can find 30 to 50% of design errors using the drawing-based design review method.

How, then, can they perform their daily design review tasks and build buildings? We found a clue for this question from interviews with the experiment participants and other professionals who did not participate in the experiments. To the third and fourth teams, we asked how they could find errors from drawings. A senior MEP coordinator answered, "We know where the fish are," and elaborated that they focused on the most congested area and gave up on other areas in order to find the largest number of errors within a short period of time. Otherwise, they would have taken much more time because when they calculated ceiling space and checked for any clashes they also needed to consider and mentally visualize things that were not shown in the drawings, such as construction clearance, insulation, brackets (hangers), and maintenance accesses.

This claim was confirmed by interviews with other practitioners after the experiments. On a daily design review task, practitioners review designs by focusing on frequently erroneous areas or areas with special issues rather than every detail, whereas the computer searches through all possible errors. Naturally, as practitioners gain more experience they learn where to look and become better in finding design errors.

In terms of search strategy, the design review strategy employed by the teams can be referred to as a targeted search strategy, as opposed to a whole search strategy. A targeted search is an information-finding method that retrieves information by focusing on a specific group or within a limited scope, whereas a whole search strategy looks for information by exploring all possible combinations. The targeted search strategy is very commonly deployed in everyday life (such as looking for a car key in places where car keys would usually be found) and is an effective means to overcoming a cognitive limitation of humans by reducing search space and information-processing time. Nevertheless, it can cause investigators to become trapped in a wrong search space if the investigation begins with wrong assumptions. Another drawback is that targeted searches are weak at finding unanticipated information. These drawbacks make targeted searches ineffective for design review, and the four experiments confirm this finding.

The next section investigates further differences between professionals' review skills when using drawing-based design reviews and when BIM-based design review was deployed. This investigation was done by analyzing the design error types detected through a drawing-based design review supplemented by design checklists and BIM-based design review in one project.

3.3 Case study: Why do many errors still exist after two cycles of extensive drawing-

based design review sessions, even when using design checklists?

3.3.1 D Center case

“D Center” is a unique case, as it adopted a BIM-based design review in the middle of construction because numerous design errors were continuously found after two iterations of a drawing- and checklist-based design review process. A design review checklist is a collection of important check items that must be carefully examined during the design review process. D Center, located in Seoul, Korea was composed of 4 basement floors and 30 floors above the ground. From the 7^{th} to the 30^{th} floors, plans were the same.

The first design validation, which used drawings and the checklist, was conducted by a total of 16 architectural designers, contractors, engineers (structural, geospatial, mechanical, electrical, plumbing, fire, and safety), and cost estimators for 15 days. The checklist used in this project was developed by the main contractor and included a total of 762 check items: 105 items were related to the spatial requirements, 161 were items related to building codes and regulations, and 496 were items related to constructability issues. A total of 124 design errors were found. The errors were categorized into three types accepted by the Korea State Contract Law (MOSF 2014). The first type is illogical design errors, such as hard and soft clashes between building elements, drawing mistakes, constructability issues, and building code violations. The second type is discrepancies between drawings, which includes term discrepancies. The third type is omission, such as missing or insufficient information and areas that do not have problems per se but that have not been updated according to review comments or design changes.

Among the 124 errors found, the majority (59%) were omissions, especially missing information (40%). Omissions generally have the least direct economic impact among design error types according to the D^3 City case study (Lee et al. 2012b), but they still require a considerable expenditure of time and effort (emails and phone calls) to fill in the missing or non-updated information. The second most common error type was illogical design errors (29%), especially constructability issues (18%). Drawing discrepancies (12%) were the third most frequent errors. No clash was identified during the first review.

The second design validation was conducted by a total of 14 contractors and engineers for another 15 days after revising and updating the items checked during the first design validation. In addition to the 124 errors detected during the first review cycle, 23 were identified during the second design review. The error patterns were the same: missing information (35%) and constructability issues (30%) represented a majority of identified errors and only one clash was found.

After the two cycles of a drawing- and checklist-based design review process by over 14 contractors and engineers before construction, the project participants believed that the drawings for the D Center project were fully coordinated. However, design errors were endlessly reported as soon as construction began.

Four months after construction had begun, the project team, which suffered from endless design errors on site, decided to check the design again using BIM. A total of ten contractors, engineers, BIM modelers, and BIM managers reviewed the building design again for 19 days.

Through the third design review using BIM, a total of 51 additional errors were detected. During the BIM-based design review process, drawing discrepancies (41%) and clashes (31%)—two types of errors that were either not the major error types or were hardly detected during the first two design reviews—comprised a major portion of the detected errors. Only one clash was detected through the two previous drawing- and checklist-based review cycles, whereas many clashes between ducts and trays were identified during the BIM-based design review process.

3.3.2 Discussions

This result indicates that BIM-based design review is especially effective in detecting clashes and discrepancies between drawings. Conversely, drawing- and checklist-based design review is limited in detecting clashes between building elements and discrepancies between drawings.

We know from a previous study (Lee et al. 2012b) that omission, the major error type found during the two cycles of drawing-based review, has little economic impact, and that illogical designs and discrepancies between drawings—the major error types detected during BIM-based review—contribute most to economic losses. Thus, being incapable of detecting a majority of clashes and discrepancies in a design is economically a critical drawback of drawing-based review. The D Center case study demonstrates another reason for practitioners, regardless of experience, to shift from a drawing-based review practice to a BIM-based review practice.

4. CONCLUSION

This study conducted design review experiments and a case study that clearly demonstrated the cognitive challenges of drawing-based review and that experience cannot overcome such cognitive challenges. The major difference between BIM and drawing-based review is that BIM enables professionals to deploy the whole search strategy in design review and to detect significantly more design errors within a relatively short period of time.

The experiments reveal that due to an overwhelming number of potential errors to review, drawing-based design review only allows professionals to deploy a targeted search strategy, which might be an effective information search method within a given or predefined search space but is limited in finding unanticipated design errors. As a result, experienced professionals could detect less than 3% of known errors on drawings during the experiments. This poor detection rate occurs because traditional drawing-based building design review imposes a heavy cognitive load on engineers, detailers, and project coordinators. Currently, design checklists with a large number of items are often employed to overcome such a cognitive load, but the checklists do not help professionals much when the professionals need to form mental visualizations of multiple layers of MEP systems to detect clashes between different trades and discrepancies between drawings (Lee 2014).

On the other hand, BIM, based on a machine-readable representation of facilities, can enable professionals to deploy a whole search strategy, which iterates through all possible search spaces and can detect even unanticipated design errors. However, neither BIM nor designs that are fully coordinated using BIM are perfect. As more and more computing power and intelligence are added to BIM, BIM can provide more reliable solutions to professionals.

Moreover, BIM is not a substitute for drawings, checklists, or experienced professionals. BIM will only maximize the design review capability and experience of professionals. As BIM advances, the role of experienced professionals as coordinators and decision-makers of a project will become more important than ever.

Although only four experiments were conducted, the small number is not a limitation of this paper because the aim of this study was not to provide statistical data, but to provide a counter instance of what has been generally believed through demonstrating that experience cannot overcome the inefficiency and cognitive limitations of drawing-based design review.

A long journey remains before the benefits of BIM can be fully maximized. Further research and efforts are required to take full advantage of the BIM-based design review process. This study is expected to contribute to the industry in various ways. It may act as a catalyst in overcoming the strong resistance to BIM that remains in practice and in encouraging experienced professionals and decision makers to adopt BIM. Moreover, we recommend that a team lead of a BIM project, which is facing a strong resistance from project participants, should conduct an experiment similar to this study on site. The gap between the expectation and the reality will be too large for anybody to simply ignore.

5. ACKNOWLEDGEMENTS

This research was supported by a grant (15-AUDP-C067817-03) from the Architecture & Urban Development Research Program funded by the Ministry of Land, Infrastructure, and Transport of the Korean government.

6. REFERENCES

Acharya, N., Lee, Y., and Kim, J. (2006). "Design errors: inefficiency or carelessness of designer?" *Journal of Performance of Constructed Facilities*, 20(2), 192-195.

AIA. (2015). "Career Stages." http://www.aia.org/careerstages/index.htm (accessed August 31, 2015).

Atkinson, A. (1998). "Human error in the management of building projects." *Construction Management and Economics*, 16(3), 339-349.

Burati, J., Farrington, J., and Ledbetter, W. (1992). "Causes of quality deviations in design and construction." *Journal of Construction Engineering and Management*, 118(1), 34-49.

Busby, J. S. (2001). "Error and distributed cognition in design." *Design Studies*, 22(3), 233-254.

Ellirtgwood, B. (1987). "Design and construction error effects on structural reliability." *Journal of Structural Engineering*, 113(2), 409-422.

Han, S., Love, P., and Peña-Mora, F. (2013). "A system dynamics model for assessing the impacts of design errors in construction projects." *Mathematical and Computer Modelling*, 57(9–10), 2044-2053.

Haydl, H. M., and Nikiel, A. W. (2000). "Design and construction errors - case studies." *Practice Periodical on Structural Design and Construction*, 5(3), 126-130.

Hwang, B., Thomas, S., Haas, C., and Caldas, C. (2009). "Measuring the impact of rework on construction cost performance." *Journal of Construction Engineering and Management*, 135(3), 187-198.

KOICA. (2013). "Professional Rating Guide." Korea International Cooperation Agency (KOICA), Seongman-si, Gyeonggi-do, South Korea.

Le May, I., and Deckker, E. (2009). "Reducing the risk of failure by better training and education." *Engineering Failure Analysis*, 16(4), 1153-1162.

Lee, G., Eastman, C. M., and Zimring, C. (2003). "Avoiding design errors: a case study of redesigning an architectural studio." *Design Studies*, 24(5), 411-435.

Lee, G., Lee, J., and Jones, S. A. (2012a). "2012 Business Value of BIM in South Korea (English)." McGraw Hill Construction, Bedford, MA.

Lee, G., Park, H. K., and Won, J. (2012b). "D3 City project — Economic impact of BIM-assisted design validation." *Automation in Construction*, 22(0), 577-586.

Lee, Y. H. (2014). "A Comparative Analysis of Detected Design Errors with and without BIM," Master's thesis, Yonsei University, Seoul.

Lopez, R., Love, P., Edwards, D., and Davis, P. (2010). "Design error classification, causation, and prevention in construction engineering." *Journal of Performance of Constructed Facilities*, 24(4), 399-408.

Lopez, R., and Love, P. E. D. (2012). "Design error costs in construction projects." *Journal of Construction Engineering and Management*, 138(5), 585-593.

Love, P., Lopez, R., Kim, J., and Kim, M. (2012a). "Influence of organizational and project practices on design error costs." *Journal of Performance of Constructed Facilities*.

Love, P., Lopez, R., Kim, J., and Kim, M. (2013). "Probabilistic assessment of design error costs." *Journal of Performance of Constructed Facilities*.

Love, P. E. D., Lopez, R., Edwards, D. J., and Goh, Y. M. (2012b). "Error begat error: design error analysis and prevention in social infrastructure projects." *Accident Analysis & Prevention*, 48(0), 100-110.

Love, P. E. D., Lopez, R., Goh, Y. M., and Davis, P. R. (2011a). "Systemic modelling of design error causation in social infrastructure projects." *Procedia Engineering*, 14(0), 161-168.

Love, P. E. D., Lopez, R., Goh, Y. M., and Tam, C. M. (2011b). "What goes up, shouldn’t come down: learning from construction and engineering failures." *Procedia Engineering*, 14(0), 844-850.

Mahalingam, A., and Levitt, R. E. (2007). "Institutional theory as a framework for analyzing conflicts on global projects." *Journal of Construction Engineering and Management*, 133(7), 517-528.

Melchers, R. E. (1989). "Human error in structural design tasks." *Journal of Structural Engineering*, 115(7), 1795-

1807.

MOSF. (2014). "General conditions of construction contract." The Ministry of Strategy and Finance (MOSF), Sejong-si, South Korea.

NBS. (2016). "NBS International BIM Report 2016." RIBA Enterprise Ltd., London, UK.

Nikkie BP Consulting Inc. (2011). "Japan 2011 BIM Survey." Nikkie BP Consulting Inc., Tokyo, Japan.

Palaneeswaran, E., Love, P., and Kim, J. (2013). "Role of design audits in reducing errors and rework — lessons from Hong Kong." *Journal of Performance of Constructed Facilities*.

PayScale. (2015). "Average Salary for Certification: Certified Professional Engineer (PE)." http://www.payscale.com/research/US/Certification=Certified_Professional_Engineer_(PE)/Salary#by_Years_Experience (accessed Aug 31, 2015).

Sacks, R., Eastman, C. E., and Lee, G. (2003). "Process improvements in precast concrete construction using top-down parametric 3-D computer modeling." *Journal of the Precast/Prestressed Concrete Institute*, 48(3), 2-11.

Samuelson, O., and Björk, B.-C. (2014). "A longitudinal study of the adoption of IT technology in the Swedish building sector." *Automation in Construction*, 37, 182-190.

SPAR Point Group staff. (2014). "U.K. gov't 2016 BIM mandate 'unachievable' ", http://www.sparpointgroup.com/news/uk-govt-2016-bim-mandate-unachievable (accessed August 31, 2015).

Sweeney, N. (1998). "Who pays for defective design?" *Journal of Management in Engineering*, 14(6), 65-68.

Taylor, J. R. (2007a). "Statistics of design error in the process industries." *Safety Science*, 45(1–2), 61-73.

Taylor, J. R. (2007b). "Understanding and combating design error in process plant design." *Safety Science*, 45(1–2), 75-105.

US Legal. (2015). "Professional Engineer Law and Legal Definition." http://definitions.uslegal.com/p/professional-engineer-pe/ (accessed August 31, 2015).

AN AUTOMATIC SIMULATION SYSTEM FOR BUILDING INFORMATION AND ENERGY-SAVING DESIGN MODELING

Po-Han Chen, Chi-Feng Hua, Po-Chuan Chuang and Thanh-Chuong Nguyen

National Taiwan University, Taiwan

ABSTRACT: *In recent years, sustainability has become a global emphasis. Although the simulation of green buildings and energy-saving designs is done using energy simulation software, some data required to run energy simulation come from BIM (Building Information Modeling) software. Nowadays, the transfer of data from BIM software to energy simulation software is time and cost consuming. Thus, integrating energy simulation software and BIM software to achieve automatic green building simulation is necessary. This research proposes a system that could facilitate the information transfer between a BIM software (Autodesk Revit) and an energy simulation software (eQUEST). Since eQUEST is recognized as an accepted analysis tool by international green building standard LEED (Leadership in Energy and Environmental Design), the proposed system will be of help in the acquisition of green building certificates. In addition, the proposed system can automatically generate a base model for a green building (or energy-saving) design before putting into green building standards analyses. It also incorporates lifecycle costing to allow the user to know the lifecycle cost of each energy-saving design and make the best decision.*

KEYWORDS: *GREEN BUILDINGS, BIM LEED、ENERGY CONSUMPTION、AUTOMATION*

1. INTRODUCTION

In recent years, green building has been a global focus (Choi et al., 2012; Nookala et al., 2012). The importance of green building not only lies in its emphasis on the eco-friendly design but also on its involvement in reducing building energy consumption, waste water resource overusing and other problems (Yu J. and Chang, B.Y. 2008).

The LEED (Leadership in Energy & Environmental Design) certification, developed by the U.S Green Building Council, has now become a popular and globally accepted standard of green buildings in the world (Azhar et al., 2011). For LEED energy consumption analyses, after a proposed design is analyzed by simulation software such as eQUEST, Energyplus and Ecotect, a baseline is needed to determine the quality of the design, or to be qualified in the EA (Energy and Atmosphere) credit section. First, the design model should be modified into a baseline model for calculation on the base of LEED criteria. Then the energy consumption is identified and used as a means to calculate its energy efficiency using the following formula:

$$\text{Energy efficiency} = \frac{\text{Baseline model annual consumption amount} - \text{Design model annual consumption amount}}{\text{Baseline model annual consumption amount}} \times 100\%$$

However, establishing a baseline model is difficult and time-consuming, and there is no tool yet to help solve this problem. Therefore, how to establish the baseline model in an efficient way is an important issue.

BIM (Building Information Modeling) collects building data and knowledge from designers from various fields, and integrates these data into the building's life cycle. This paper proposes a concept, in which the author applied BIM to establish a basic and automatic system to resolve the above-said problems. Users can apply the system and insert the building and weather information into the energy consumption simulation software (this research uses eQuest as an example) to calculate the data of annual power consumption and comparable criterion modeling of LEED.

2. LITERATURE REVIEW

In recent year, there have been numerous studies about the integration of BIM tools in green buildings standards, such as the LEED certifications. Roderick et al. (2009) proposed a BIM computational simulation to quantitatively benchmark the energy consumption in three popular green building systems: LEED, BREEAM and Green Star. Azhar et al. (2011) and Bank et al. (2010) developed conceptual frameworks to establish the relationship between BIM-based sustainability analyses and the LEED certification process. Krygiel and Nies (2008) conducted in-depth studies about BIM applications in various building systems with successful implementation of BIM in the LEED certification. However, the integration of BIM in green building certification such as the LEED standard still has limitation. Krygiel and Nies (2008) stated that "many of the tools used to measure the impact of sustainable design strategies, old or new, are not directly accessible within a BIM model itself; therefore, data needs to be exported to another application or imported from a data source". Wong and Kuan (2014) pointed out that LEED users still need to use an "indirect" method, that is, read analysis results from BIM software schedules and put back to LEED standards for manual calculations. In other words, designers still have to use indirect methods by exporting models and data among different software for analysis.

At present, calculations by simulation software can evaluate the energy efficiency of proposed designs. However, the building model in energy simulation software still has drawbacks and the process is time-consuming, which is why the energy consumption simulation software is not so popular.

3. RESEARCH OBJECTIVES

This research proposes a system that could facilitate the information transfer between Autodesk Revit and eQUEST to minimize the required time for information transfer and to automate this process. In addition, the system can help automatically generate a base model for a green building or energy-saving design.

At last, this research incorporates lifecycle costing into the developed system, allowing users to know the lifecycle cost of each energy-saving design and make the best decision.

4. RESEARCH METHODOLOGY

A BIM tool (Autodesk Revit), an energy simulation tool (eQUEST), and a database storage tool (Microsoft Excel) will be integrated as the backbone of the proposed system to calculate energy-saving efficiency, green building standards (LEED EA credit 1) criteria, and lifecycle costs. Visual Studio/C# and Revit API (Application Programming Interface) are used for the integration of Autodesk Revit, eQUEST, and Microsoft Excel. For each green building design, the corresponding resource or energy-saving efficiency (such as the savings on electricity, water, etc.) will be studied and/or experimented to facilitate the calculation of lifecycle costs.

4.1 Related software applications and the development of prototype system

Every item including walls, roofs, windows, floors etc., in BIM software (e.g. Autodesk Revit) has its own parameter. By reading the parameter and the database, the parameter is processed into the data format that is compatible in eQUEST. The design model is used to calculate the annual energy consumption. By switching it to the Baseline Model according to the requirements of LEED, the scores of LEED EA credit 1 could be obtained by checking at the result table. Revit and eQUEST were integrated as a system by Visual Studio 2008 to establish the developing background with C# as program language and Excel as database system (The system structure was shown in Fig. 1). The software used in the study is introduced as follows.

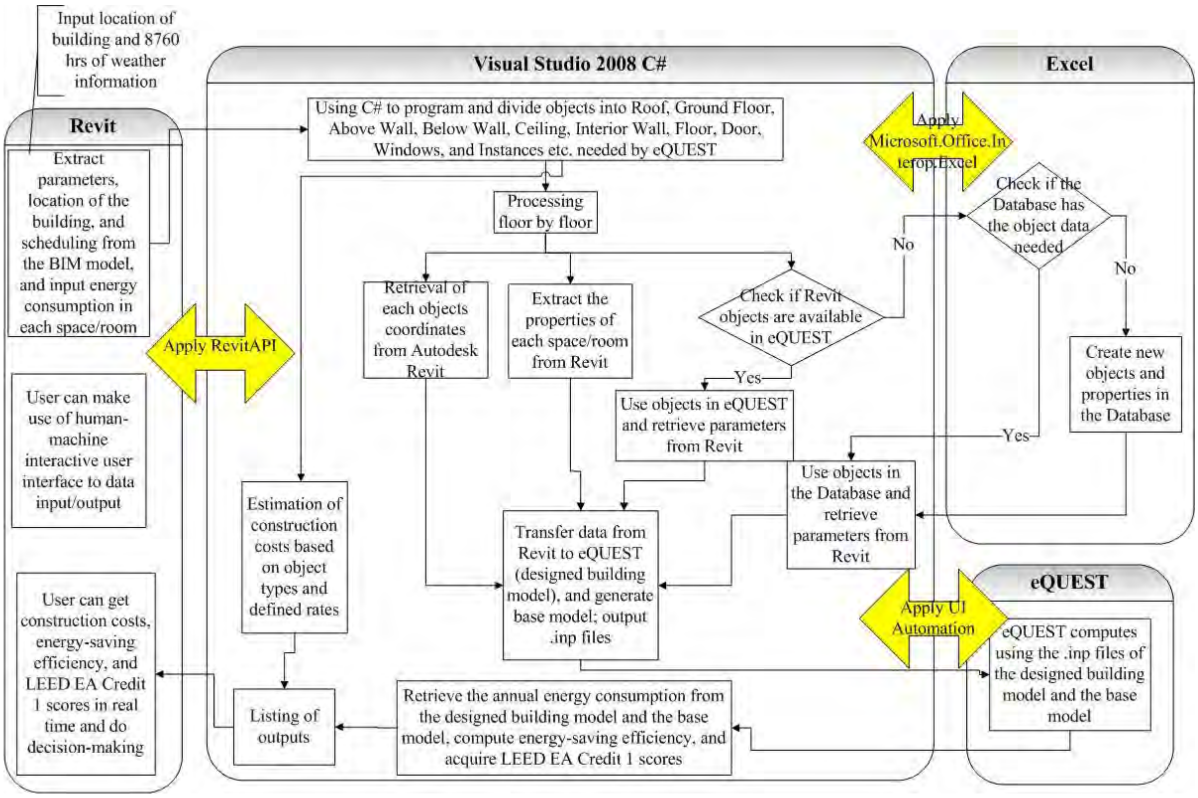


Figure 1. Flowchart of System Development

4.2 BIM software-Revit

Autodesk Revit was the predominant BIM software used by a majority of AEC professionals (Bynum et al., 2013). The Revit API (Application Programming Interface) provided by Autodesk Revit could help users to expand the functions of Revit. The prototype system proposed in this study read the parameters in BIM model and incorporated with other software to achieve the research goals. The major task was to read the coordination of the replaced items and the parameters being adjusted and inputted when users were using Autodesk Revit as BIM. Another task was to show the results of energy-saving efficiency and LEED EA Credit 1 on the user interface for users to choose the ideal options.

4.3 Energy-consumption simulation software-eQUEST

The software used for energy-saving dynamic analysis in the study is eQUEST. eQUEST had earned the public trust internationally and was widely adopted by energy and air-conditioning industry. Being freely-download and by continually updating, eQUEST maintains the reliability and fairness. By inputting the local climate data and the building information (location, size, appearance, location of windows, materials of the walls, and air-conditioning systems etc.) through graphical interface into the computing core DOE-2, the detailed annual 8760 hours' energy-consuming results could be analyzed. The hourly loading change of energy consumption could be calculated by eQUEST.

One of the main reasons to use eQUEST in this paper was because it's a very common and easy to use energy simulation tool. Some charts in Evaluation Manual for Green Building Material (2009) was actually simulated by eQUEST. Another reason to use the eQUEST was because of the friendly user interface (UI). Compared to DOE-2.2, another popular energy-simulation software, it is easier to check if the input model and data is correct.

5. SOFTWARE DEVELOPMENT

5.1 Revit LEED EAc1 Credit plugin

The developed plugins in this study is integrated into the BIM-LEED toolbar in Autodesk Revit, and the credits EAc1 can be accessed through the LEED Energy and Atmosphere UI (user interface) under the BIM-LEED toolbar (Figure 2). The Energy and Atmosphere UI displays the result of each credit, as well as total LEED points in the Energy and Atmosphere category.

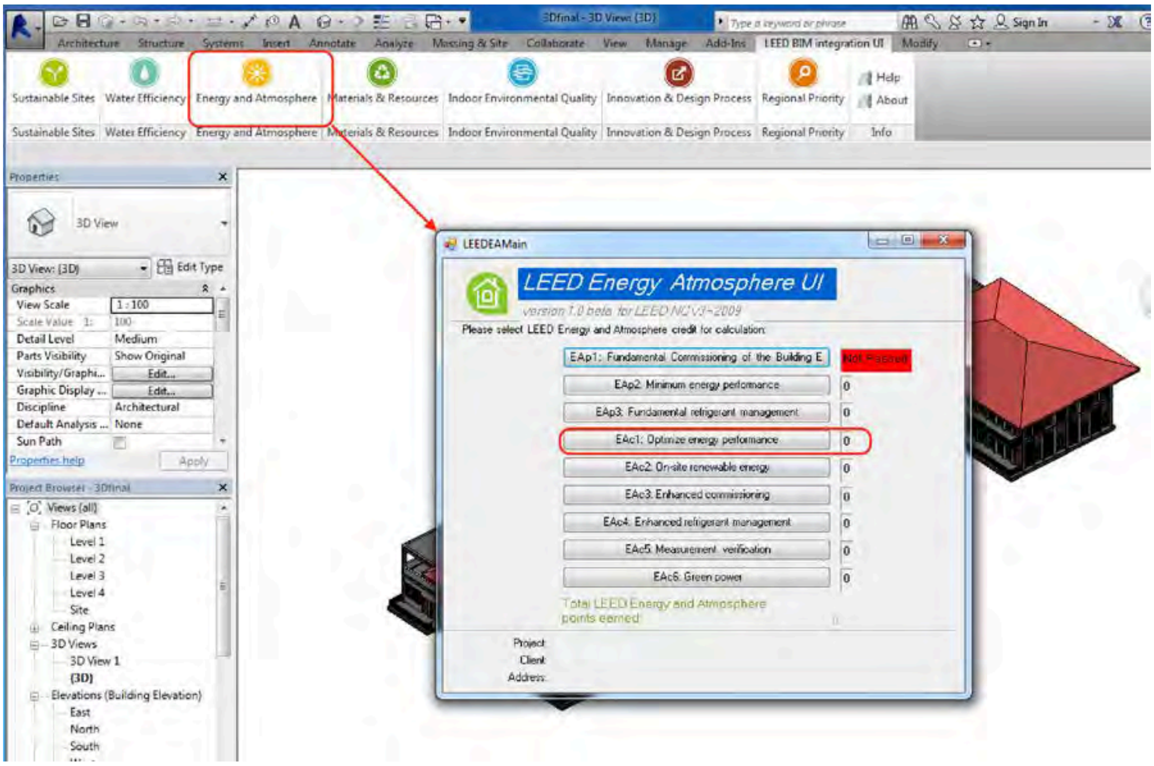


Figure 2. LEED Energy and Atmosphere UI panel

5.2 System Integration

As shown in figure 1, users build up the model using BIM tools. The prototype system developed in the study could process all the information inputted from Revit API and BIM after users build up the BIM model, including the information of every material, the sizes, locations, and the building location.

5.3 Revit to eQUEST

After BIM processes all the information, all the objects will be separated according to the information request of eQUEST into Roof, Room, Above Wall, Below Wall, Ceiling, Interior Wall, Floor, Door, Windows, and other objects needed in energy-saving software (e.g. Instances). But there are different data formats between Revit and eQUEST, and the both software also have different coordinate systems, too. In Revit, start and end points are recorded for each line segment, but in eQUEST each line segment is a parameter and recorded as counterclockwise (as shown in figure 3). So coordinate transformation is required. This research presented a way to solute the coordinate problem. First step is data exporting and categorizing, using programing to set a matrix to storage start point and end point from Revit, then find the same coordinates on left and bottom. If the coordinates is start point, then find the end point and vice versa. The program then compares two coordinates to find the righter one, and keep doing until the running circle finishes.

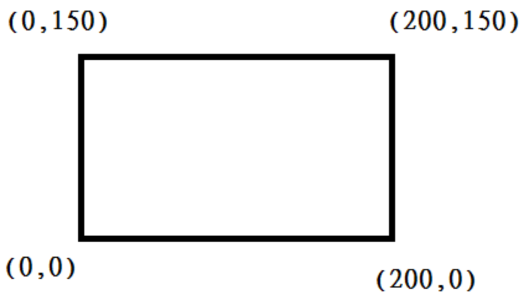


Figure 3. coordinate example

Table 1. Coordinate example in Revit

Start Point_	Start Point_	End Point_X	End Point_Y
0	0	200	0
0	150	200	150
200	150	200	0
0	150	0	0

Table 2. Coordinate example in eQUEST

V1	(0,0)
V2	(200,0)
V3	(200,150)
V4	(0,150)

The building information needed to be inputted by floors is in *.inp file format in eQUEST. Also, the logical relations of all the building objects in each floor should be inputted. Thus, in the execution process of the prototype system it would be integrated with the relational data method, which was often used in program designing (as shown in figure 4). Due to enormous information, the following figure presented only a few relation of the information.

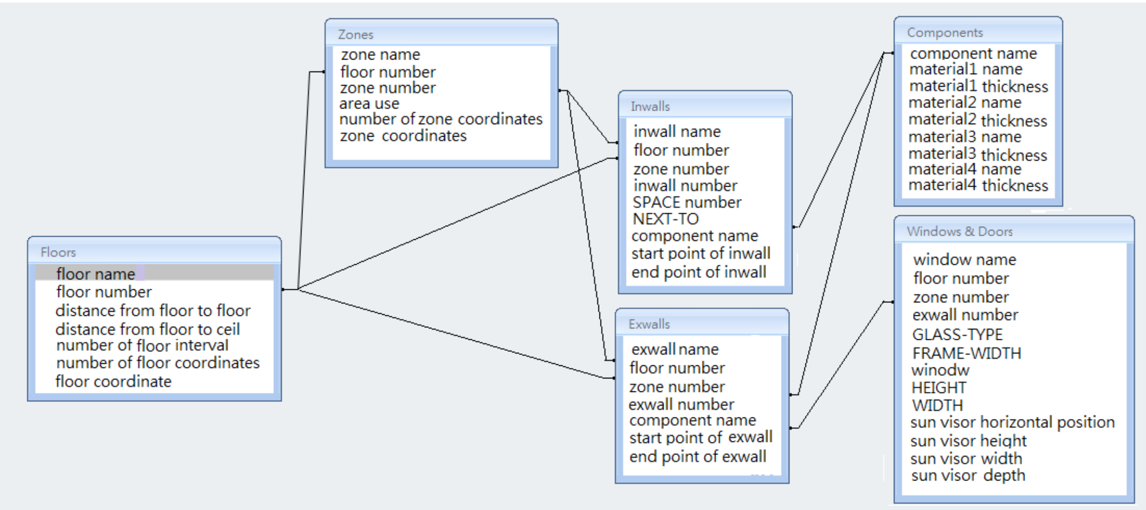


Figure 4. A part of embryo model's relational data

5.4 Establish baseline building

Vertical fenestration areas shall equal to that in the proposed design or 40% of gross above grade wall area, whichever is smaller, and shall be distributed on each face of the building in the same proportions in the proposed design. Skylight area shall be equal to that in the proposed building design or 5% of the gross roof area that is part of the building envelope, whichever is smaller. (ASHRAE Standard 90.1-2007)

Each material's insulation factor should be modified to the basic value, if there is any sun-shading or automatic lighting control, it should be removed in baseline building, too.

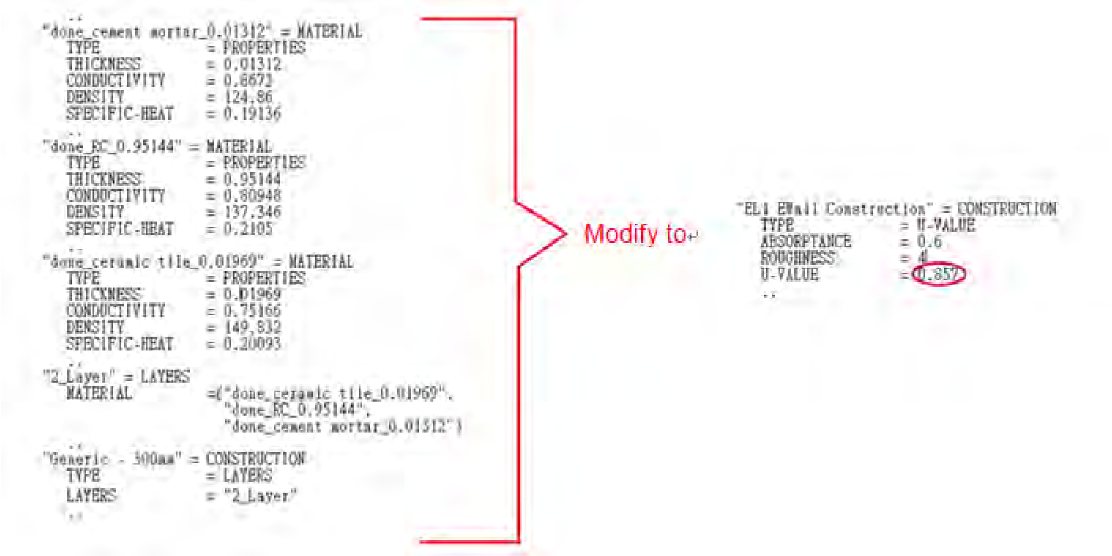


Figure 5. Modification of *.inp file

After the insulating-factor modification, the baseline building performance shall be generated by simulating the building with its actual orientation, and do again after rotating the entire building 90, 180, and 270 degrees. The results are then averaged. The building shall be modeled so that it does not shade itself (ASHRAE Standard 90.1-2007).

To achieve above-mentioned goal, the eQUEST's *.inp file is modified by the developed system. The system automatically finds the corresponding object to modify insulating factor and delete the automatic control setting (comply with ASHRAE Standard 90.1-2007 appendix G).

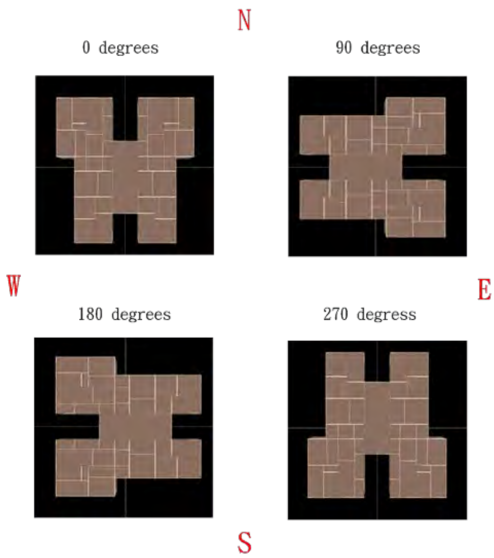


Figure 6. Automatic orientation simulate in eQUEST by programing

6. SYSTEM DEMONSTRATION

The case study of the proposed model used in this paper is a public housing design in Taipei, Taiwan (figure 7).

Figure 7. Model established by Revit

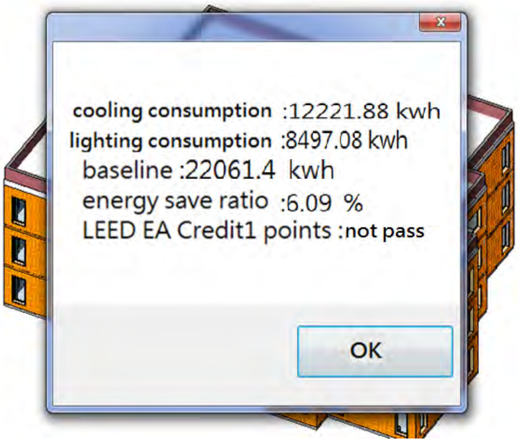


Figure 8. Execution results

After the model is constructed, the researcher runs the system and obtains the results shown in figure 8. According to the results, the energy saving ration was 6.09% computed by LEED's standard. However, the requisite ratio in the LEED EA Credit 1 criteria should be over 10%. Therefore, more energy saving design is required for example, thickening the glass wool insulation on roof (figure 9). The results of the second run conforms the LEED EA Credit 1 standard, for the cooling consume actually decreases in figure 10.

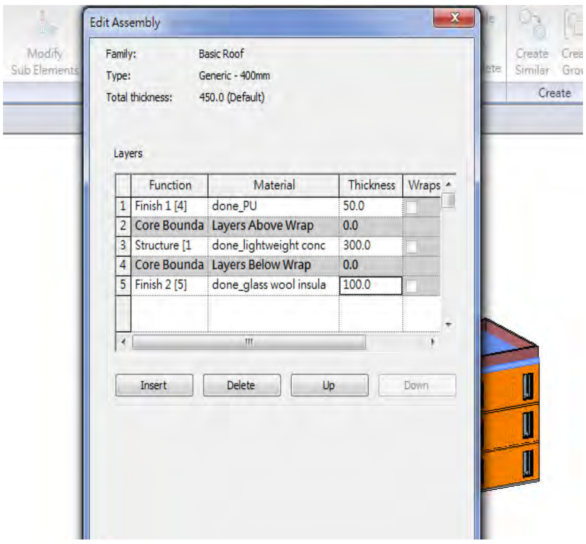


Figure 9. changing material on roof

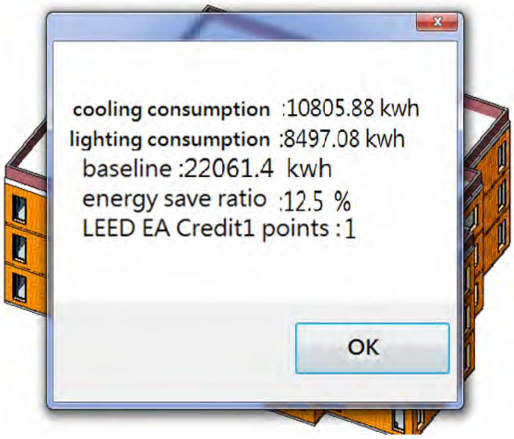


Figure 10. Execution results after changing material

By interviewing with the expert consulting with the concept of the present study, it could be concluded that the energy-saving design would be fast and effectively carried out after the system was fully developed and further acquired the LEED EA credit 1.

7. CONCLUSIONS AND RECOMMENDATIONS

The prototype system developed in this paper is only to represent the concept and idea in the study. When the prototype system is fully developed, it would be very useful because it usually took about a week, even a month, to build the eQUEST model.

Through the case study and consulting with the project manager, it can be concluded that by using the developed system, the time spent on planning how to reduce the energy consumption in order to get the LEED credit 1 could be largely shortened. The process of making design changes could be simplified. Also, due to the non-slot process, the possible mistakes when inputting the information could be largely reduced compared to the procedure that was done manually.

Recently, there are efforts to use the energy simulation software. But the promotion of using eQUEST is not easy because it often takes enormous time to build the eQUEST model. Except for producing engineering graphs, elevation graph, and 3D graphs, the designers have to use eQUEST to simulate the energy consumption, which increases the difficulty for promoting the use of eQUEST. If the model is built using Revit to place the objects into the building model, all the graphs could be produced simultaneously. After the prototype system is fully developed, the building information is transferred into the eQUEST, thus the BIM and energy simulation software can be widely applied in project use.

Many energy simulation software could calculate the annual energy consumption of the building and the building cost per year, so it is suggested to integrate the life cycle cost NPV value into the future study, for it could be used as reference in terms of cost, energy-saving efficiency, and LEED EA credit 1 for owner to choose the best design strategy. Recent applications of BIM used in the early stage of evaluating the cost still have some difficulties. For example, different types and amounts of building objects in the model are not necessarily accorded with the actual building materials in the project. Sometimes the scaffolds and moldboards might be excluded in the model. Therefore, the building cost cannot be accurately estimated if the model only calculated the objects built in the BIM model. It was recommended to carefully investigate the logical relation between the actual materials and the objects built in the model so as to accurately estimate the building cost.

8. REFERENCES

Azhar, S., Carlton, W.A., Olsen, D., Ahmad, I., 2011. Building information modeling for sustainable design and LEED® rating analysis. Autom. Constr. 20, 217–224. doi:10.1016/j.autcon.2010.09.019

Bank, L.C., McCarthy, M., Thompson, B.P., Menassa, C.C., 2010. Integrating BIM with system dynamics as a decision-making framework for sustainable building design and operation, in: First International Conference on Sustainable Urbanization. Presented at the ICSU 2010, Hong Kong, China.

Barnes, S., Castro-Lacouture, D., 2009. BIM-enabled integrated optimization tool for LEED decisions, in: 2009 ASCE International Workshop on Computing in Civil Engineering, June 24-27, 2009, Austin, TX.

Bynum, P., Issa, R., Olbina, S., 2013. Building Information Modeling in Support of Sustainable Design and Construction. J. Constr. Eng. Manag. 139, 24–34. doi:10.1061/(ASCE)CO.1943-7862.0000560

Choi, K., Son, K., Woods, P., Park, Y.J., 2012. LEED Public Transportation Accessibility and Its Economic Implications. J. Constr. Eng. Manag. 138, 1095–1102. doi:10.1061/(ASCE)CO.1943-7862.0000441

Krygiel, E., Nies, B., 2008. Green BIM: Successful Sustainable Design with Building Information Modeling. Wiley.

Nookala, S., Said, H., Kandil, A., Cai, H., Al-Derham, H., Senouci, A., El-Gafy, M., 2012. Developing a Framework for Pre-Design Process Simulation for Green Buildings, in: Construction Research Congress 2012@ sConstruction Challenges in a Flat World. pp. 1700–1709.

Roderick, Y., Wheatley, C., Mcewan, D., Alonso, C., 2009. A comparative study of building energy performance assessment between LEED, BREEAM and Green Star schemes, in: 11th International Building Performance Simulation Association Conference. Presented at the International IBPSA Conference, University of Strathclyde, Glasgow, Scotland, pp. 1167–1176.

Wong, J.K.-W., Kuan, K.-L., 2014. Implementing “BEAM Plus” for BIM-based sustainability analysis. Autom. Constr. 44, 163–175. doi:10.1016/j.autcon.2014.04.003

Wong, K., Fan, Q., 2013. Building information modelling (BIM) for sustainable building design. Facilities 31, 138–157. doi:10.1108/02632771311299412

American Society of Heating, Refrigeration and Air-Conditioning Engineers (2007).Energy Standard for Building

Except Low-Rice Residential Buildings

United State Green Building Council (2010). LEED 2009 for New Construction and Major Renovations Rating System

Lin, H.T. and Huang, K.T. (2004). The Study and Application of Taiwan TMY2 Standard Meteorological, Energy Commission, Ministry of Economic Affairs

Su, T.C. (2009). A Study on the Energy Consumption Certificate of Residential Buildings, Ph.D. Thesis, National Cheng Kung University.

Timo, H., Ju, G. and Fischer, M. (2008). Areas of Application for 3D and 4D Models on Construction Projects, Journal of Construction Engineering and Management, Vol. 134, No.10, 776-785.

Yoon, Y. J., Moeck, M., Mistrick, R.G. and Bahnfleth, W.P. (2008). How Much Energy Do Different Toplighting Strategies Save? Journal of Architectural Engineering, Vol. 14, No. 4, 101-110.

Yu, C. and Chang, B.Y. (2008). Green Building Development Analysis in Taiwan, Far East learned journal, Vol. 25, No. 3, 443-452.

Zeng, X.D. and Zhao, A. (2006). Study on the Application of Energy Efficiency Building Design Based on BIM Technology, Journal of Chongqing Jianzhu University, Vol. 28, No. 2.

DESIGN CHANGE MANAGEMENT IN CONSTRUCTION PROJECTS BASED ON BUILDING INFORMATION MODELING

Valeh Moayeri, Osama Moselhi, and Zhenhua Zhu

Department of Building, Civil, and Environmental Engineering, Concordia University, Montreal, Canada

ABSTRACT: *Design changes after awarding the contract are typical during the construction phase of a project. The changes do not only affect the original project schedule, but also produce additional construction costs. They cause the potential contractual disputes among project parties (e.g. general contractor, sub-contractor, designers, and owners). As a result, the design changes have been considered as one major cause of leading to the project failure. In order to effectively manage design changes, it is necessary to provide the prompt feedbacks about the impacts of the changes on the project schedule and cost upon receiving the design change request. The objective of this paper is to propose the use of building information modeling (BIM) technologies to facilitate design change management. Specifically, any potential design change in a construction project is virtually implemented into its building information model. Then, the components affected by the change are identified in the model. These components are further linked with construction cost and schedule information. This way, the parties in the project has a preliminary idea about the impacts of the design changes and their ripple effects, which helps the owner to make a final, well-informed decision on approving or rejecting the requested changes to the project's design. The research work presented in this paper has been tested in the case study of a 3-story residential building project. The results showed that the impacts of the changes in terms of time and cost could be reasonably estimated before implementing the changes in the project.*

KEYWORDS: *Design Change, Ripple Effects, Building Information Modeling, Change Management.*

1. INTRODUCTOIN

Design changes, including any addition, deletion and modification in the design or construction of a project after awarding the contract, are expected during the construction phase of a project. This is partly because project owners might change their minds in line with the changing economic climate to meet the market demands (Ibbs, 2012). In addition, designers might produce inadequate or inconsistent detailing of drawings, which lead to a large margin of error and omission and create problems of coordination between the architectural, structural, mechanical, electrical and other systems (Hegazy et al. 2001). For example, the fire-rated walls have to be relocated due to and architectural restrictions or the air supply ducts need to be rerouted under the limitations in available space (Pilehchian, Staub-French, 2015).

The construction project performance in terms of schedule and cost is significantly impacted by design changes. For example, Kumaraswamy et al. (1998) found that 50 percent of the projects surveyed suffered delays that originated from design changes. Assaf et al. (2006), after studying construction projects in Saudi Arabia reported that 70% of the construction projects faced time overruns and design changes were the most frequent source of delay.

In order to manage design changes in an effective manner, it is necessary to give prompt feedback about the impacts of the changes and their related ripple effects on the project performance. However, this might be difficult, especially considering the fact that the owner’s requests for design changes are usually made at short notice. So far, most of existing research studies have been conducted for change management. They focused on creating the guidance for best practice in change management (CII, 1994) and quantifying the overall impacts that changes have on construction project performance (Serag et al. 2010; Ibbs, 2012; Ibbs et al. 2005). Recently, the idea of developing project information models has been proposed. The information models are expected to facilitate the coordination of design information through the management of design changes (Xue et al. 2012; Hegazy et al. 2001).

The main objective of this paper is to investigate the impacts of design changes and their ripple effects on the project performance in terms of cost and schedule with the aid of building information modeling (BIM) technologies. Specifically, suppose the project building information model has been created in advance. Any potential design change requested by the owner or designer in the project could be virtually implemented into its building information model. Then, the new model (i.e. as-changed model in this study) is compared with the original model (i.e. as-planned model) to identify the components directly and indirectly affected by the change. These components are further linked with construction cost and schedule information, which provides a preliminary idea about the impacts of the design changes and their ripple effects on the project in terms of schedule and cost. This information could help the project owner to make a final, well-informed decision on approving or rejecting the requested changes to the project’s design and avoid potential construction disputes between different parties. The research work presented in this paper has been tested in the case study of a 3-story residential building project. The results in the case study showed that the impacts of the changes in terms of time and cost could be reasonably estimated with the BIM technologies.

2. RELATED WORK

A change has the impacts on the project delay and cost overrun (Arain and Pheng, 2005). Also, it affects the quality of construction work, labor productivity, etc., which cause legal disputes between different parties involved in the project (Mirchekarlou, 2012). Moreover, one change itself could be further spread and escalated. As a result, a series of additional changes are produced as ripple effects. However, such ripple effects of the change are not always easy to be identified. It requests enough experience and expertise to predict or estimate the impacts of all possible consequences of the change in the project.

So far, several research studies have been proposed for the purpose of quantifying the impacts of the change in the project. They relied on different computing techniques, such as regression/statistical analysis, artificial intelligence, system dynamics, decision tree, and case based reasoning. For example, Hanna et al. (2002a) grouped the factors that correlate with whether a project is impacted by changes through statistical hypothesis testing, and then developed models to predict the probability of a project being impacted using logic regression techniques. In one of their other studies, they also presented a hybrid approach to quantify the impact of changes on construction projects using statistical regression and fuzzy logic (Hanna et al. 2002b). Lee et al. (2004) developed a decision tree model to classify and quantify the labor productivity losses due to the cumulative impact of changes for electrical and mechanical projects. Similarly, Moselhi et al. (2005) proposed the idea of evaluating the percentage loss of labor productivity due to changes with an artifical neural network. Yitmen et al. (2006) presented a prototype expert system to quantitatively model how different changes affect the time and cost of a project in North Cyprus construction industry. Motawa et al. (2007) integrated a fuzzy logic-based change prediction model with the system dynamics to evaluate the negative impacts of changes on construction performance and also discover the "cause-and-effect relationships" of the change events. Isaac and Navon (2008) created a change control tool to identify the scope of the implications of a change as soon as it is proposed. The feasibility of the tool in practice has been illustrated in several pilot studies (Isaac and Navon, 2008). Arian (2008) presented a knowledge-based decision support system for the management of changes in educational building projects in Singapore. The system was expected to assist project managers by providing accurate and timely information for their analysis and decision making of changes (Arian, 2008). Serag et al. (2010) created two regression models; and the models were used to estimate the impact of change on a contract price in heavy construction projects in Florida. Zhao et al. (2010) developed a change prediction model to help project management teams to manage project changes in a proactive and efficient manner. In the model, they relied on the activity-based dependency structure matrix (DSM) to model the process that may occur as a result changes, and then Monte Carlo Simulation to analyze the change probability of activities involved in construction projects (Zhao et al. 2010). Nahod and Radujković (2011) developed a Dynamic Planning and Control Methodology (DPM) to facilitate the objective decision making in approving changes in construction practice. Moreover, Ibbs (2012) studied hundreds of project data collected from the work of Leonard (1988) and Ibbs (2005), and produced a set of curves and reference points that indicate the relationships between the amount and likelihood of change and the amount and nature of its impacts.

Recently, the research studies of using BIM technologies to quantify the impact of a change on the project performance has been initiated. Building information model is a digital representation of building physical and functional characteristics, which is composed of digital objects corresponding to real world components such as doors, walls, and windows with associated relationships, attributes and properties (NBIMS, 2007; IBC, 2011). There are several benefits regarding the use of, including the better management of design documents and ability to simulate construction operations prior to physical implementation. Therefore, BIM is expected to help to trace the pattern in the changes that happen during the life cycle of a project and identify the types of changes (Akcamete et al. 2009; Koch and Firmenich, 2011). Langroodi and Staub-French (2012) presented a case study, which examined change management in the context of a multi-disciplinary collaborative BIM environment during the design and construction of a fast-track project. They found that it was possible to document numerous changes and identify their essential attributes with BIM (Langroodi and Staub-French, 2012). Based on these findings, they further developed an approach to represent, coordinate, and track changes within a collaborative multi-disciplinary BIM environment (Pilehchian et al. 2015). In addition, Liu et al. (2014) developed an integrated framework for embedding change management in BIM.

3. OBJECTIVE AND PROPOSED METHODOLOGY

The objective of this research study is to investigate the potential of using the BIM technologies to visualize, identify and analyze the ripple effects of a change and quantifies its impacts on the project cost and schedule. The basic idea is that the change requested by the owner or designer is first virtually implemented in the building information model. Then, the new model (i.e. as-changed model in this study) is compared with the original model (i.e. as-planned model). The comparison is conducted at the model component level. Therefore, the project work breakdown structure (WBS) is required to be defined at a micro level, where each component in the model has its own ID, location, time, and cost information, as shown in Figure 1.

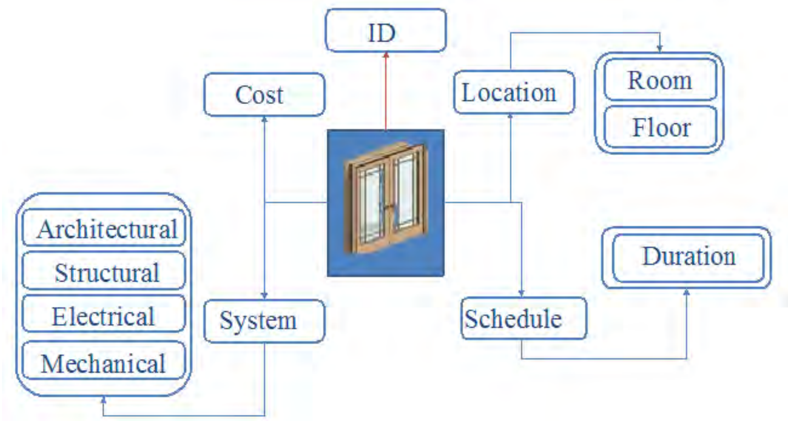


Figure 2: Composition of a Model Component

When a change has been requested in the as-changed model, the components directly affected by the change are identified through a simple component-by-component comparison. Specifically, both as-planned and as-changed models are checked. If the components are found in the as-planned model but not in the as-changed model, it means these components are removed by the change. If the components are found in the as-changed model but not in the as-planned model, these components are newly added by the change. If the components exist in both models, their specifications are further checked to find whether they are modified or not by the change. As a result, the direct impacts from the change are determined.

In addition to the direct impacts from the change, its ripple effects are also identified by finding the components indirectly affected by the change. In doing so, all the components that are connected to those directly affected by the change are detected. If the modifications are found on those components, they are recorded. Moreover, further detections are made on those components, until there are no more modifications that have been found in their connections. As a result, the list of all the components indirectly affected by the change could be produced. The design change path or the change sequence is determined. For each component due to the change, it can be classified into three categories: addition, deletion, and modification.

The way in which this occurs is thus: the proposed model traces indirect impacted components (via the ripple effect) by first finding the level (e.g. 1st floor) at which the selected direct change is located. The model then checks the components that are connected to the direct change in other levels, searching level by level until every floor is scanned. The model starts at the first level and finds connected components to the selected direct change, identifying all found components and matching component IDs with the component IDs in the impacted component database. Then it selects all the impacted components one by one and identifies the connected components in the next level (2^{nd} floor). This process is continued up the levels. From the components found in the next level, the model identifies the impacted components using the same matching process. Then it selects the first impacted component in the 2^{nd} level and finds the components that are connected to it in the next level (3^{rd} floor). The process is the same to the last level. When the proposed model gets to the last component in the last level it saves this path. Then it will follow the saved path to return to the first impacted component in the first level. There it selects the next impacted component in the first level and performs the same procedure to get to the last level and again get back to the first level by using the second saved path. The model again checks for the next impacted component till there are no more impacted components left in the first level that the selected direct change is connected to.

To summarize, the proposed model for each select individual direct change traces all the related components in the horizontal level and in then in the vertical level. It starts with one of the impacted components in the first horizontal level and it goes horizontally down levels till there are no more levels left and it finds the path of impacted component throughout all the levels; then it goes backward to get to the first level. Then, the same process is enacted for the all impacted components in the first horizontal level till there are no more impacted components in that level left. The ripple effect works as a tree diagram: on top of the tree the individual direct change is located, and in the other levels are all the other components that are connected to the direct change.

Based on the list of the components affected by the design change, the time and cost impacts on the project due to the change are quantified. The time impact analysis is to calculate the number of days that need to be added or reduced from the project's total duration. When a component is added or modified, the new duration for the component is estimated and inserted into the project schedule. When a component is deleted, its duration information is removed from the project schedule. Therefore, the project schedule is updated correspondingly.

Also, the cost incurred due to the change is estimated. They includes the direct cost, indirect cost, and impact cost, considering the change affects construction productivity on the components even if they are not modified in the project. The direct cost is composed of those from project labor, material, equipment, and sub-contractors. The indirect cost mainly includes project overhead. The impact cost here is focused on productivity and time-related ones that represent the loss of productivity on percentage change in the project. All the costs are added up to provide the basic project cost information about the change. It allows the project owner to compare the cost of the change with the project original cost to see if the requested change is beneficial or worth.

4. CASE STUDIES

The proposed methodology was developed as add-ons in the environment of Autodesk Revit 2014. The add-ons were implemented using the Revit Application Programming Interface (API). They could automatically 1) detect the changes between the as-planned and as-changed models; 2) detect the cause and effect relationship between the changed components in the model; 3) calculate and quantify the ripple effects in terms of project cost and schedule; and 4) filter the change impact reports.

The add-ons were tested in a three-story residential building with eight units in each level as shown in Figure 2. Three types of the changes were requested by the owner. The comparison between the as-changed and as-planned models was illustrated in Figure 3, where the red, green and yellow colors denote for the deletion, addition, and modification separately.

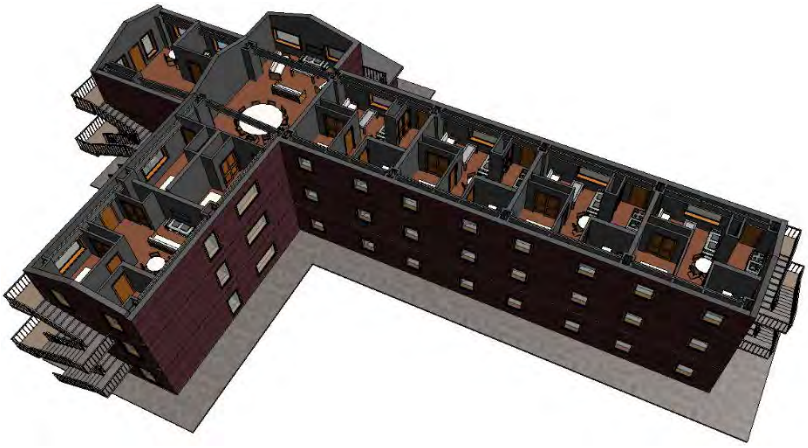


Figure 2: Model of a three-story building

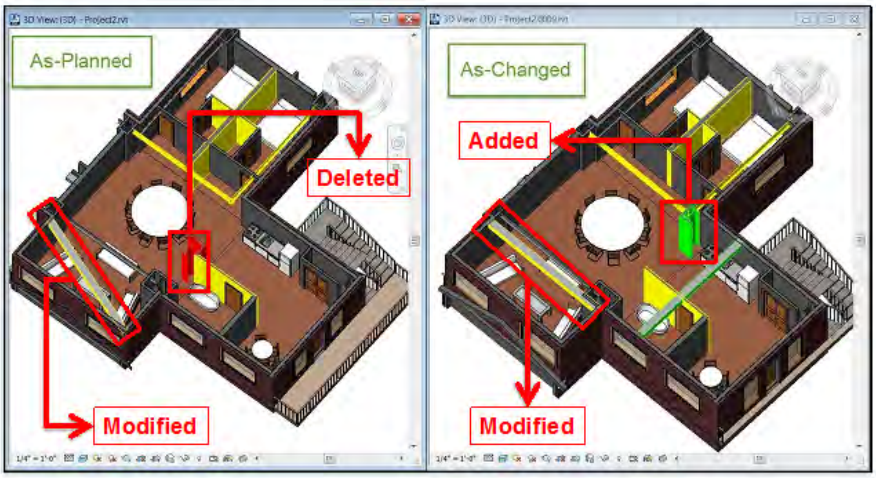


Figure 3: Comparison between as-planned model and as-changed model in a three-story residential building

Moreover, the ripple effects for those components that were impacted due to the design change could be highlighted. As shown in Figure 4, the ripple effects of each changed component are detected in the same area where the component is located as well as in the surrounding areas.

Figure 4: Ripple effects detected

Another case study (i.e. a one-story residential building with two units) was performed to check whether the impact of the change on the project could be quantified in terms of schedule and cost. In the case study, the original model was modified and the comparison between the as-planned model and as changed model was illustrated in Figure 5 and 6. Moreover, the comparison results were reported, where the modified and/or deleted components in the as-planned model were listed in one side and the modified and/or added components in the as-changed model were listed in the other side.

Based on the components added, modified and deleted in the report, the project schedule and cost were then updated correspondingly. The duration for each component impacted or non-impacted was calculated using the component's quantity information, as shown in Figure 7. In order to clearly describe the impacts of the change on project costs, the cost report is separated into different sections, as shown in Figure 7. Section 1 in the report estimated the cost of each impacted component. The type of the work and type of the impact specified in Section 2 was mainly used to estimate the productivity related and time related costs incurred due to the change. After the indirect cost of the project per day was manually input in Section 3, the total project costs due to the change were approximated. Compared with the original total projects, the owner was expected to make a wise and informed decision on whether the change should be approved or not.

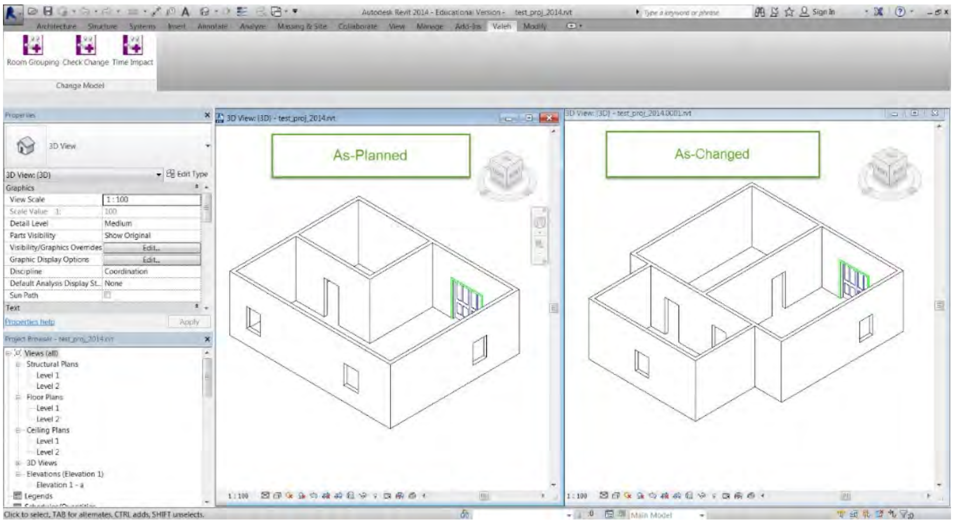


Figure 5: Comparison between as-planned and as-changed model in a one story residential building

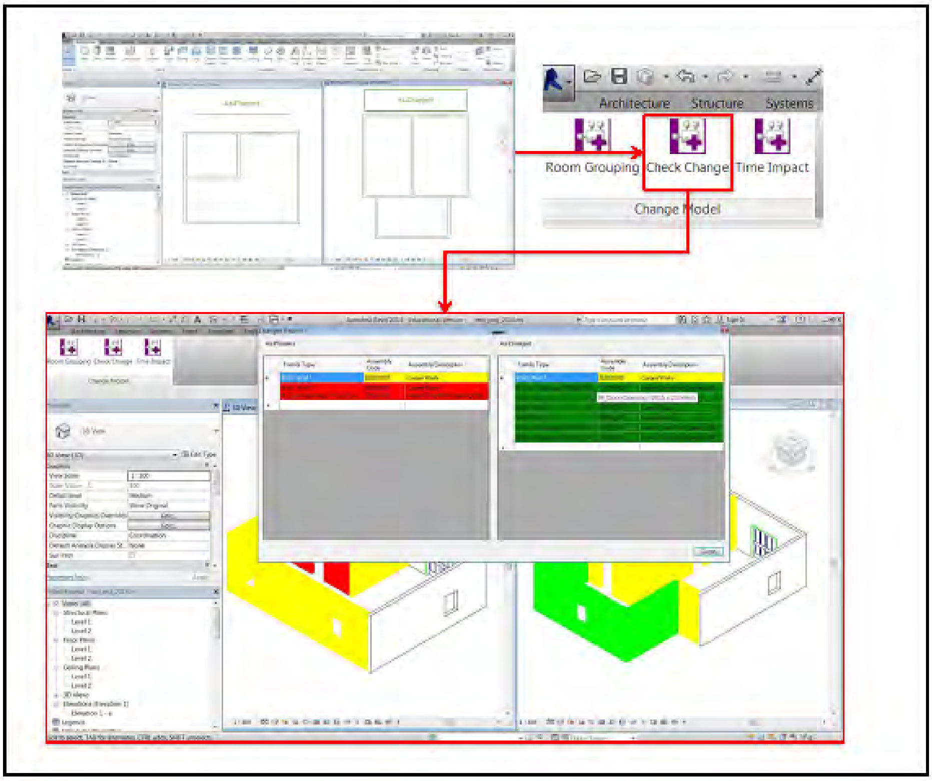


Figure 6: Impacted components due to the requested change

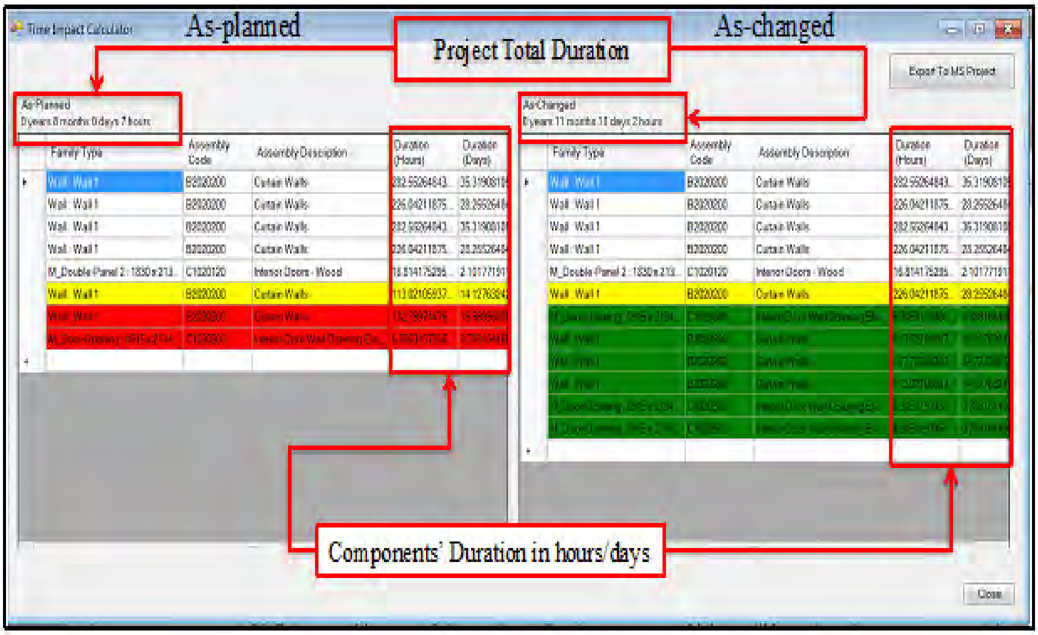


Figure 7: Durations of impacted and non-impacted components

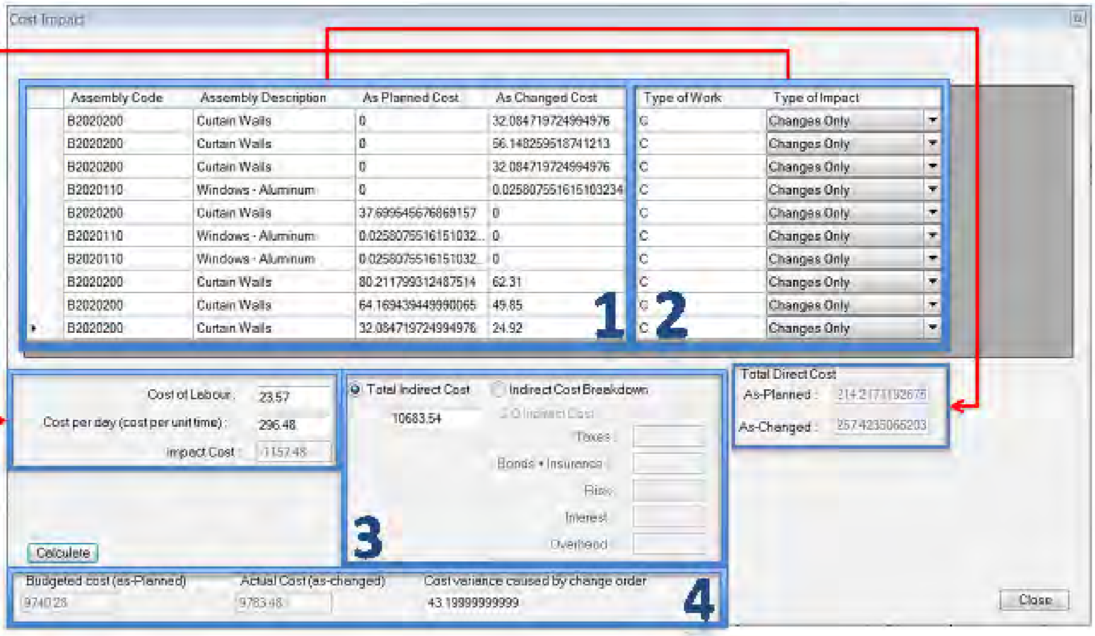


Figure 8: Project cost estimation due to the change

5. CONCLUSIONS

Owner-requested design changes are common in building construction projects. Understanding the ripple effects of the design changes is critical for the project owners to make rational decisions on finally approving the changes in construction projects. This paper investigated the potential of using BIM technologies to detect the ripple effects and quantify their impacts on the project performance in terms of schedule and cost. Specifically, potential design changes are virtually implemented to generate an as-changed model. The as-change model is further compared with the as-planned model to identify the change and its ripple effects. Moreover, their impacts are further considered to update the project schedule and budget correspondingly.

The proposed research work has been tested in two residential buildings. The comparison results between the as-planned model and as-changed model in each building showed that the building components affected by the changes could be detected, classified and visualized. Moreover, their impacts could be further quantified to update the project schedule and cost. The proposed research study is expected to help the project owner make a wise decision on requesting and approving design changes during the construction of a project.

6. REFERENCES

Akcamete, A., Akinci, B., Garrett, J. Jr. (2009). “Motivation For Computational Support For Updating BIMs.” 2009 ASCE International Workshop on Computing in Civil Engineering, Austin, Texas, U.S.: June 24-27, 2009.

Arain, F.M., and Pheng, L.S. (2005). “The Potential Effects of Variation Order on Institutional Buildings Projects.” Facilities, Vol. 23, No. 11/12, 496-510.

Arain, F. M. (2008). “IT-based approach for effective management of project changes: A change management system (CMS).” Advanced Engineering Informatics, Vol. 22, No. 4, 457–472.

Assaf, S.A. and Alheji, S. (2006). Causes of Delay in Large Construction Projects. International Journal of Project Management, Vol. 24, No. 4, 349–357.

CII (1994). “SP43-1 – Project change management.” <http://kb.construction-institute.org/Best-Practices/Change-Management/Topics/RT-043/pubs/SP43-1>

Chen, J.H. (2008). “KNN based knowledge-sharing model for severe change order disputes in construction.” Automation in Construction, Vol. 7, No. 6, 773–779.

Hegazy, T., Zaneldin, E., and Grierson, D. (2001). “Improving design coordination for building projects. I: information model.” Journal of Construction Engineering and Management, 127 (4), 322–329.

Hanna, A., Camlic, R., Peterson, P., and Nordheim, E. (2002a). "Quantitative Definition of Projects Impacted by Change Orders." Journal of Construction Engineering Management. Vol. 1, No. 57, 57-64.

Hanna, A., Lotfallah, W., and Lee, M. (2002b). "Statistical-Fuzzy Approach to Quantify Cumulative Impact of Change Orders." Journal of Computing Civil Engineering. Vol. 16, No. 4, 252-258.

Ibbs, C. and Allen, W. (1995). “SD-108 - Quantitative impacts of project change.” Research report SD-108, <http://kb.construction-institute.org/Best-Practices/Change-Management/Topics/RT-043/pubs/SD-108>

Ibbs, C.W. (2005). “Impact of Change’s Timing on Labor Productivity.” Journal of Construction Engineering and Management, Vol. 131, No. 11, 1219-1223.

Ibbs, C.W. (2012). "Construction Change: Likelihood, Severity, and Impact on Productivity." Journal of Legal Affairs and Dispute Resolution in Enginerring and Construction. Vol; 10, No. 1061, pp. 67-73.

Institute of BIM in Canada. (2011). Environmental Scan of BIM Tools and Standards. Canadian Construction Association. https://www.ibc-bim.ca/wp-content/uploads/2014/10/EnvironmentalScanBIMtoolsStandards.pdf.

Isaac, S. and Navon, R. (2008). "Feasibility Study of an Automated Tool for Identifying the Implications of Changes in Construction Projects." J. Constr. Eng. Manage., 10.1061/(ASCE)0733-9364(2008)134:2(139), 139-145.

Lee, M., Hanna, A., and Loh, W. (2004). "Decision Tree Approach to Classify and Quantify Cumulative Impact of Change Orders on Productivity." Journal of Computing Civil Engineering. Vol: 18, No. 2, 132-144.

Leonard, C. (1988). “The Effects of Change Orders on Productivity,” M.S. Thesis, Concordia University; Montreal, Quebec.

Liu, F., Jallow, A., Anumba, C., and Wu, D. (2014) A Framework for Integrating Change Management with Building Information Modeling. Computing in Civil and Building Engineering (2014): pp. 439-446.

Langroodi, B., Staub-French, S. (2012). Change Management with Building Information Models: A Case Study. Proceedings from the Construction Research Congress VI, 1182-1191.

Koch, C., and Firmenich, B. 2011. An approach to distributed building modeling on the basis of versions and changes. Advanced Engineering Informatics, 25 (2): 297–310.

Kumaraswamy, M. M. (1998). “Claims for Extensions of Time in Civil Engineering Projects.” Construction Management and Economics, Vol. 16, No. 3, 283-294.

Motawa, I.A., Anumba, J., Lee, S., Pena-Mora, F. (2007) "An integrated system for change management in construction." Automation in Construction. Vol: 16, No. 3, pp. 368–377.

Moselhi, O., Assem, I., El-Rayes, K. (2005), "Change Orders Impact on Labor Productivity." ASCE, Journal of Construction Engineering and Management, Vol: 131, No. 3, 354-259.

Mirshekarlou, B. R. (2012). “A Taxonomy for Causes of Changes in Construction.” (Master Thesis). The Middle East Technical University, Dept. of Civil Engineering.

Nahod, M. and Radujković, M. (2011, January) "Procedure for change management in the realization phase of construction projects.” Proceedings of the 27th Annual Conference of Association of Researchers. Bristol: United Kingdom.

National Institute of Building Sciences. (2007). United States National Building Information Modeling Standards - Version 1- part 1: Overview, Principals, and Methodologies. Retrieved from http://www.wbdg.org/pdfs/NBIMSv1_p1.pdf

Pilehchian, B., Staub-French, S., and Nepal, M. (2015). “A conceptual approach to track design changes within a mult-disciplinary building information modeling environment.” Canadian Journal of Civil Engineering, 2015, 42(2): 139-152, 10.1139/cjce-2014-0078

Serag, E., Oloufa, A., Malone, L., and Radwan, E. (2010). “Model for Quantifying the Impact of Change Orders on Project Cost for U.S. Roadwork Construction, Journal of Construction Engineering and Management.” Vol. 136, No. 9, 1015-1027.

Xue, X., Shen, Q., Fan, H., Li, H., and Fan, S. (2012). “IT supported collaborative work in A/E/C projects: A ten-year review.”, Automation in Construction, Vol. 21, Januaray 2012, pp. 1-9.

Yitmen, I., Sevay, H., Taneri, C., Yalciner, H. (2006). "An expert system for quantifying the impact of change orders on project performance." Proceeding from the oint International Conference on Computing and Decision Making in Civil and Building Engineering. Montréal, Quebec: Canada.

Zhao, Z., Lv, Q., Zuo, J., Zillante, G. (2010). "Prediction System for Change Management in Construction Project." Journal of Construction Engineering Management, Vol: 10, No. 1061, pp. 659-669.

A BIM-BASED FACILITY MANAGEMENT FRAMEWORK FOR AUTOMATIC SCHEDULING OF MAINTENANCE WORK ORDERS

Weiwei Chen, Keyu Chen and Jack C.P. Cheng

Department of Civil and Environmental Engineering

The Hong Kong University of Science and Technology, Hong Kong

Abstract: *Although facility management (FM) software and computerized maintenance management systems (CMMS) are available for facility maintenance management (FMM), they are currently used for solely storing and organizing information related to facility operation and maintenance (O&M), but not for making facility maintenance decisions directly. Therefore, the decision making process of scheduling a large number of facility maintenance work orders and tasks is still manual and tedious. As a relatively new field in the AEC/FM industry, building information modeling (BIM) has a great potential not only in visualization and management of rich information of building components in 3D models, but also in facilitation and optimization for facility O&M. This paper presents an automatic work-order scheduling framework based on BIM and FM software for efficient facility maintenance decision making. The framework connects FM software and BIM software for synchronizing facility components and work-order information in these two systems. It enables FM staff to check real-time maintenance work orders in BIM models and properly locate the corresponding components. Moreover, the developed work-order scheduling framework contains a dynamic programming engine based on modified Dijkstra's algorithm for finding the shortest maintenance path among broken components. The engine considers problem type, maintenance tools, emergency level and distances between broken components. It is an automatic decision making process to make maintenance management more convenient. A campus case scenario is presented to demonstrate the developed framework and validate the dynamic programming algorithm.*

Keywords: *Facility Maintenance, Facility Management, Building Information Modeling, Decision Making, Work-Order Scheduling*

1. INTRODUCTION

Facility management (FM) is an integrated approach to operating, maintaining, improving and adapting building and infrastructure assets in order to support the primary objectives of the occupants, owners and facility managers (Atkin & Brooks, 2009). Among FM, facility maintenance management (FMM) accounts for more than half of the cost in the whole building lifecycle (Lavy & Jawadekar, 2014). Facility maintenance can be supported by computerized maintenance management systems (CMMS) and FM software as fundamental information resources, providing FM staff (facility managers and maintenance workers) with a wealth of support-related information as well as assisting management in decision making. Currently, there are many FM software in the market (e.g. ARCHIBUS, FM system, Maximo, EcoDomus, etc.), which are available to manage the building maintenance process and provide a more organized information platform. They are usually used to store, retrieve, and manage facility information related to building components and assets, such as inventory list, installation date, working request, maintenance work orders, etc. However, the function of these software ignores the fact that when FM staff are planning the schedules of a large number of work orders, the process still heavily relies on manual decisions.

In addition, facility maintenance scheduling is time-consuming and complicated, and sometimes it also leads to some errors when lots of maintenance work orders need to be done and broken components are located in different places. A comprehensive maintenance scheduling involves maintenance work orders, building component type, location, building component dimension, maintenance problem type, the time needed, tools needed, urgency level, etc. In fact, part of the information can be stored in CMMS/FM software, while the other part of information, such as component dimensions and floor plans, is traditionally stored in 2D drawings. However, FM staff using 2D drawings in FMM need to spend much time on searching information for scheduling maintenance work orders. For instance, some components are maintained or replaced after handover and their dimensions are changed. As a result, FM staff cannot access accurate information according to 2D drawings.

Currently, building information modeling (BIM) is an intelligent model-based process that facilitates the management of buildings and civil infrastructures. It creates a digital database of all building assets and can support virtual 3D coordination of construction and operational activities, including operation and maintenance (O&M). BIM can be used to track, update, and maintain facility management information to support better planning, operations, and maintenance decision-making throughout a building lifecycle. Therefore, BIM has a large potential value for FM, for example, in visualization of broken components, acting as an information hub, and showing the shortest maintenance path. On the other hand, FM software has many functions, such as registering building and asset data, planning and execution of facility processes, workflow management, etc. Moreover, FM software is able to integrate with other IT systems like ERP software, GIS solutions, or CAD software to extend their functions. This paper aims to leverage these advantages of BIM and FM software to close the gap that FM staff have difficulties to access accurate location information of broken components and that they always manually schedule the maintenance work orders.

Therefore, this paper proposes an integrated BIM-FM framework for automatic scheduling of maintenance work orders for facility maintenance management, which is user-friendly, efficient and object-based. The framework enables FM staff to visualize corresponding maintenance work orders in BIM and achieve automatic decision making for maintenance scheduling. This paper is organized as follows. Section 2 provides literature review of facility maintenance, BIM, and work-order scheduling. Section 3 explains the methodology, including the proposed BIM and FM integration framework and work-order scheduling algorithm, followed by a demonstrative example in Section 4. Finally, the whole study is concluded in Section 5.

2. LITERATURE REVIEW

2.1 Facility Maintenance and BIM

There are some studies related to facility maintenance decision making. For example, Lee et al. (2013) proposed a multi-agent system that automates data gathering to monitor condition of facilities. However, the system did not combine 3D technology to visualize the facility as well as maintenance records. Among the facility management areas, some researchers have tried to apply 3D visualization technology to visualize facilities targeted for facility management including spatial navigation systems established for museums, campuses, and cities (Tamada et al., 1994). However, the functionality of 3D visualization in these systems is limited to navigating the overview of a facility. Mozaffari et al. (2005) devised a 3D CAD model for subordinate construction facilities by using virtual reality technology. Chen et al. (2013) presented an expert system model for the maintenance and management of existing facilities in a 3D facility model, and they also proposed a database schema to facilitate decision making during maintenance. These studies only applied 3D visualization technology to support the operation and management of facilities, thus have not yet been integrated with analytical functions as intelligent systems to support decision-making in FMM.

In as-built BIM models, every element of design may entail geometric information (dimension, location, etc.) and semantic information (serial number, product data, maintenance manuals, warranty data, etc.). As-built models play a key role in successfully using BIM during the O&M phases of buildings and civil infrastructures. Recent studies have identified the advantages and requirements of BIM to support building maintenance (Becerik-Gerber et al., 2011; Motamedi et al., 2014). McArthura (2015) proposed a BIM framework and illustrated a case study to show that there are many challenges when using BIM model for building operations, maintenance and sustainability. In addition, some researchers pay attention to conducting maintenance management using advanced technology. For example, BIM and GIS (Geographical Information System) are used to improve the maintenance process of railways (Shr & Liu, 2016). However, among these studies, maintenance scheduling has been largely ignored when people try to leverage BIM for FM, and there is little research about integrating BIM and FM to automatically schedule maintenance work orders.

2.2 Work-Order Scheduling

Currently, CMMS work is mainly based on regular services. Traditionally, maintenance work-order records are used by finance department of enterprises for cost control (Gupta & Gandhi, 2014). On the other hand, the maintenance planners use the historical records of maintenance work orders for estimation of resources for subsequent maintenance activities. Some researchers have applied equipment classification systems, preventive maintenance (PM) scheduling models, and work-order management systems for prioritizing repair requests for industrial facilities and manufacturing companies (Grigoriev et al., 2006; Pongpech & Murthy, 2006). For example, Xu et al. (2002) studied an agent-oriented approach to manage work orders for circuit breaker maintenance. Hamdi et al. (2012) designed an intelligent healthcare management system, and proposed a work-order prioritization model for medical equipment maintenance requests. However, there is little research related to maintenance work-order scheduling in buildings and civil infrastructures.

Scheduling problem is a part of many problems in logistics operation (Karger et al., 1998). The most commonly used methods for work-order scheduling of repair requests are variants of the first-come, first-served (FCFS) method. While the FCFS approach might be acceptable for many applications, it is not always appropriate when applied to the maintenance scheduling. For example, when a vital machine undergoes failure and it is out of service, it may lead to serious consequence, and the machine should be fixed as early as possible.

Moreover, work-order scheduling problems in practical situations are very complex. Usually these problems cannot be solved by classical optimization algorithms in a suitable time. Lewandowski et al. (2013) studied a new methodology to prioritize event-driven maintenance workloads driven by information from condition monitoring systems, and Gupta & Gandhi (2014) proposed a genetic algorithm to rebuild an existing working plan automatically. However, these methods are not built in intelligent FM software and BIM model to directly visualize the result in a 3D facility model. Besides, they do not consider the real 3D scene, such as the distances between maintenance sites and emergency level.

Therefore, the following section will present an integrated BIM-FM framework to realize the automatic maintenance work-order scheduling, which uses a modified Dijkstra algorithm based on different factors.

3. METHODOLOGY

3.1 BIM and FM Integration Framework

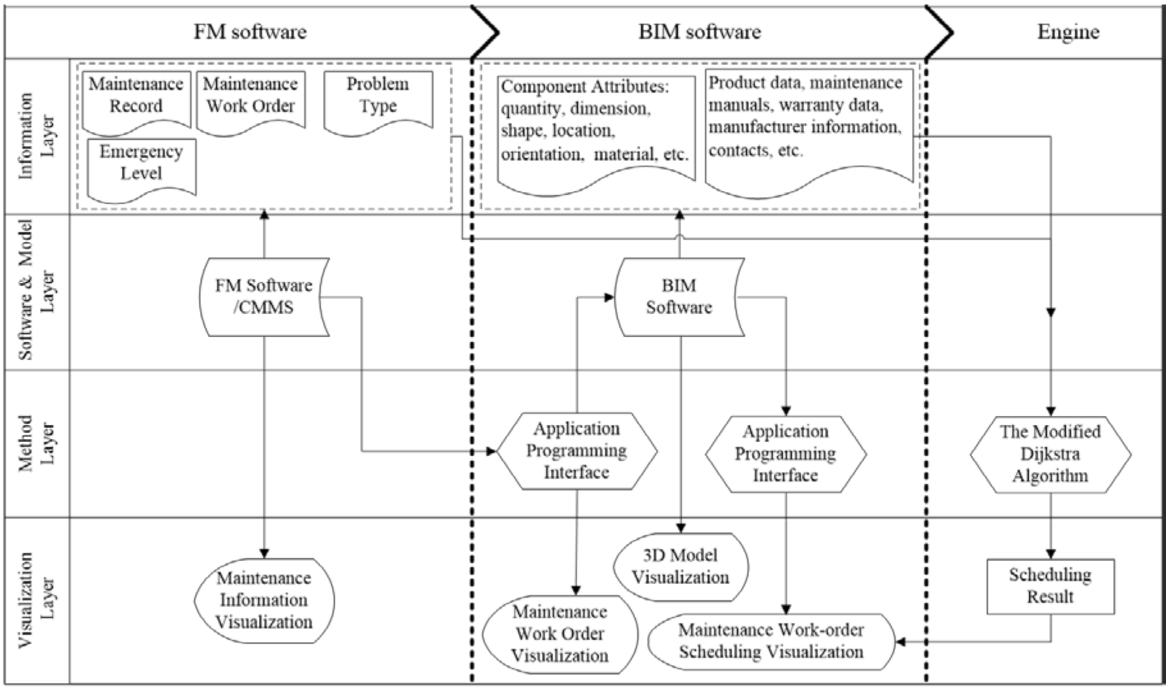


Fig. 1: The proposed BIM-based framework for automatic maintenance work-order scheduling

Fig. 1 illustrates the proposed BIM-FM integration framework for automatically scheduling facility maintenance work orders. The process is supported by FM software/CMMS and BIM software. Specifically, in the information layer, FM software provides information such as emergency level, problem type, maintenance work orders, maintenance records, etc. BIM models generally contain information of quantity, dimension, shape, location, orientation, and material of different facility components. Moreover, BIM model can include more detailed information, such as product data, maintenance manuals, warranty data, manufacturer information and contacts. Therefore, BIM models provide rich information to be integrated with FM software or CMMS for planning facility maintenance tasks.

The majority of FM software, such as ARCHIBUS and Maximo, are based on web browsers. The data in FM software are usually stored in an external FM database. BIM models are object-based and information-rich. Geometric information of facility components can be maintained and modified in BIM models. Frequent data exchange between BIM software and FM is needed because maintenance activities are common. Therefore, in the method layer of the developed framework, an API (application programming interface) connecting FM software and BIM software is developed, and it is used to get the real-time maintenance records and work orders from FM software and show this information in BIM software. Meanwhile, the element ID acts as the key to retrieve required data from FM database. In this way, FM staff can select a broken component in a BIM model as well as view the corresponding maintenance records and work orders. Moreover, the API enables FM staff to easily locate broken components in 3D environment and obtain distances among broken components using measurement tool in BIM, even though they are located on different floors. The distance obtained from BIM models can be used in the following scheduling part.

After checking broken components in BIM models, FM staff can directly get maintenance work orders and component attributes from the information layer. These information and the distances between different broken components act as the input for maintenance scheduling. The Dijkstra algorithm is used and modified in this framework to automatically schedule the maintenance work orders for FM staff. The scheduling algorithm is showed in Section 3.2. Finally, the generated maintenance schedule is visualized in another API of BIM software for FM staff.

3.2 Work-Order Scheduling Algorithm

Before scheduling maintenance work orders, one needs to identify the kind of necessary information that will be used and the factors that should be considered. The scheduling problem is then formulated into a mathematic expression. In this paper, the work-order scheduling problem is formulated as a symmetric Travelling Salesman Problem (TSP) because scheduling maintenance work orders also follows the principle of finding the shortest path. TSP is an NP-hard problem in combinatorial optimization, important in operations research and theoretical computer science. The work-order scheduling problem is a symmetric one because the distances between facility maintenance tasks are the same for both directions. Therefore, the work-order scheduling can be represented as an undirected graph.

Dijkstra's algorithm is an algorithm for finding the shortest path between nodes in a graph, which may represent, for example, road networks. It was conceived by a computer scientist in 1956 and published three years later (Dijkstra, 1959). Due to the complexity of TSP, the problem was simplified to be solved by the Dijkstra’s algorithm in order to find the shortest path from each of the unfinished working orders. The whole scheduling problem is broken down to several shortest path sub-problems, in which Dijkstra’s algorithm is applied to each connection in order to find the shortest path to the next point. Based on the methodology of heuristic algorithm – combination of dynamic programming concept and the Dijkstra’s algorithm, a modified Dijkstra algorithm is developed in this study to achieve automated decision making of the work-order scheduling problem.

In the process of calculating maintenance schedule using the modified Dijkstra algorithm, several important factors should be considered, including emergency level, problem type, maintenance working time, and distance between components. The proposed formula to calculate the shortest path in programming and the modified calculation steps are shown as follows. Besides, to use this solution, a distance matrix for all the work orders needs to be inputted.

a. Formula explanation

$$MC_0 = (B, \emptyset) = W_{AB} = x(A) \tag{1}$$

where: MC_0 represents the minimum cost; A and B represent the origin and the destination respectively; $\emptyset$ represents via point; W_{AB} represents the distance from A to B. The formula means that the minimum cost from A to B finally via no other point equals the distance from A to B which is x. Under such route, A is the predecessor of point B.

b. Calculation steps

Step 1: Identify the broken components to be maintained.

Step 2: Calculate the distances between each two components.

Step 3: Generate the distance matrix.

Step 4: Consider the broken components with the highest emergency level first. Maintenance workers need to go back to warehouse and change tools if the current working order type is different from the next one, which will increase the total distance cost.

Step 5: Find the shortest path among these components with the highest emergency level using above formula.

Step 6: Repeat Step 4 and Step 5 to consider the broken components with the second highest emergency level, until all broken components are calculated.

Step 7: Generate the maintenance schedule in BIM.

4. DEMONSTRATIVE EXAMPLE

4.1 The Maintenance Process in Demonstrative Example

In this study, the library building in the Hong Kong University of Science and Technology (HKUST) was selected as the demonstrative example. The HKUST library is a five-storey building with floor area of 12,350 square meters. With a strong focus on technology and network access, the library building contains various facilities and equipment for computing, digital applications, enhanced information retrieval, and wireless network connectivity. The HKUST library had 1,064 maintenance tasks in the year 2014/15 only. The maintenance work of HKUST library is currently managed in the reactive manner using solely 2D floor plans, an online reporting system and paper-based inspection data. Based on interviews and data collected from the HKUST library facility manager, several existing problems have been identified with the on-going maintenance working process. Fig. 2 shows the current routine maintenance process for the HKUST library. HKUST library is maintained by the Facility Management Office (FMO) of HKUST.

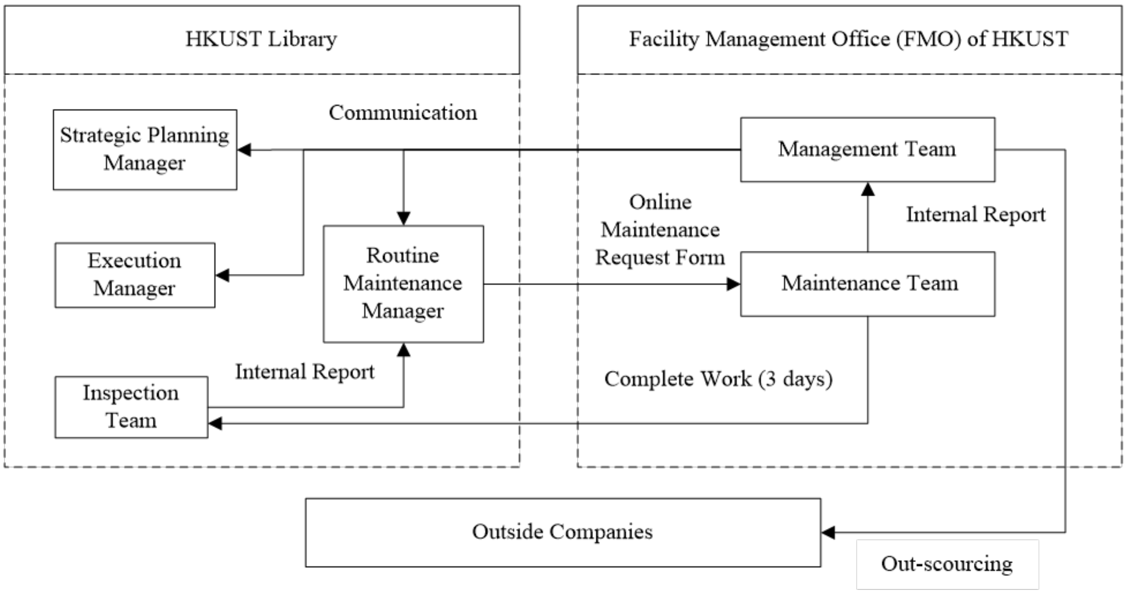


Fig. 2: The current routine maintenance process for the HKUST library

In this process, the facility manager of maintenance team at FMO decides the maintenance schedule according to his own experience. When there are many maintenance work orders, it is complicated for the facility manager to decide the maintenance schedule. Although FMO has been using Maximo for asset management, its main value is to collect and organize information of assets for facility manager, not including intelligent decision makings for facility maintenance management. Facility managers and staff can schedule the pending work orders but the decision is often subjective because many quantitative factors may not be considered. Needless to say that it also takes too much time. Other campus buildings also have similar problems with the library building. Therefore, the proposed framework was applied to address the existing problems in the library and other campus buildings.

4.2 Model Creation

In this demonstrative example, Autodesk Revit is used as the BIM platform whereas ARCHIBUS is used as the FM software for illustrative purpose. A BIM model of the HKUST library, as shown in Fig. 3, was created using Autodesk Revit to improve the 3D environment. The BIM model acts as a visual representation that can be used to integrate with FM software for locating broken components and for checking their corresponding maintenance work orders.

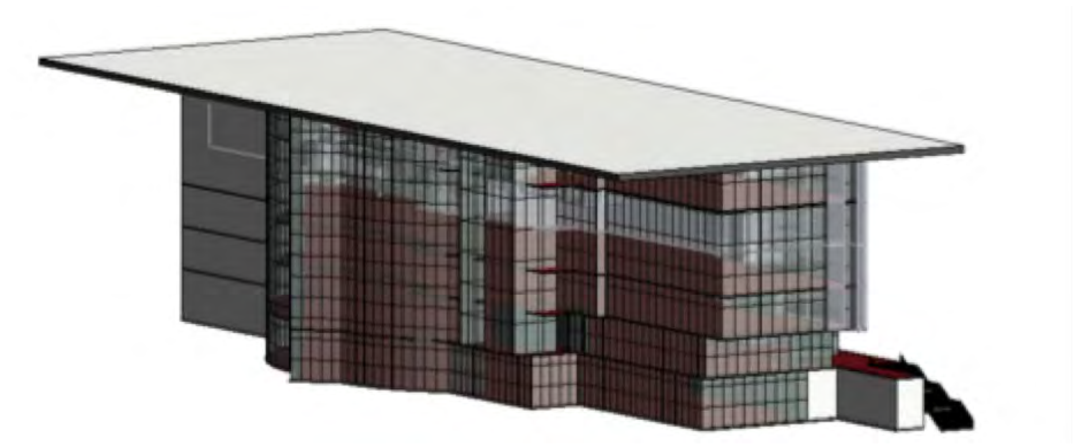


Fig. 3: The Revit BIM model of the HKUST library

4.3 Checking Broken Components in BIM Model

With a comprehensive BIM model containing component information and facility maintenance information, FMO staff could easily get access to attributes of broken components such as manufacturer information, purchased time and material information of the broken components. In order to show the corresponding maintenance work orders and the condition of each component, a user interface was developed using Revit API for integrating BIM and FM software. As shown in Fig. 4, when FMO staff click a component in Revit, maintenance information such as work-order ID, building ID, problem type, location, is showed in the developed interface. It is more convenient and information-rich than using only FM software for FMO staff to conduct facility maintenance management.

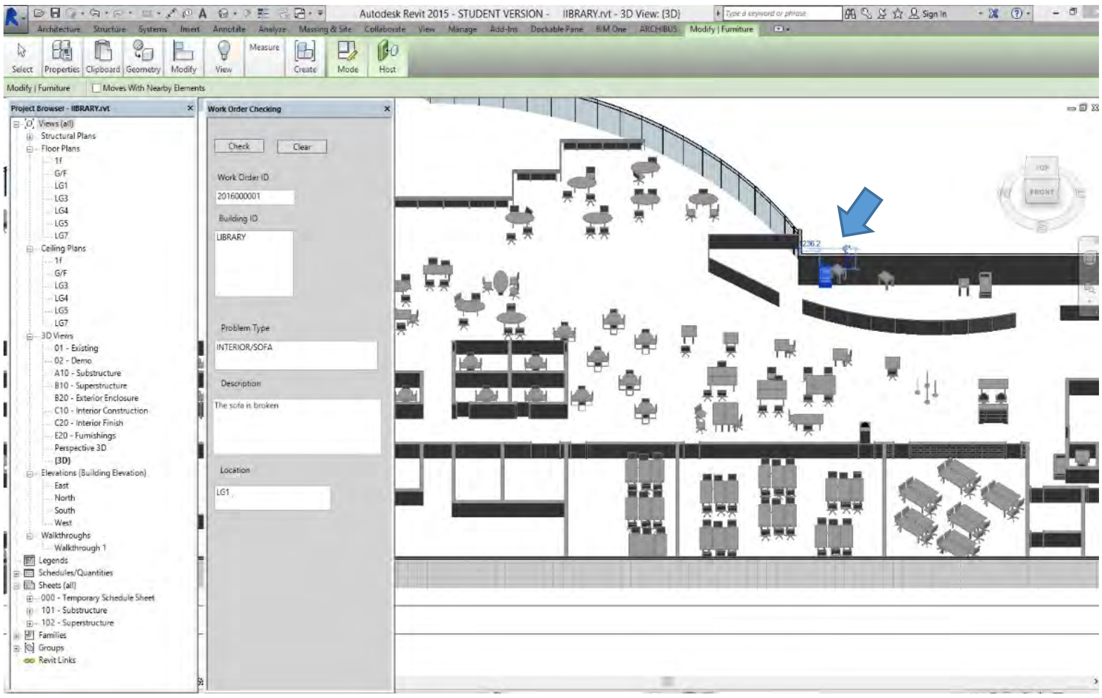


Fig. 4: Condition checking of the selected broken component using the developed interface in Autodesk Revit

4.4 Automatic Maintenance Work-order Scheduling

After identifying existing broken components and obtaining the maintenance work-order information in BIM models, FMO staff need to have a maintenance plan using the work-order scheduling algorithm. In fact, the maintenance staff need to maintain, repair or replace building components on the whole campus. In order to reflect the actual maintenance scheduling problem, a real maintenance case on HKUST campus was chosen.

The work-order information of demonstrative example is shown in Table 1. The notation, emergency level, problem type and working time of each task are obtained from FM software. The locations of components are obtained from Revit and distances among them are transferred into walking time. To obtain the walking time between two locations, we actually walked from one location to the other and recorded the time it took. Besides, there are three emergency levels. Emergency level I is the most urgent while level III is the least. Level I means the problem continues to cause damage. Level II means no further damage but the problem interrupts the daily operations. Level III represents no further damage and the broken components can be temporarily substituted by other facilities.

Fig. 5 (a) illustrates the locations of broken components on the HKUST campus map for the demonstrative example, whereas Fig. 5 (b) shows the walking time diagram of the demonstrative example. Note that the numbers in Fig. 5 (b) represent the walking time between two locations, and the unit is minute. Because task sites are located on different floors, these lines do not represent real distances.

Table 1: Demonstrative example information

Tasks notation	Location	Emergency Level	Problem Type	Working Time (min)
A	FMO Office, Lift 15 5/F			
X	Warehouse			5
B	Library G/F female toilet	I(high)	Water leakage	120
C	Library LG3	I	Electric wire burnt	60
D	Room 5619, Lift 31 5/F Window	I	Electric wire burnt	60
E	Library LC	II	Glass broken	45
F	LT-A	II	Light bulb burnt	15
G	LT-D	II	Light bulb burnt	15
H	Bridge Link	III(low)	Repair	20
I	UG Hall 2	III(low)	Repair	20

J	Library Entrance	III(low)	Repair	20

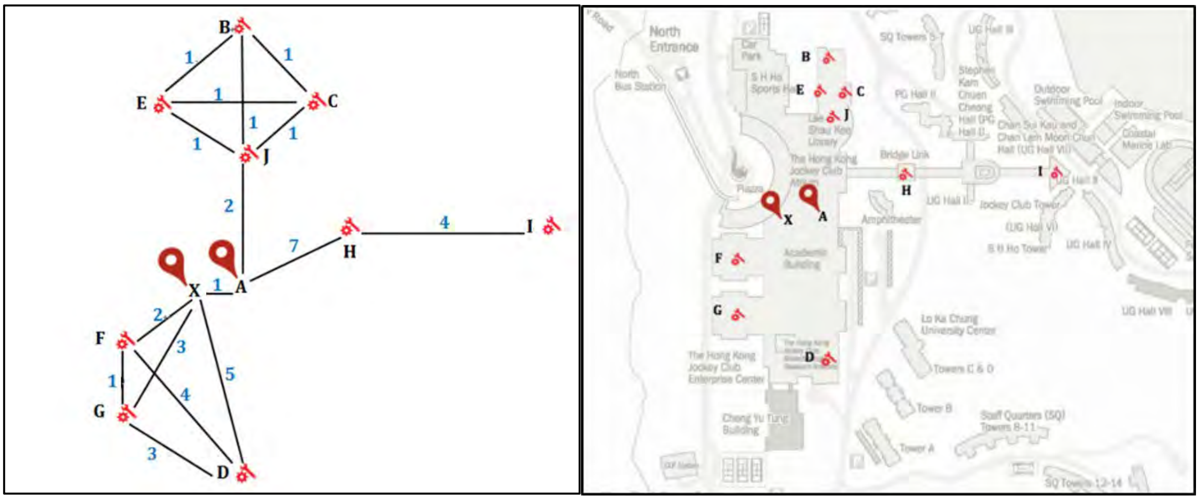
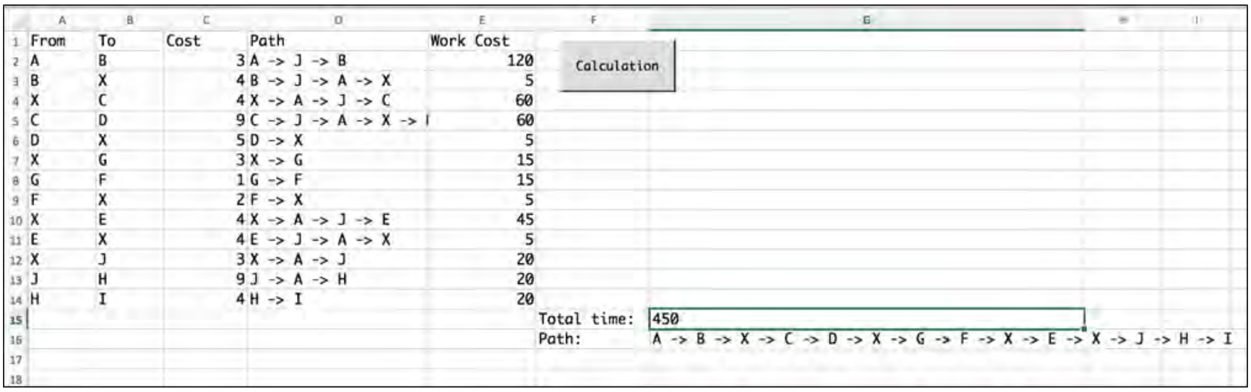


Fig. 5 (a) Location of the sites (b) Diagram showing walking time (in minutes) between different locations in the demonstrative example



From	To	Cost	Path	Work Cost
A	B	3	A -> J -> B	120
B	X	4	B -> J -> A -> X	5
X	C	4	X -> A -> J -> C	60
C	D	9	C -> J -> A -> X ->	60
D	X	5	D -> X	5
X	G	3	X -> G	15
G	F	1	G -> F	15
F	X	2	F -> X	5
X	E	4	X -> A -> J -> E	45
E	X	4	E -> J -> A -> X	5
X	J	3	X -> A -> J	20
J	H	9	J -> A -> H	20
H	I	4	H -> I	20

Calculation

Total time: 450

Path: A -> B -> X -> C -> D -> X -> G -> F -> X -> E -> X -> J -> H -> I

Fig. 6: Work-order scheduling result automatically generated for the demonstrative example

According to the map and distances (walking time) between different location points, the distance matrix is generated. The distance matrix and other factors (emergency level, problem type, location, etc) act as the inputs of the modified Dijkstra algorithm. Eventually the maintenance scheduling and total maintenance time are automatically generated for FMO staff to conduct maintenance, as illustrated in Fig.6.

5. CONCLUSION

This paper proposes a framework that integrates BIM software and FM software to improve the decision making process for FM staff in facility maintenance management. A user interface was developed in BIM software to show the corresponding work-order information of each broken component in buildings, and the Dijkstra algorithm was modified to realize automatic work-order scheduling. Besides, another user interface that shows the scheduling result was developed. Finally, an illustrative example was demonstrated using this proposed framework to validate the feasibility.

In this paper, the walking time was obtained manually by physically walking different paths on the HKUST campus. In the future, a method to automatically calculate distances and travel time between different locations on different floors based on BIM will be studied.

Acknowledgement

The authors would like to thank the partial support for this research that was provided by the Innovation and Technology Fund (ITP/047/15LP).

REFERENCES

Atkin, B, & Brooks, A. (2009). Total Facilities Management, 3rd edit: Wiley-Blackwell (ISBN: 9781405186599).

Becerik-Gerber, Burcin, Jazizadeh, Farrokh, Li, Nan, & Calis, Gulben. (2011). Application areas and data requirements for BIM-enabled facilities management. *Journal of Construction Engineering and Management,* 138(3), 431-442.

Chen, Hung-Ming, Hou, Chuan-Chien, & Wang, Yu-Hsiang. (2013). A 3D visualized expert system for maintenance and management of existing building facilities using reliability-based method. *Expert Systems with Applications,* 40(1), 287-299.

Dijkstra, Edsger W. (1959). A note on two problems in connexion with graphs. *Numerische mathematik*, 1(1), 269-271.

Grigoriev, A., van de Klundert, J., & Spieksma, F. C. R. (2006). Modeling and solving the periodic maintenance problem. *European Journal of Operational Research*, 172(3), 783-797. doi: 10.1016/j.ejor.2004.11.013

Gupta, Piyush, & Gandhi, OP. (2014). Equipment redesign feasibility through maintenance-work-order records using fuzzy cognitive maps. *International Journal of System Assurance Engineering and Management*, 5(1), 21-31.

Hamdi, Naser, Oweis, Rami, Zraiq, Hamzeh Abu, & Sammour, Denis Abu. (2012). An intelligent healthcare management system: A new approach in work-order prioritization for medical equipment maintenance requests. *Journal of Medical Systems*, 36(2), 557-567.

Karger, D, Stein, C, & Wein, J. (1998). *Handbook of Algorithms and Theory of Computation*, chapter Scheduling Algorithms: CRC Press.

Lan, J. H. (2016). Developing BIM-enabled facility management information system in interior design. *In International Conference on Human Aspects of IT for the Aged Population* (pp. 57-69). Springer International Publishing.

Lavy, S., & Jawadekar, S. (2014). A case study of using BIM and COBie for facility management. *International Journal of Facility Management*, 5(2).

Lee, Jae-Hoon, Lee, Myung-Soo, Lee, Sang-Hoon, Oh, Se-Ghok, Kim, Bo-Hyun, Nam, Sung-Ho, & Jang, Joong-Soon. (2013). Development of computerized facility maintenance management system based on reliability centered maintenance and automated data gathering. *International Journal of Control and Automation*, SERSC, 6(1), 1-12.

Lewandowski, M., Siebenand, O., Oelker, S., & Scholz-Reiter, B. (2013). Maintenance work order based on event-driven information of condition-monitoring systems—a Genetic Algorithm for scheduling and rescheduling of dynamic maintenance orders. *In Dynamics in Logistics* (pp. 395-404). Springer Berlin Heidelberg.

McArthur, J. J. (2015). A building information management (BIM) framework and supporting case study for existing building operations, maintenance and sustainability. *Procedia Engineering*, 118, 1104-1111.

Motamedi, Ali, Hammad, Amin, & Asen, Yoosef. (2014). Knowledge-assisted BIM-based visual analytics for failure root cause detection in facilities management. *Automation in Construction*, 43, 73-83.

Mozaffari, E., Hammad, A., & El-Ammari, K. (2005). Virtual reality models for location-based facilities management systems. *In Proceedings of the 1st CSCE Specialty Conference on Infrastructure Technologies, Management and Policy*.

Pongpech, Jarumon, & Murthy, DNP. (2006). Optimal periodic preventive maintenance policy for leased equipment. *Reliability Engineering & System Safety*, 91(7), 772-777.

Shr, Jin-Fang, & Liu, Li-Shih. (2016). Application of BIM (Building Information Modeling) and GIS (Geographic Information System) to railway maintenance works in Taiwan. *Journal of Traffic and Transportation Engineering*, 4, 18-22.

Tamada, T., Nakamura, Y., & Takeda, S. (1994). An efficient 3D object management and interactive walkthrough for the 3D facility management system. *In Industrial Electronics, Control and Instrumentation*. IECON'94, 20th International Conference on (Vol. 3, pp. 1937-1941). IEEE.

Xu, X., Kezunovic, M., & Wong, D. (2002). Agent-oriented approach to work order management for circuit breaker maintenance. *In IEEE PES Summer Meeting*.

Part III: BIM, GIS and Urban Computing

THE INTEGRATED SLOPLAND CONSERVATION AND DISASTER PREVENTION MANAGEMENT SYSTEM, TAIWAN

Kuei-Lin Fu & Yu-Te Chou

Soil and Water Conservation Bureau, Taiwan

National Taiwan University, Taiwan and Geoforce Technologies Co., Taiwan

Shih-Chung Kang, Men-Han Tsai and Kun-Che Chen

National Taiwan University, Taiwan

National Taiwan University, Taiwan

Soil and Water Conservation Bureau, Taiwan

ABSTRACT: This research develops a conservation and disaster prevention management system to improve governance and information transparency for integrated slopeland. The Soil and Water Conservation Bureau promotes comprehensive slopeland management and disaster prevention efforts in Taiwan and expects to publish and pin exact locations on maps for the purpose of data searching and to avoid data recollection. The two challenges of developing this system include: (1) there are millions of reports and data owed to summit with each separately stored in different departments; and (2) there are a variety of data formats, which hinders its presentation in a user-friendly way, and it is a data security risk. The Bureau and the Geoforce Technologies Co initiated a collaborative research project. The project adopted the Google Earth Enterprise system to efficiently integrate data and provide 2D, 3D, and chronological information for display and search functionality. It can protect data from being copied, rewritten, and reproduced as well as ensuring continuous functionality. Also, this system was built for autonomous use and to enable the private sector to upload the latest data to be examined by administrators. Data Driven Documents (D3) is a JavaScript data visualization library that has been applied to enhance its visual performance. The feasibility of this system was experimented when the Lotus, Soudelor, and three other typhoons occurred in 2015 and with its in-time service and interactive search tools proved that it can produce solid evidence that it supports decision making. With this system, Taiwanese professional associations, engineering construction companies, the departments of soil and water conservation of 23 local authorities, and six sub-bureaus can utilize this information to identify vulnerable areas, monitor sensitive places, and plan disaster relief actions. Most of all, the knowledge of geographic information and upcoming incidents will enable populations to prepare for evacuation in advance.

KEYWORDS: *3D Geographic Information System, Big Data, Integration of Published Information, Governance and Transparency, Cross-platform application, Autonomous System, Location-Based Service*

1. Purpose

Conservation and control works of Soil and Water Conservation Bureau (SWCB) at Council of Agricultural of Executive Yuan include watershed area overall investigation, planning and promotion; torrent above watershed and river juncture soil and water conversation planning, conservation, control and supervision; planning, coordination and promotion of erosion and sediment control and slopeland disaster emergency operation; slopeland soil and water conservation and erosion and flood protection project planning, coordination and promotion; watershed area above reservoir storage range conservation planning, coordination and promotion; slopeland soil and water resource conservation planning, guidance and promotion; slopeland afforestation planning, research, development, promotion and supervision; engineering, administration, set up construction contract sample and construction standard; construction schedule control and quality management planning and supervision, etc.

In addition to construction, the system of relevant conservation control works on engineering management includes “watershed control plan information integrate system”, “soil and water control engineering management and assessment system”. Relevant information includes conservation control enforcement plan, engineering basic information, watershed area overall investigation and planning, etc. As the volume of business system and information was great, SWCB began establishing physical data geological storage center, archiving spatial information acquired from all projects since 2006. In 2010, the theme data reached peak volume at 6,196 files. The Central Government began promoting resource sharing and Open Data et al policies in 2013, and SWCB focused mainly on producing information of SWCB business and thus slowed down the data accumulation. In 10 years, by annual average, SWCB collected 2,547 files, which was great amount of spatial information. However, there was no horizontal communication channel and standard in such a volume, and there also lacked the ability in spatial management and planning.

The current erosion and sediment control disaster prevention could no longer rely on single management mechanism for controling and needing diversified resources integration with 3D mapping service for larger range conservation control planning; a mechanism of horizontal database also needs to be established for mutual application and integration for the management to be conducted through single integrated decision making platform. SWCB therefore established Data Driven Document (D3) in 2013, hoping to use the N to 1→1 to N concept to integrate complex data and system into one platform for management. This single platform would provide multiple device service, allowing users to conduct relevant business promotion.

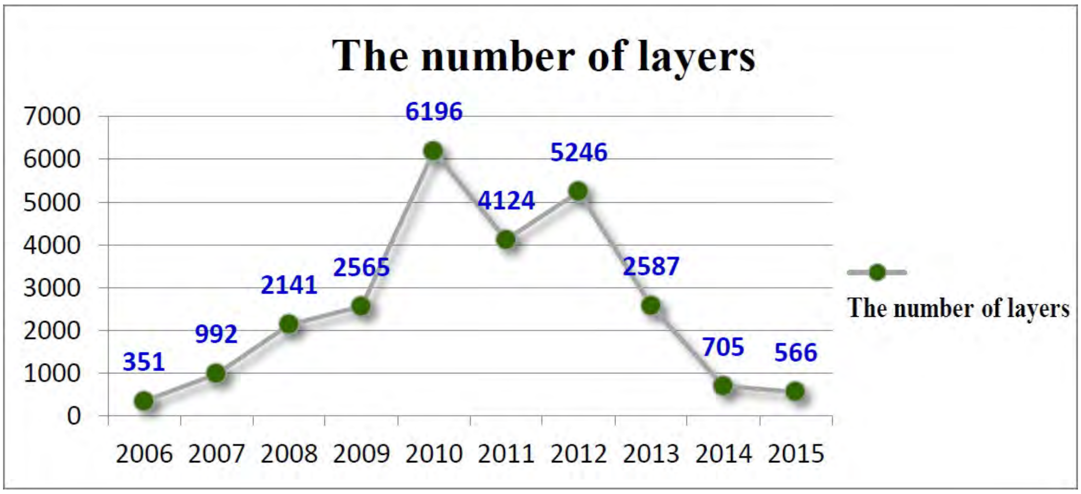


Figure 1. 2006 to 2015 spatial information volume statistics

2. D3 system development goal

Besides integrating Soil and Water Conservation Bureau conservation and control information, the development of D3 was also in concern with the system sustainable developing mechanism and thus the stages of D3 standard format were defined from “key area control”, “control strategy and enforcement” to “result of control”, etc. procedures. D3 functionality establishment was entrusted to corresponding team to upload the function, provided corresponding teams of each stage upload authorization and data format. The unit that was in charge could review based on the data uploaded by the corresponding team to ensure the quality of system data source. On the administrative side, the corresponding team was inquired to perform upload and the data was examined through system review mechanism. Thus from involving corresponding team to unit in charge in the data construction process on the data end of D3, the system was given a mechanism to grow, achieving the goal of co-constructing the information.

3. D3 system service module

D3 is a “single integrated information service platform” for integrating SWCB conservation and control related business information; it is open to professional engineering consulting companies and engineer associations. To provide non-stop safe environment, D3 adopts Google Earth Enterprise to construct a D3 private cloud platform, creating a safe environment for all information from being “copied”, “rewritten”, and “reproduced” for inquiry. D3 is introduced to the soil and water conservation engineering full life cycle operation, creating a brand new conservation and control service module and achieving overall system optimization, providing integration service, location-based service (LBS), and innovation service.

D3 includes 11 core operation systems and 5 service modules to manage the nation’s slopeland conservation and control, establishes over millions of soil and water control information, and provides service to 6 sub bureaus, soil and water conservation units of each city and country government, relevant engineering consulting companies and engineer associations. D3 targets users' different needs to provide 5 types of service modules that not only elevate usability and expedite effective service but also possesses the convenience of cross-device and cross-browsers. The five types of service modules are:

3.1 "D3-Web-Intranet", internal service platform web page

This service is offered to the users within SWCB through using account and password provided by SWCB on the web page. All the conservation control business are categorized into 11 core databases for integration, using single 3D GIS data inquiry platform for all business data to conduct document inquiry by location and location inquiry by document functions. Other complete functions are shown in the following figure.

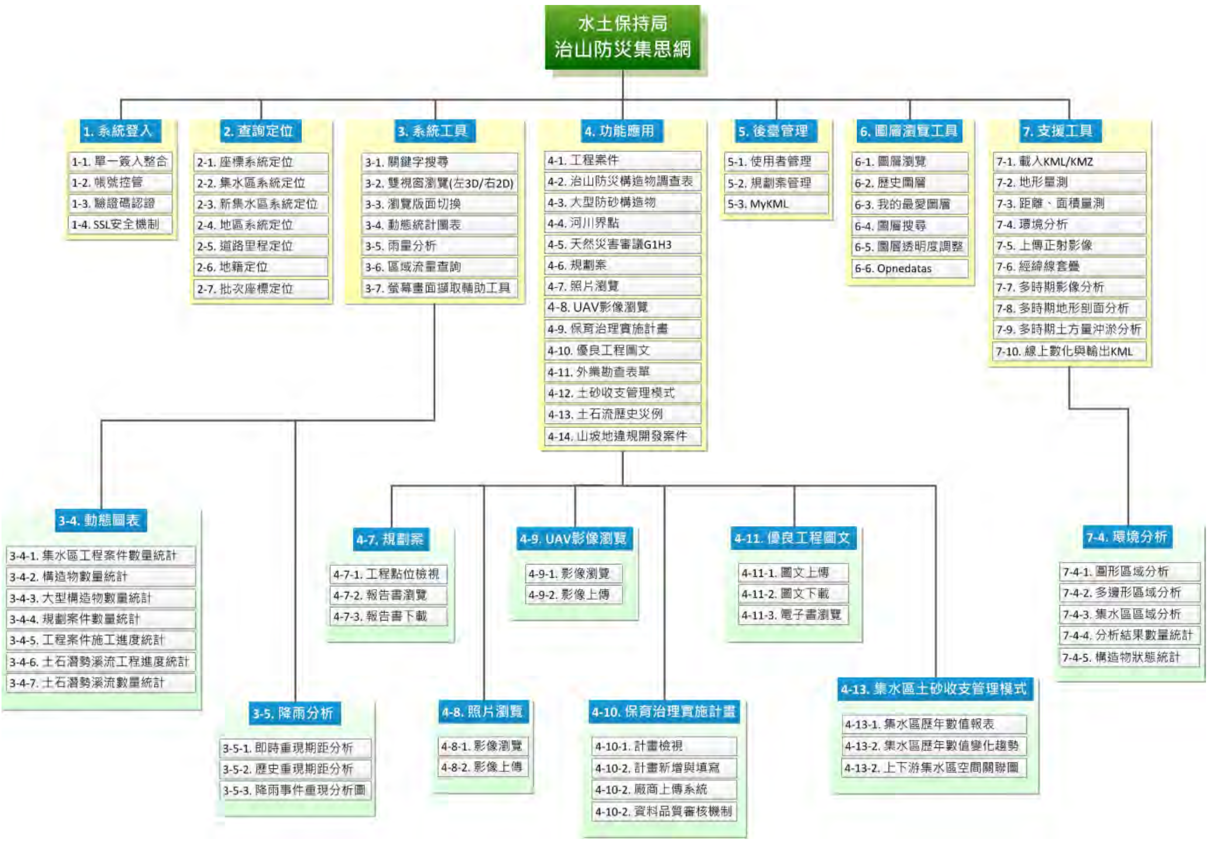


Figure 2. Structure of "D3-Web-Intranet" system functions

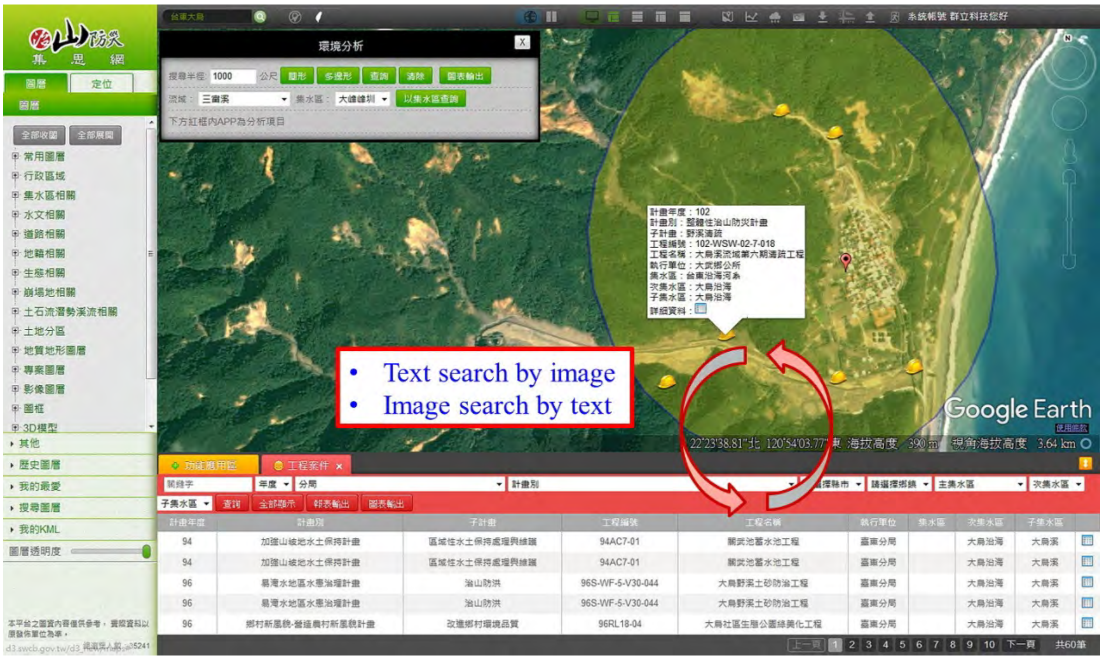


Figure 3. "D3-Web-Intranet" web page service module

3.2 "D3-Web-Intranet", service platform for professionals web page

Professionals (engineering consulting companies, engineer associations, etc) are required to apply for using the service through membership; and the basic functions are the same as D3-Web-Intranet. This service is open to the public and thus sensitive information (such as cadastral data, etc.) and internal use functions will be filtrated before offering to professionals for planning conservation and control.

3.3 "D3-Web-Theme Service", open service platform web page

The service is provided according to the theme of current events through backend database management with information co-construct mechanism. Manager could swiftly produce relevant theme service based on concurrent event to provide general public and the media a display platform in releasing instant information.

3.3.1 Case application: post Typhoon Soudelor Nanshi River impact assessment

In the water clarity of Nanshi River that affected the domestic water use of greater Taipei area, D3-Web-Theme Service quickly used theme map combination to calculate the area ratio of slopeland and forest compartment land within the source water protection area (slopeland 31.9%; forest compartment land 66.4%), and displayed through spatial information, grasping the information of historical landslide impact for the reference to decision makers.

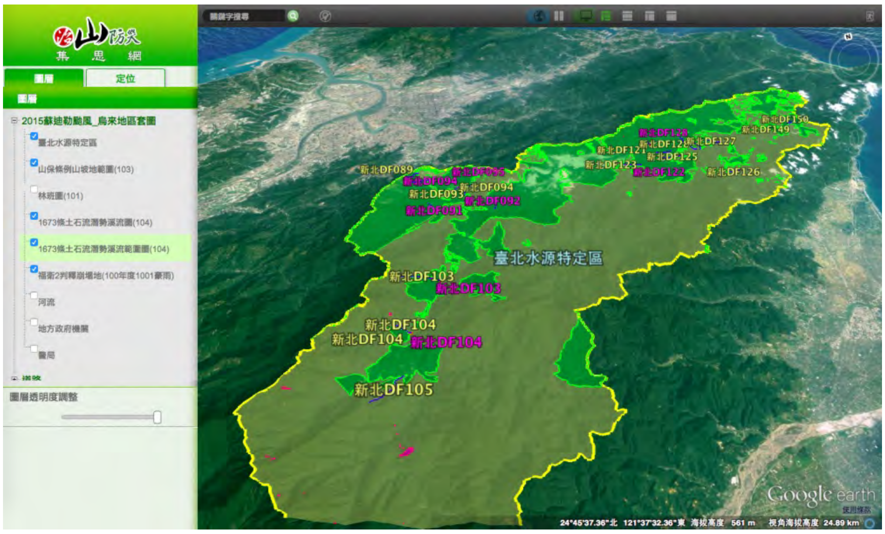


Figure 4 Nanshi River impact assessment theme map service

3.4. "D3-App-Public Service", APP

This service is open to the public for free download, provides genera public with mapping service of the soil and water control information such as debris flow potential rivers, impact range of debris flow potential rivers, slopeland range, forest compartment land range and watershed area, etc. This service also provides LBS service so that the users could acquire watershed area of users' location, the nearby debris flow potential rivers, forest compartment land and slopeland interpretation et al information.

3.5 "D3-APP-Professional Application", APP

This service provides users at SWCB to use through internal account and passwords. In addition to soil and water control GIS data service and LBS, this service also includes on-site survey repot and off-line application service mechanisms. On the on-site survey report, users could fill out on-site survey information and photography the site instantly through APP, combine with LBS analysis results and send back to internal database immediately for the manager to grasp the on-site information at the same time, which also achieved paperless operation. On off-line application service, users could use GIS data browsing service when there is no internet available; LBS analysis service could also be conducted through SMS. This service is capable of adapting to harsh environment of slopeland where no internet service is available, making it efficient in executing erosion and sediment control.

3.5.1 Application Case: post Typhoon Soudelor Nanshi River on-site survey

Wulai area was left without internet service after Typhoon Soudelor; the on-site survey utilized off-line application service to conduct LBS analysis and off-line GIS data inquiry function to take hold of site environment factors, photographed the site, and sent back to the system for follow up restoration planning.

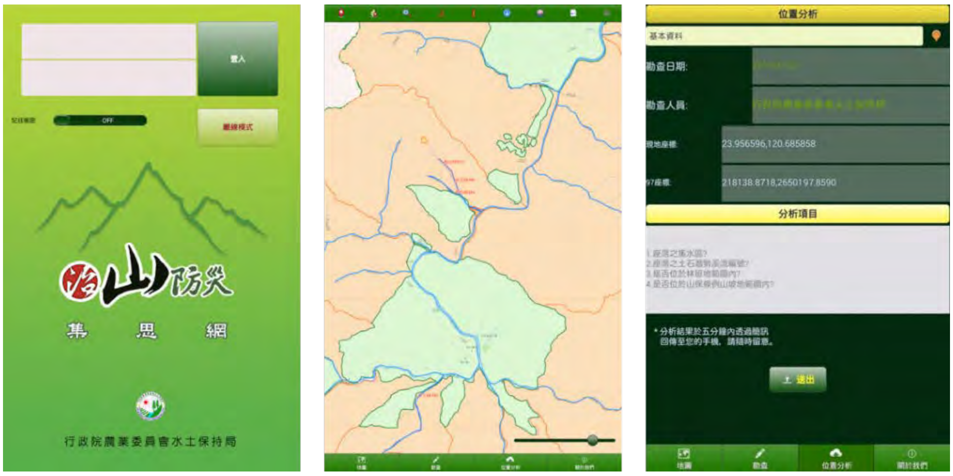


Figure 5 “D3-App” mobile APP service module

4. D3 system technology

D3 combines two major GIS service platform and provides system with 5 types of service module. Front end service interface mainly uses Google Earth Enterprise private cloud steaming service mechanism to provide high efficacy 3D GIS browsing mechanism. Back end database management mainly uses ArcGIC spatial database management mechanism to provide complete interpretation to the information archiving and spatial analysis inquiry mechanism. The relevant core technologies are as following:

4.1 Google private cloud platform – a safe 3D GIS data co-sharing environment

Google Earth Enterprise is an independent 2D/3D GIS earth databases, the set includes Google Earth Enterprise Fusion, Google Earth Enterprise Server, Google Earth API, Google Mobile Solution, etc. and is capable of merge and organize images, terrain elevation, vectors, models et al information and publishes through Google Earth Enterprise server. By using comprehensive and easy to use Google Earth client interface, users can smoothly access the data established by Google Earth Enterprise. Google Earth Enterprise supports over 1,000 users online, over 500 people connect to one single GIS data at the same time; and is equipped with mobile solution to provide diversified use for smart phones.

4.2 Spatial information inquiry and analysis service

ArcGIS space database is the core for spatial inquiry and analysis, providing GIS data, spatial inquiry and analysis service. This service develops multi period image inquiry, terrain cross-section analysis, earthwork analysis and sediment budget module analysis et al spatial inquiry analysis functions.

4.2.1 Multi period image inquiry

After user block selects a specific area on the platform, the system will analyze and compare with image database through WMS (Web Map Service) technology for user to compare the changes in the past years immediately. WMS is a map inquiry service of OGC (Open GIS Consortium); its original design concept is to collect database geological and property information scattered across the internet to generate customized maps that are normally saved under JPEG, GIF, or PNG formats. This function also supports SVG and WebCGM that are the most direct tools to display visualized geological graphic information. The rule of WMS is the standard method in which the client end requests GIS data from server end and how the server's end presents the map data. WMS server end interacts with users through http; therefore the user interacts with WMS server end by sending CGI (Common Gateway Interface) parameter through URL.

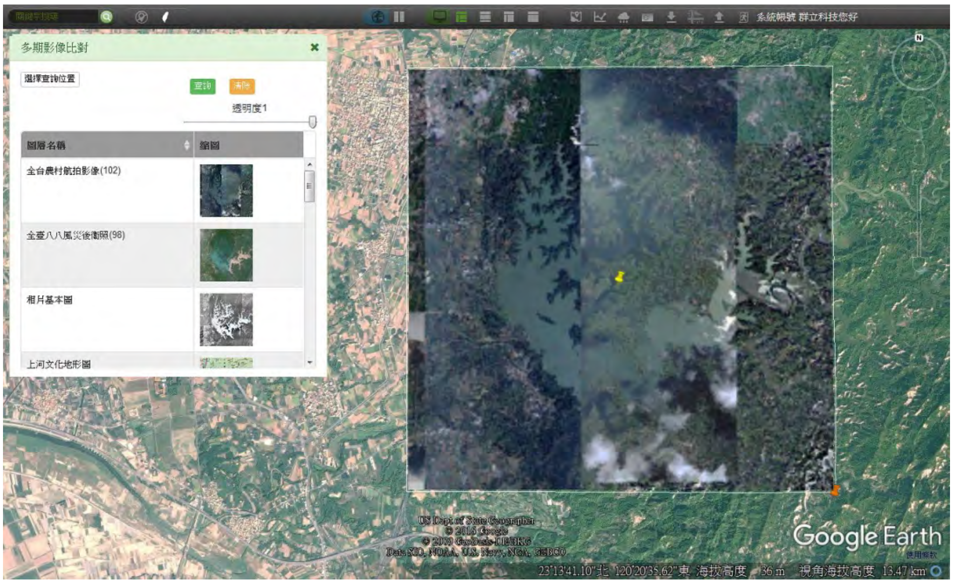


Figure 6　Multi period image analysis function

4.2.2 Multi period terrain cross-section analysis

This function transfers topography information generated from years of satellite images, aerial images and images taken by unmanned aerial vehicle (UAV) into spatial database for the use of cross-section analysis function. After drawing a line on the system platform, the system will then bring out the list of multiple period topography information of the area covered under the line; the user can select the desire terrain to perform cross-section analysis. The system analyzes the terrain elevation data of each period, compares and calculates the difference and uses line chart with terrain elevation to display cross-section analysis results on the platform. Users can easily and immediately understand the earlier and later period terrain difference through graphic image and learn about the terrain elevation information of one certain in each period.

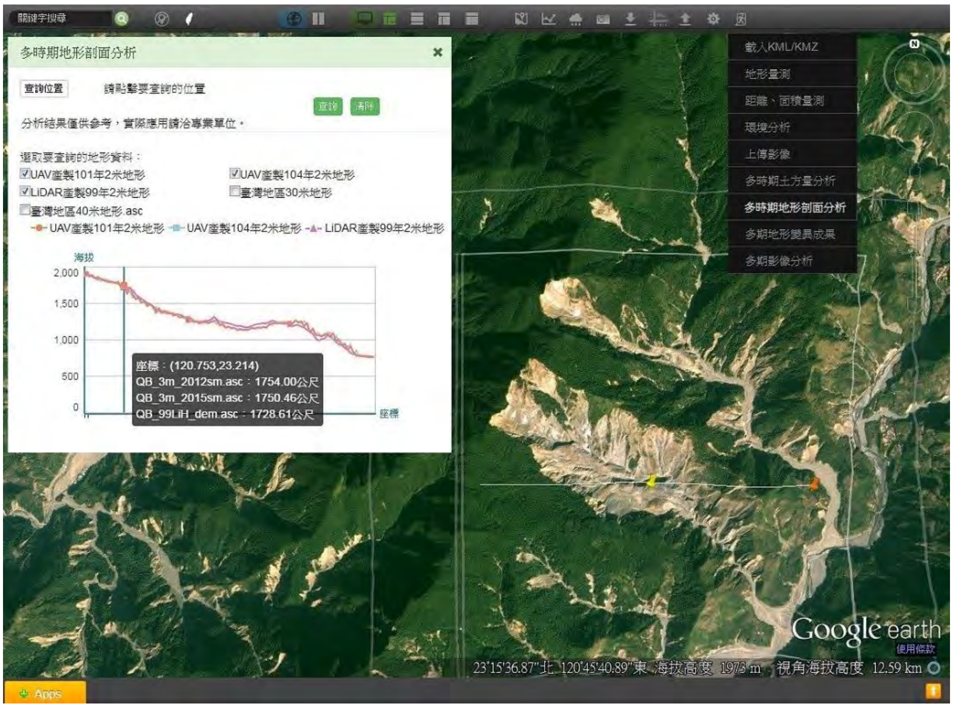


Figure 7 Multi period terrain cross-section analysis function

4.2.3 Multi period earthwork erosion analysis

Block select a set distance range on the platform, the system will automatically bring out the terrain information of the blocked area from all period of time. Choose the desired information to analyze the terrain elevation information and this function will compare the terrain change in earlier and later period, calculate the earthwork difference and set corresponding colors for sectional height. It will then use grids to display the result on the platform, using different color shading to represent the terrain information and sediment erosion of the area. SWCB business unit uses the graphic result with sediment budget to analyze the watershed area sediment changing trend as the reference for planning the watershed area sediment control engineering.

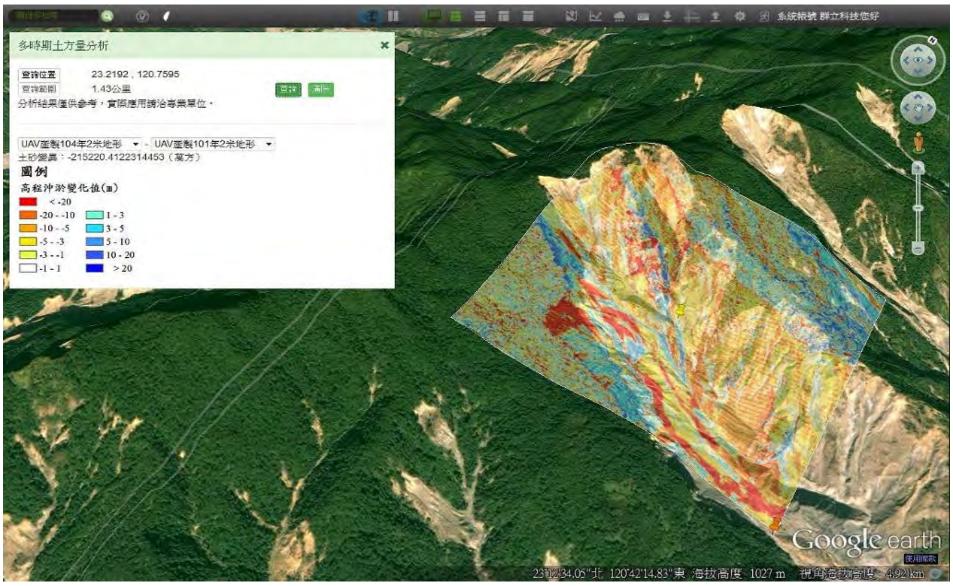


Figure 8 Multi period earthwork erosion analysis function

4.2.4 Sediment budget management module

This function uses watershed area on main Taiwan island as the unit, and sediment investigation, monitoring and assessing analysis result as the foundation to monitor watershed terrain change by diversified monitoring methods; analyzes and assess watershed area slope sediment yield and river way erosion. The function also compiles statistic figures of each year and sets up management module; it also estimates the possible future sediment change trend through current sediment condition in watershed areas and the setting of precipitation event to serve as the vital decision making reference for SWCB on watershed control. The system converts watershed GIS data to spatial information database, using interface for graphics and display on system platform to present the connection of watershed area upper and lower stream through data link. On the other hand, the system integrates the previous data with annual sediment budget to display the “sediment yield, discharge and change” parameters of the analysis figures by charts and line charts, using figures and graphic display for the business units to have a clear understanding of the past, present and future change of watershed area.

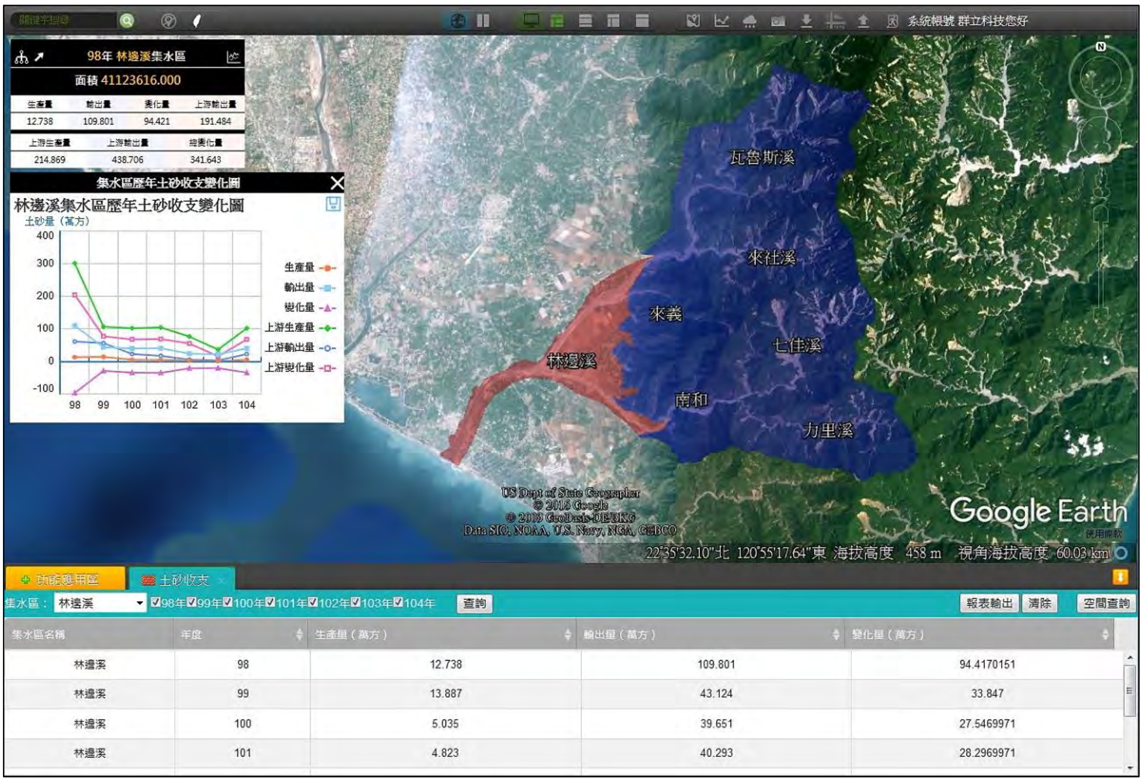


Figure 9 Watershed sediment budget management module function

5. Overall effect and conclusion

D3 was developed in 2014, working for SWCB from administration to functionality. Its GIS data integrated SWCB own GIS data and connected to government's other open data, consisted at a total of 2,547 theme graphic information. The integrated database covered 11 business systems and developed 5 service modules; covering over 80% of the SWCB business. The internal system was utilized by 4,777 people per month by average, mostly during the flood control season, with maximum 13,288 users on line on a single day, and at a monthly average of 33,268 browsing on the GIS data. Following are the overall effects:

5.1 Integrating soil and water control resources, shaping a brand building service module

Aside from integrating SWCB's own spatial storage GIS data from the data end, D3 also integrates all conservation control business system database from the business application end including engineering management and assessment system; structure investigation system, natural disaster review, project management system, conservation control enforcement plan management system, engineering drawing and document management system, key control areas management system and sediment budget management system, etc. D3 consolidates bureau resourcesby building 5 types of slopeland digital information service modules in oder to meet users' different demands.

5.2 Co-constructing information elevates decision making efficiency

D3 integrates resource horizontally; and on the vertical information supply end, the entrusted corresponding team and hosting unit form a data co-constructing mechanism for the data end to self grow and examine to avoid repeatedly investing data production cost, making slopeland data flowing fast both internally and externally, and greatly elevates the decision making efficacy.

5.3 Open service combines strength of specialists, coheres the slopeland disaster prevention energy

Slopeland disaster prevention is a task that must be directed by the government yet also needs to combine with the strength of civil professionals to predict and deploy ahead of time during prevention stage; and conducts immediate rescue and speedy restoration during rescue stage. For that, D3 offers 2 open service modules hoping to combine the strength of government and civil specialists, adding value through government resources and localized civil information to cohere the slopeland disaster prevention energy.

5.4 Off line data support decision making

The off line application service of D3 can be used in the environment where no internet is available. The service is suitable for slopeland site where the interest environment is harsh for performing on-site survey and data report, which is helpful for executing relevant works.

5.5 Business system 3D mapping service

Previously, in addition to having large quantity of listed information, information on terrain change was the highlight of slopeland disaster prevention decision making. D3 introduces 3D spatial mapping service to conduct spatial management on the listed information; on the other hand, D3 also integrated and released terrain information through functionality, including multi period terrain cross-section survey, multi period earthwork erosion and sediment budge calculation, etc functions to provide users reference in making decision.

6. Reference

D3 system maintenance and function expand project, Soil and Water Conservation Bureau, Council of Agricultural, Executive Yuan (2015)

Google Earth Enterprise result display platform system maintenance and function expand project, Soil and Water Conservation Bureau, Council of Agricultural, Executive Yuan (2015)

NEAR-ROAD ENVIRONMENT SENSITIVITY ANALYSIS FOR HEAVY VEHICLE FREIGHT TRANSPORTATION BY BIM AND GIS INTERGRATION SYSTEM

Yongze Song, Xin Liu, & Xiangyu Wang

Australasian Joint Research Centre for Building Information Modelling, School of Built Environment, Curtin University, Australia

Yi Tan, & Jack C.P. Cheng

Department of Civil and Environmental Engineering, The Hong Kong University of Science and Technology, Hong Kong

ABSTRACT: Heavy vehicle freight transportation is one of the most important sources of urban air emissions, which has severe impact on near-road environment and surrounding communities. Currently, transportation departments have tried to manage heavy vehicles with policies of road levels and restrictions. Heavy vehicles could only be driven on certain roads or in limited periods, so that their impacts on the near-road environment can be reduced. In addition, they intend to charge for the environment destruction behaviours of heavy vehicles. However, the policies and charges are limited in quantitative and geographically local measurement and evaluation of the road damage and environment threats. They are the key to evaluate the near-road environment sensitivity related to freight transportation. The near-road environment sensitivity varies across the geographical space, and is also related to the loading and basic conditions of heavy vehicles. Therefore, it should be analysed from two aspects: road maintenance and environment carrying capacity. Multiple proxy variables are used for depicting both kinds of impacts of heavy vehicles. For road maintenance, building information modelling (BIM) provides detail information of its proxy variables such as specifications of freight. The proxy variables also include heavy vehicles conditions, their real loadings, and traffic volumes in each road sections from historical data. For environment carrying capacity, the impacts of transportation emissions on local environment can be examined by spatial models with its proxy variables land use conditions, levels of road networks, population density in urban areas, topological relations between roads and nature reserves, etc. Therefore, with the quantitative analysis of the impacts of heavy vehicles on road maintenance and environment carrying capacity, this research can generate near-road environment sensitivity maps to improve the management effectiveness of freight transportation for transportation departments.

KEYWORDS: *Freight transportation, Heavy vehicle, BIM, environmental sensitivity, spatial analysis.*

1. INTRODUCTION

Air pollution is a primary risk to the environment and to human health. Ambient air pollution is estimated to cause 1.3 million annual deaths worldwide (Organization). Road traffic is usually the most important source of pollutant emissions, especially in urban areas (Querol, Viana et al. 2007). Studies have demonstrated that traffic frequently contributes 5-80% of airborne concentrations of particulate matters (PM) in different locations in the world (Pant and Harrison 2013). Traffic emissions also cause 26% of the energy-related greenhouse gases (GHG) globally leading to severe air pollution (Chapman 2007, Xia, Nitschke et al. 2015).

Further, traffic-related air pollutant exposures are significantly related to various diseases including cardiovascular diseases (Babisch, Ising et al. 1999), respiratory illnesses (Brauer, Hoek et al. 2002), pregnancy outcomes (Laurent, Wu et al. 2013, Li, Laurent et al. 2016), and mortality (Künzli, Kaiser et al. 2000, Chandran, Kahn et al. 2013). Longer periods spent near traffic emission sources leads to higher risk of exposure to traffic-related pollutants, because concentrations of traffic related pollutants are much higher than those in ambient outdoor environments (Westerdahl, Fruin et al. 2005, Zhu, Eiguren-Fernandez et al. 2007). In Austria, France and Switzerland, about half of all deaths caused by air pollution are linked with road traffic (Künzli, Kaiser et al. 2000).

Western Australia is one of the places with the lowest emission concentrations in the world, but adverse health effects are caused by local traffic air pollution. For instance, exposure to traffic-related air pollution in mid to late pregnancy was associated with an odds ratio of 1.31 for foetal growth restriction (Pereira, Cook et al. 2012). Particularly, risk of foetal growth restriction is higher for pregnancies with increased fine particulate ($PM_{2.5}$) exposure in the second trimester than were other Australian pregnancies (Pereira, Bell et al. 2014).

Heavy vehicle freight transportation is essential for industrial development, since it is an important component of industry and continuously promotes economic growth for most countries. However, it causes severe environmental problems. Most heavy vehicles run on diesel engines, which are the primary sources of nitrogen oxides, PM and GHG. These environmental problems still lead to a high risk for human health (Schreyer, Schneider et al. 2004, Felder, Burgess et al. 2014).

Therefore, any decisions of transportation authorities to reduce the traffic environmental impacts have to include heavy vehicle management. The efforts being made primarily consist of optimization of traffic management and applying tighter emission standards (Chapman 2007, EC 2011). But the decisions design with the consideration of heavy vehicle environmental impacts appears only in limited nations (Parrish and Zhu 2009). The decisions and relevant research include the following aspects. (1) Direct traffic control. Aggressive emission controls on automobiles and the limitations on heavy trucks have been practiced in Beijing. Chinese decision-makers are also starting to pay attention to promote energy efficiency of freight transportation (He, Huo et al. 2005). The proposed vehicle emission standards in China could help to decrease emissions by 50 - 83% compared with uncontrolled scenarios (Huo, Zheng et al. 2015). (2) Emission control of certain particulates. Research in Belgium shows simple reduction of emissions is costly and does not usually gain an overall benefit (Schrooten, De Vlieger et al. 2006). Additionally, retrofitting particulate filters is beneficial for controlling PM emissions, but lacks the quantitative consideration of other traffic emissions. (3) Changing speed limits. Speed management decisions have been implemented in Barcelona to decrease traffic-related air pollution, with practical results demonstrating that variable speed policy is a benefit for pollution reduction, but the policy of simple speed limit has no effect (Bel and Rosell 2013, Bel, Bolancé et al. 2015).

Unfortunately, there is still limited quantitative evidence of decisions designed to address the problems of traffic environmental impacts. Previous and current traffic-environment decisions lack the quantitative analysis of traffic environmental impacts. Though traffic environmental problems are significantly related to traffic emissions, road and traffic conditions, and weather conditions, these parameters are not integrated into decision making processes. In addition, the traffic-environment problems are not accurately managed and addressed by decision-makers due to the lack of geographical considerations. Actually, the measurement and analysis of geographically related regional environmental impacts caused by road traffic are practically useful and valuable (Kennedy, Cuddihy et al. 2007).

To address these gaps, development of geospatial models for mapping traffic environmental impacts is proposed to make more flexible and accurate traffic-environment decisions for heavy vehicle freight transportation. With the help of traffic network and volume data, near-road environmental sensitivity maps are generated for assessing traffic environmental impacts.

2. DATA AND METHODS

The study area includes 43 local government areas (LGAs) in Wheatbelt region in Western Australia. Wheatbelt region is one of the most important grain production regions in Western Australia. Heavy vehicle is a primary tool for the transportation of grain and industrial production. In Wheatbelt, there are 3435 road segments distributed within ten road networks by restricted access vehicles (RAVs). The classification of RAV networks is based on Prime Mover, Trailer Combinations - Vehicle Categories, RAV 2016. According annual report 2015, volumes of traffic and heavy vehicle are monitored annually from 2008/09 to 2013/14 at 821 monitoring sites distributed in Wheatbelt region. The daily volume of heavy vehicle is mapped in Figure 1. Seen from this map, only a quarter of road segments are monitored. Volumes in most of road segments are not monitored, even though they are also very important RAV networks. Therefore, it is necessary to predict heavy vehicle volumes in the road segment without monitoring data before evaluating the impacts of heavy vehicle.

Geospatial models could be used to recognise spatio-temporal regulars, exploring potential factors, predicting spaito-temporal variations and enabling decision making. Ordinary kriging, a widely used spatial interpolation method in geostatistics field, is used to predict the distributions of heavy vehicle volumes. The primary idea is an optimal and unbiased estimation for regionalised variables within a limited spatial area on the basis of variogram theory (Goovaerts 1997). With this geospatial model, volumes of heavy vehicle in all RAV networks could be predicted. Further, the near-road environmental impact is assessed by both volumes and masses of heavy vehicle in road segments.

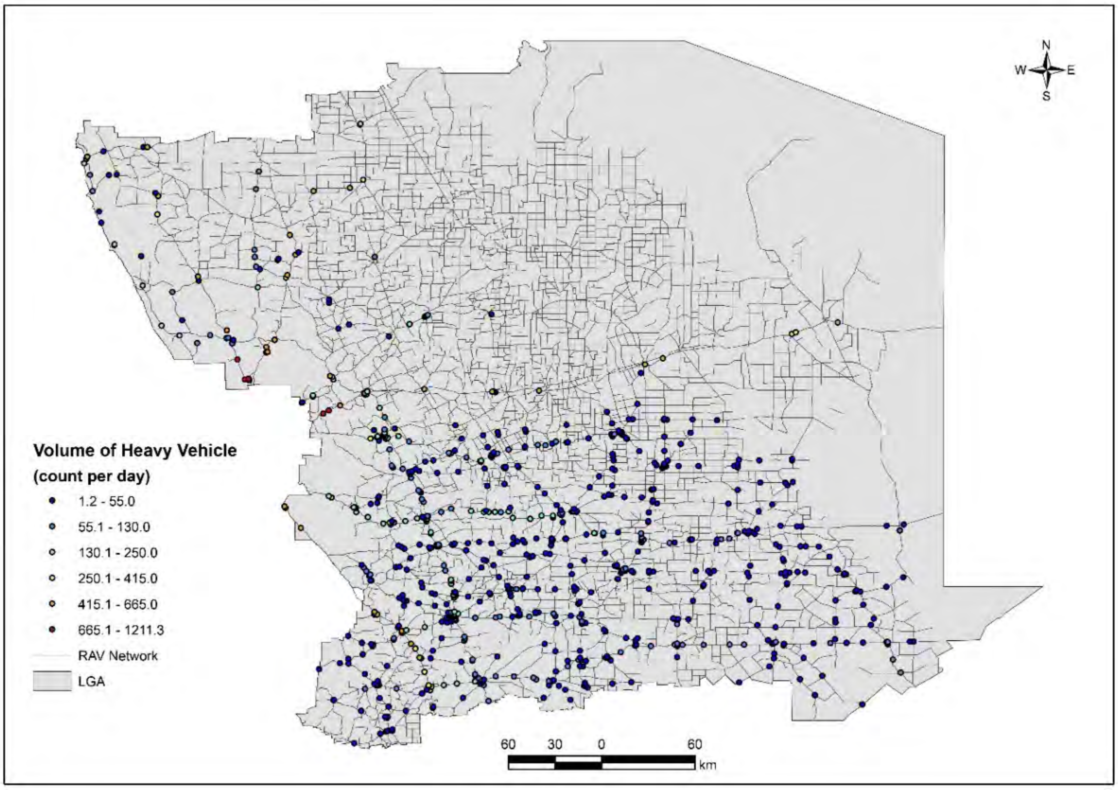


Fig. 1: Volume of heavy vehicle at monitoring sites in Wheatbelt

3. RESULTS AND DISCUSSION

In this research, near-road environmental sensitivity is analysed and assessed using road segment based mass of heavy vehicle and corresponding burden of road network. Road segment based mass of heavy vehicle is modelled using geospatial interpolation method with RAV network and volume of heavy vehicle data. The predicted volume of heavy vehicle is mapped in Figure 2. The prediction fitness between the predicted values and observations in 821 monitoring sites is $R^2 = 0.59$. Together with the mass information of each category of RAV network, the total mass of heavy vehicle in each road segment is estimated in Figure 3. In general, both volume and mass are relatively high in northern Wheartbelt region and low in southern part. The heavy vehicle prediction maps are benefit for assessing traffic impact on environment, surrounding communities and road maintenance. Therefore, road segment based mass reflects road burden. The more mass means more environmental and road maintenance burden.

This research innovatively develops geospatial models that have been proposed in recent years but have yet been used in the geovisualisation of traffic environmental impacts. Compared to previous methods, these models help generate accurate traffic environmental impacts maps based on a limited number of observations. As the models include a consideration of multiple variables, such as traffic volumes, road types and the attributes of heavy vehicles, it is expected that the accuracy of predicting on-road and near-road environmental impacts will be significantly improved.

Air pollution is a primary risk to global climate change and human health, and road traffic is the primary source of pollutant emissions. Freight transportation by heavy vehicle is essential for industrial development, but it also causes severe environmental problems such as pollution, noise, land use deterioration and climate change risk. As such, establishing flexible and accurate heavy vehicle-related decisions is imperative. This research provides accurate and regional environmental impact maps of heavy vehicles under various scenarios. It will support flexible decision making, such as variable speed decisions. Meanwhile, as the decisions are based on accurate traffic environmental impacts maps, the use of such decisions can help mitigate the negative impacts of traffic on the environment.

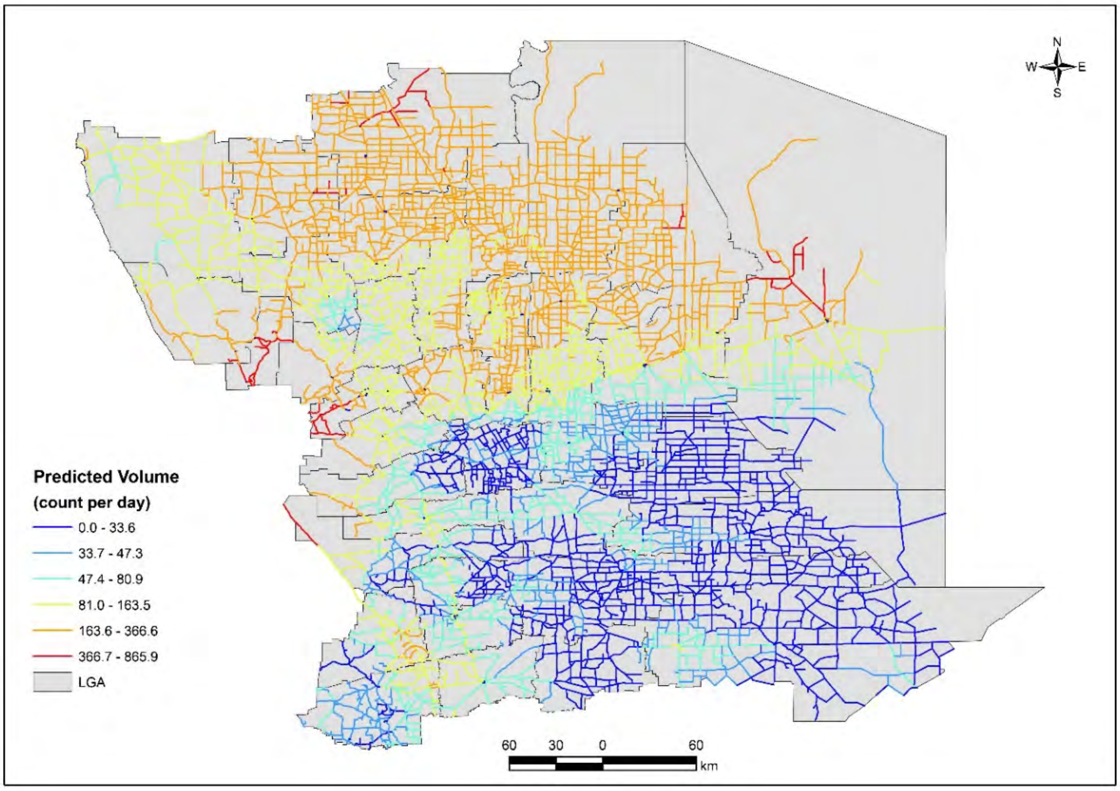


Fig. 2: Predicted volume in each road segment using geospatial models

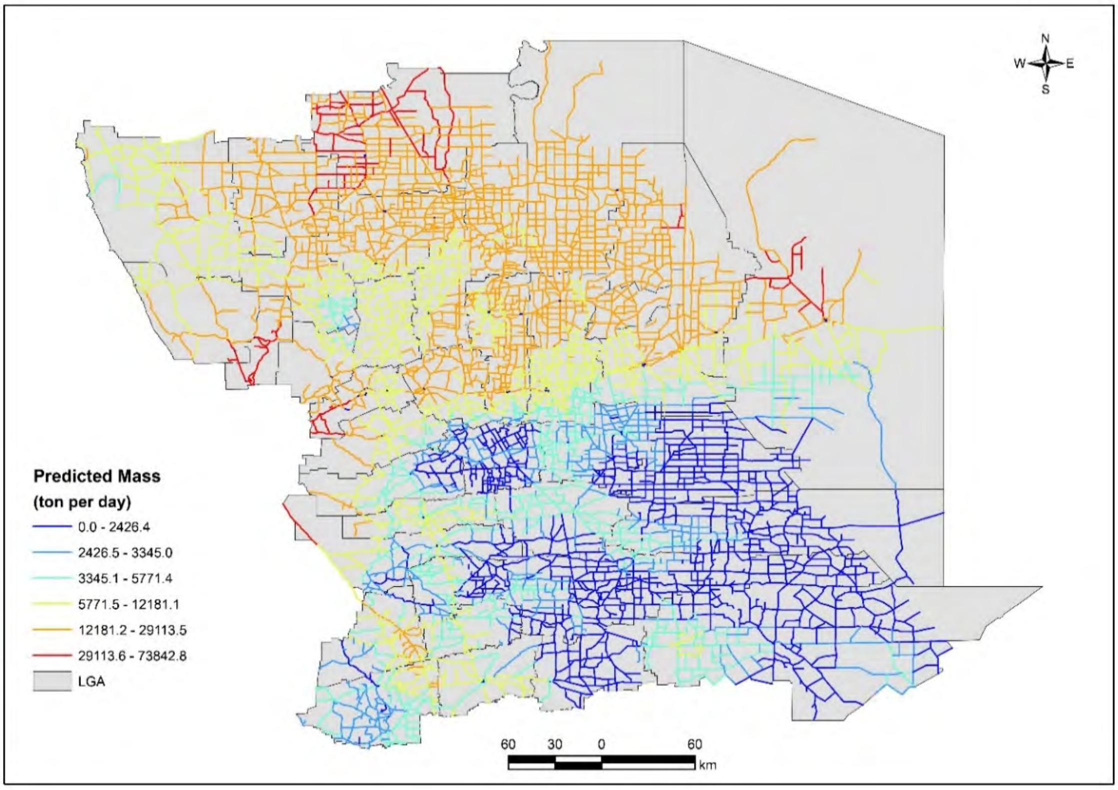


Fig. 3: Predicted mass of heavy vehicle in each road segment

4. CONCLUSION

Heavy vehicle plays an important role in freight transportation and economic development, but it has severe impact on environment, surrounding communities and road conditions. This research utilises heavy vehicle road network and volume in Wheatbelt region in Western Australia as an example to quantitatively explain the impact of heavy vehicle. Geospatial models are used to predict road segment based volume and mass of heavy vehicle. Results show that the prediction is accurate and reliable, which enables accurate geovisualisation with near-road environment sensitivity maps. Accurate prediction maps are benefit for wise decision making on the economic input and output, improving environmental performance of heavy vehicle, and regular road maintenance. Therefore, this research proposes quantitative and geospatial methods for assessing the impact of heavy vehicle, and provides accurate and high spatial resolution evidence for flexible decision making of heavy vehicle.

ACKNOWLEDGMENTS

This research was undertaken with the benefit of a grant from the Australian Research Council Linkage Project (No. LP140100873, No. LP130100451). We acknowledge the Heavy Vehicle Services, Main Roads Western Australia, Australia for their roles in making available the road networks by restricted access vehicles (RAVs) data set and heavy vehicle standards.

REFERENCES

Babisch, W., H. Ising, J. E. Gallacher, P. M. Sweetnam and P. C. Elwood (1999). "Traffic noise and cardiovascular risk: the Caerphilly and Speedwell studies, third phase-10-year follow up." Archives of Environmental Health: An International Journal **54**(3): 210-216.

Bel, G., C. Bolancé, M. Guillén and J. Rosell (2015). "The environmental effects of changing speed limits: A quantile regression approach." Transportation Research Part D: Transport and Environment **36**: 76-85.

Bel, G. and J. Rosell (2013). "Effects of the 80km/h and variable speed limits on air pollution in the metropolitan area of barcelona." Transportation Research Part D: Transport and Environment **23**: 90-97.

Brauer, M., G. Hoek, P. Van Vliet, K. Meliefste, P. H. Fischer, A. Wijga, L. P. Koopman, H. J. Neijens, J. Gerritsen and M. Kerkhof (2002). "Air pollution from traffic and the development of respiratory infections and asthmatic and allergic symptoms in children." American journal of respiratory and critical care medicine **166**(8): 1092-1098.

Chandran, A., G. Kahn, T. Sousa, F. Pechansky, D. M. Bishai and A. A. Hyder (2013). "Impact of road traffic deaths on expected years of life lost and reduction in life expectancy in Brazil." Demography **50**(1): 229-236.

Chapman, L. (2007). "Transport and climate change: a review." Journal of transport geography **15**(5): 354-367.

EC (2011). Road to a Single European Transport Area - Towards a Competitive and Resource Efficient Transport System. European Commission White Paper, Brussels. **2832011 COM(2011) 144 Final**.

Felder, M., M. Burgess and J. Arnold (2014). A low-budget road traffic noise model for individual building evaluation-a case study in Western Australia. INTER-NOISE and NOISE-CON Congress and Conference Proceedings, Institute of Noise Control Engineering.

Goovaerts, P. (1997). Geostatistics for natural resources evaluation, Oxford University Press on Demand.

He, K., H. Huo, Q. Zhang, D. He, F. An, M. Wang and M. P. Walsh (2005). "Oil consumption and CO 2 emissions in China's road transport: current status, future trends, and policy implications." Energy policy **33**(12): 1499-1507.

Huo, H., B. Zheng, M. Wang, Q. Zhang and K.-B. He (2015). "Vehicular air pollutant emissions in China: evaluation of past control policies and future perspectives." Mitigation and Adaptation Strategies for Global Change **20**(5): 719-733.

Kennedy, C., J. Cuddihy and J. Engel-Yan (2007). "The changing metabolism of cities." Journal of industrial ecology **11**(2): 43-59.

Künzli, N., R. Kaiser, S. Medina, M. Studnicka, O. Chanel, P. Filliger, M. Herry, F. Horak, V. Puybonnieux-Texier and P. Quénel (2000). "Public-health impact of outdoor and traffic-related air pollution: a European assessment." The Lancet **356**(9232): 795-801.

Laurent, O., J. Wu, L. Li, J. Chung and S. Bartell (2013). "Investigating the association between birth weight and complementary air pollution metrics: a cohort study." Environ Health **12**(18): 10.1186.

Li, L., O. Laurent and J. Wu (2016). "Spatial variability of the effect of air pollution on term birth weight: evaluating influential factors using Bayesian hierarchical models." Environmental Health **15**(1): 1.

Organization, W. H. Air quality and Health, Fact sheet no 313, September 2011.

Pant, P. and R. M. Harrison (2013). "Estimation of the contribution of road traffic emissions to particulate matter concentrations from field measurements: a review." Atmospheric Environment **77**: 78-97.

Parrish, D. D. and T. Zhu (2009). "Clean air for megacities." Science **326**(5953): 674-675.

Pereira, G., M. L. Bell, K. Belanger and N. de Klerk (2014). "Fine particulate matter and risk of preterm birth and pre-labor rupture of membranes in Perth, Western Australia 1997–2007: A longitudinal study." Environment international **73**: 143-149.

Pereira, G., A. G. Cook, F. Haggar, C. Bower and N. Nassar (2012). "Locally derived traffic-related air pollution and fetal growth restriction: a retrospective cohort study." Occupational and environmental medicine: oemed-2011-100509.

Querol, X., M. Viana, A. Alastuey, F. Amato, T. Moreno, S. Castillo, J. Pey, J. De la Rosa, A. S. De La Campa and B. Artíñano (2007). "Source origin of trace elements in PM from regional background, urban and industrial sites of Spain." Atmospheric Environment **41**(34): 7219-7231.

Schreyer, C., C. Schneider, M. Maibach, W. Rothengatter, C. Doll and D. Schmedding (2004). External costs of transport: update study; final report, Infras.

Schrooten, L., I. De Vlieger, F. Lefebre and R. Torfs (2006). "Costs and benefits of an enhanced reduction policy of particulate matter exhaust emissions from road traffic in Flanders." Atmospheric Environment **40**(5): 904-912.

Westerdahl, D., S. Fruin, T. Sax, P. M. Fine and C. Sioutas (2005). "Mobile platform measurements of ultrafine particles and associated pollutant concentrations on freeways and residential streets in Los Angeles." Atmospheric Environment **39**(20): 3597-3610.

Xia, T., M. Nitschke, Y. Zhang, P. Shah, S. Crabb and A. Hansen (2015). "Traffic-related air pollution and health co-benefits of alternative transport in Adelaide, South Australia." Environment international **74**: 281-290.

Zhu, Y., A. Eiguren-Fernandez, W. C. Hinds and A. H. Miguel (2007). "In-cabin commuter exposure to ultrafine particles on Los Angeles freeways." Environmental science & technology **41**(7): 2138-2145.

BUILDING POLYGON RECTIFICATION FOR AUTOMATIC GENERATION OF 3D BUILDING MODELS

Kenichi Sugihara

Gifu Keizai University, Japan

Takahiro Murase

ChukyoGakuin University, *Japan*

ABSTRACT: *A 3D city model is important in architectural and construction industry. However, creating these 3D models are labor-intensive. In order to automate laborious steps, a GIS (Geographic Information System) and CG integrated system is proposed for automatically generating 3D building models, based on building polygons on a digital map. These polygons are usually orthogonal. A complicated orthogonal polygon can be partitioned into a set of rectangles. The proposed integrated system partitions orthogonal building polygons into a set of rectangles and places rectangular roofs and box-shaped building bodies on these rectangles. Since technicians are drawing these polygons manually with digitizers, depending on aerial photos, not all building polygons are precisely orthogonal. But, when placing a set of boxes as building bodies for creating the buildings, there may be gaps or overlaps between these boxes if building polygons are not precisely orthogonal. In our proposal, after approximately orthogonal building polygons are partitioned and rectified into a set of mutually orthogonal rectangles, each rectangle knows which rectangle is adjacent to and which edge of the rectangle is adjacent to, which will avoid unwanted intersection of windows and doors when building bodies combined.*

KEYWORDS: *3D building model, automatic generation, GIS, 3D urban model, building polygon, polygon partitioning, shape rectification*

1. INTRODUCTION

A 3D city model, such as the one shown in Fig. 1 right, is important in urban planning and gaming industries. Urban planners may draw the maps for sustainable development. 3D city models based on these maps are quite

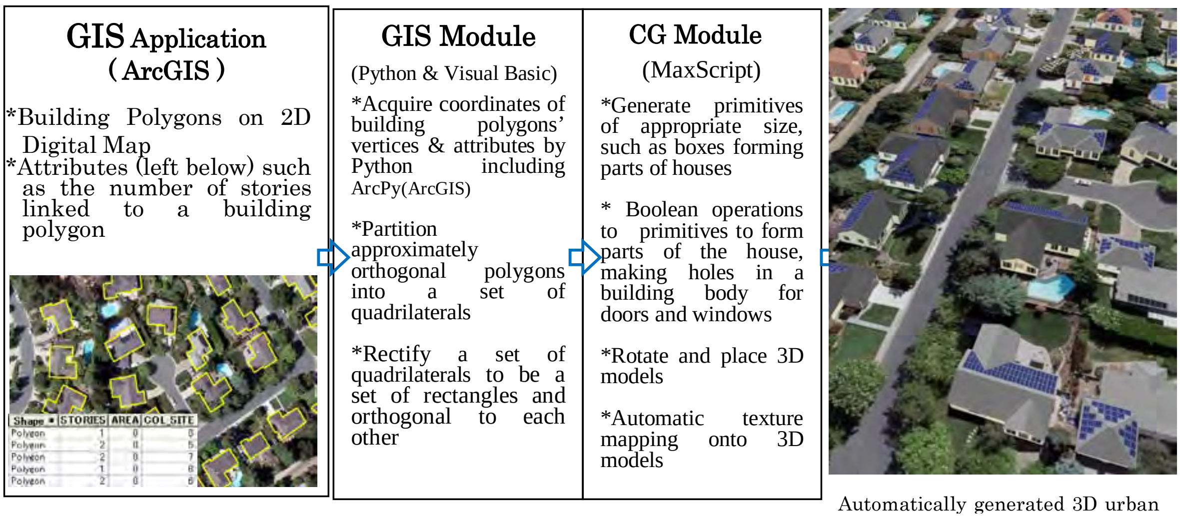


Figure 1: Pipeline of Automatic Generation for 3D Building Models

effective in understanding what if this alternative plan is realized. However, enormous time and labor has to be consumed to create these 3D models, using 3D modelling software such as 3ds Max or SketchUp. In order to automate laborious steps, we proposed a GIS (Geographic Information System) and CG integrated system for automatically generating 3D building models, based on only building polygons i.e. building footprints on a digital map shown in Fig. 1 left.

A complicated orthogonal polygon can be partitioned into a set of rectangles. The proposed integrated system partitions orthogonal building polygons into a set of rectangles and places rectangular roofs and box-shaped building bodies on these rectangles. In order to partition an orthogonal polygon, we also proposed a useful polygon expression (RL expression: edges' Right & Left turns expression) and a partitioning scheme for deciding from which vertex a dividing line (DL) is drawn.

Since technicians are drawing building polygons manually with digitizers, depending on aerial photos or satellite imagery as shown in Fig. 1 left, not all building polygons are precisely orthogonal.   When placing a set of boxes as building bodies for forming the buildings, there may be gaps or overlaps between these boxes if building polygons are not strictly orthogonal. Our contribution is the new methodology for rectifying the shape of building polygons and constructing 3D building models without any gap and overlap. In our proposal, after approximately orthogonal building polygons are partitioned and rectified into a set of mutually orthogonal rectangles, each rectangle knows w[illegible]angle is adjacent to and which edge of the rectangle is adjacent to, which will avoid unwanted intersection of windows and doors when building bodies combined.

2. RELATED WORK

As Since 3D urban models are important information infrastructure that can be utilized in several fields, the researches on creations of 3D urban models are in full swing. Various types of technologies, ranging from computer vision, computer graphics, photogrammetry, and remote sensing, have been proposed and developed for creating 3D urban models. Procedural modelling is an effective technique to create 3D models from sets of rules such as L-systems, fractals, and generative modelling language (Parish et al. 2001). Müller et al. (2006) have created an archaeological site of Pompeii and a suburbia model of Beverly Hills by using a shape grammar that provides a computational approach to the generation of designs. They import data from a GIS database and try to classify imported mass models as basic shapes in their shape vocabulary. If this is not possible, they use a general extruded footprint together with a general roof obtained by the straight skeleton computation defined by a continuous shrinking process (Aichholzer et al. 1995).

By using the straight skeleton, Kelly et al. (2011) present a user interface for the exterior of architectural models to interactively specify procedural extrusions, a sweep plane algorithm to compute a two-manifold architectural surface.

More recently, image-based capturing and rendering techniques, together with procedural modelling approaches, have been developed that allow buildings to be quickly generated and rendered realistically at interactive rates. Bekins et al. (2005) exploit building features taken from real-world capture scenes. Their interactive system subdivides and groups the features into feature regions that can be rearranged to texture a new model in the style of the original. The redundancy found in architecture is used to derive procedural rules describing the organization of the original building, which can then be used to automate the subdivision and texturing of a new building. This redundancy can also be used to automatically fill occluded and poorly sampled areas of the image set.

Aliaga et al. (2007) extend the technique to inverse procedural modelling of buildings and they describe how to use an extracted repertoire of building grammars to facilitate the visualization and modification of architectural structures. They present an interactive system that enables both creating new buildings in the style of others and modifying existing buildings in a quick manner.

Vanega et al. (2010) interactively reconstruct 3D building models with the grammar for representing changes in building geometry that approximately follow the Manhattan-world (MW) assumption which states there is a predominance of three mutually orthogonal directions in the scene. They say automatic approaches using laser-scans or LIDAR data, combined with aerial imagery or ground-level images, suffering from one or all of low-resolution sampling, robustness, and missing surfaces. One way to improve quality or automation is to incorporate assumptions about the buildings such as MW assumption.

Jianxiong (2014) presents a 3D reconstruction and visualization system to automatically produce clean and well-regularized texture-mapped 3D models for large indoor scenes, from ground-level photographs and 3D laser points. The key component is a new algorithm called “Inverse CSG” for reconstructing a scene in a Constructive Solid Geometry (CSG) representation consisting of volumetric primitives, which imposes regularization constraints to exploit structural regularities. However, with the lack of ground-truth data preventing them from conducting quantitative reconstruction accuracy evaluations, they have to manually overlay their model with a floor plan image.

By these interactive modelling, 3D building models with plausible detailed façade can be achieved. However, the limitation of these modelling is the large amount of user interaction involved (Nianjuan et al. 2009). When creating 3D urban models for urban planning or facilitating public involvement, 3D urban models should cover lots of citizens’ and stakeholders’ buildings involved. This means that it will take an enormous time and labor to model a 3D urban model with hundreds of building.

Thus, the GIS and CG integrated system that automatically generates 3D urban models immediately is proposed, and the generated 3D building models that constitute 3D urban models are approximate geometric 3D building models that citizens and stakeholder can recognize as their future residence or real-world building.

3. PIPELINE OF AUTOMATIC GENERATION

As shown in Fig. 1, the proposed automatic building generation system consists of GIS application (ArcGIS, ESRI Inc.), GIS module and CG module. The source of the 3D urban model is a digital residential map that contains building polygons linked with attributes data shown in Fig. 1 left bellow, consist of the number of storeys, the image code of roof, wall and the type of roof (gable roof, hipped roof, gambrel roof, mansard roof, temple roof and so forth). If a digital map is given, the only manual labor is to input these attributes. The maps are then preprocessed at the GIS module, and the CG module finally generates the 3D urban model. As a GIS module, a Python program including ArcPy(ArcGIS) acquires coordinates of building polygons' vertices and attributes. Preprocessing at the GIS module includes the procedures as follows:

(1) Filter out an unnecessary vertex whose internal angle is almost 180 degrees. **(2)** Partition or separate approximately orthogonal polygons into a set of quadrilaterals. **(3)** Generate inside contours by straight skeleton computation for placing doors, windows, fences and shop façades which are setback from the original building polygon. **(4)** Rectify a set of quadrilaterals to be a set of rectangles and orthogonal to each other. **(5)** Export the coordinates of polygons' vertices, the length, width and height of the partitioned rectangle, and attributes of buildings.

The CG module receives the pre-processed data that the GIS module exports, generating 3D building models. In GIS module, the system measures the length and inclination of the edges of the partitioned rectangle. The CG module generates a box of the length and width, measured in GIS module. In case of modelling a building with roofs, the CG module follows these steps:

(1) Generate primitives of appropriate size, such as boxes, prisms or polyhedra that will form the various parts of the house. **(2)** Boolean operations applied to these primitives to form the shapes of parts of the house, for examples, making holes in a building body for doors and windows, making trapezoidal roof boards for a hipped roof and a temple roof. **(3)** Rotate parts of the house according to the inclination of the partitioned rectangle. **(4)** Place parts of the house. **(5)** Texture mapping onto these parts according to the attribute received. **(6)** Copy the 2nd floor to form the 3rd floor or more in case of building higher than 3 stories.

CG module has been developed using Maxscript that controls 3D CG software (3ds MAX, Autodesk Inc).

4. FUNCTIONALITY OF GIS MODULE

4.1 Polygon Expression and Partitioning Scheme

At map production companies, technicians are drawing building polygons manually with digitizers, depending on aerial photos or satellite imagery as shown in Fig. 1 and 2. This aerial photo and digital map also show that most building polygons are approximately orthogonal polygons. An approximately orthogonal polygon can be replaced by a combination of rectangles. When the vertices of a polygon are numbered in clockwise order and edges of a

polygon are followed clockwise, an edge turns to the right or to the left by 90 degrees. It is possible to assume that an orthogonal polygon can be expressed as a set of its edges' turning direction; an edge turning to the 'Right' or to the 'Left'.

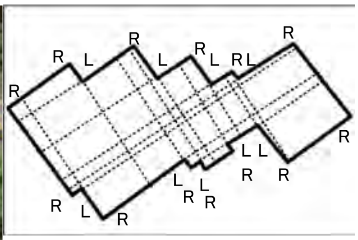


Fig.2: Building polygons on satellite image, expressed as a set of its edges' turning direction; RRLRLRLRLRRRLLRRLRLRLR

Fig.3: Two DLs from L vertex. 9 L vertices, so 18 DLs can be drawn from each L vertex

We proposed a useful polygon expression (RL expression: edges' Right and Left turns expression) for specifying the shape pattern of an orthogonal polygon. For example, an orthogonal polygon with 22 vertices shown in Fig.2 is expressed as a set of its edges' turning direction; RRLRLRLRLRRRLLRRLRLRLR where R and L mean a change of an edge's direction to the right and to the left, respectively.

The more vertices a polygon has, the more partitioning scheme a polygon has, since the interior angle of a 'L' vertex is 270 degrees and two DLs (dividing lines) can be drawn from a L vertex. In the polygon shown in Fig. 3, there are 9 L vertices, so 18 DLs can be drawn from each L vertex as shown in dotted lines. In our proposal, among many possible DLs, the DL that satisfies the following conditions is selected for partitioning.

(1) *A DL that cuts off 'one rectangle'.*

(2) *A DL whose length is shorter than the width of a 'main roof' that a 'branch roof' is supposed to extend to, where a 'branch roof' is a roof that is cut off by a DL and extends to a main roof.*

How the system is finding 'branches' is as follows. The system counts the number of consecutive 'R' vertices (=n_R) between 'L' vertices. If n_R is two or more, then it can be a branch. One or two DLs can be drawn from 'L' vertex in a clockwise or counter-clockwise direction, depending on the length of the adjacent edges of 'L' vertex. How the DL is drawn (clockwise or counter-clockwise), that is, 'dividing pattern' is used for reconstructing a rectified polygon and saved at the divided rectangle.

4.2 Process of Polygon Partition and Shape Rectification

Fig.4 shows detailed process of polygon partition and shape rectification, generation of a 3D building model. The system executes the partitioning procedure as follows:

(1) Classify the branches by the number of successive 'R' vertices, and the length of the edge especially incident

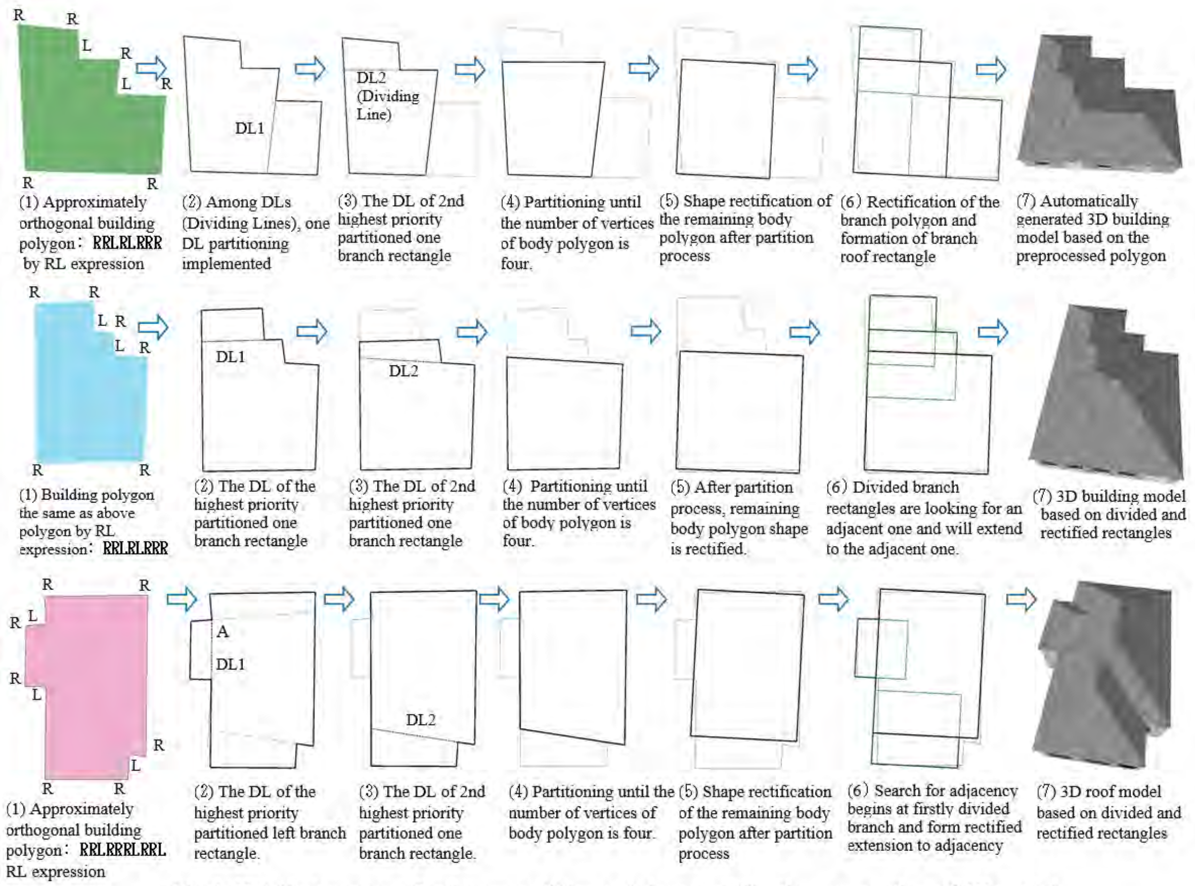


Fig.4: Detailed process of polygon partition and shape rectification, generation of 3D model

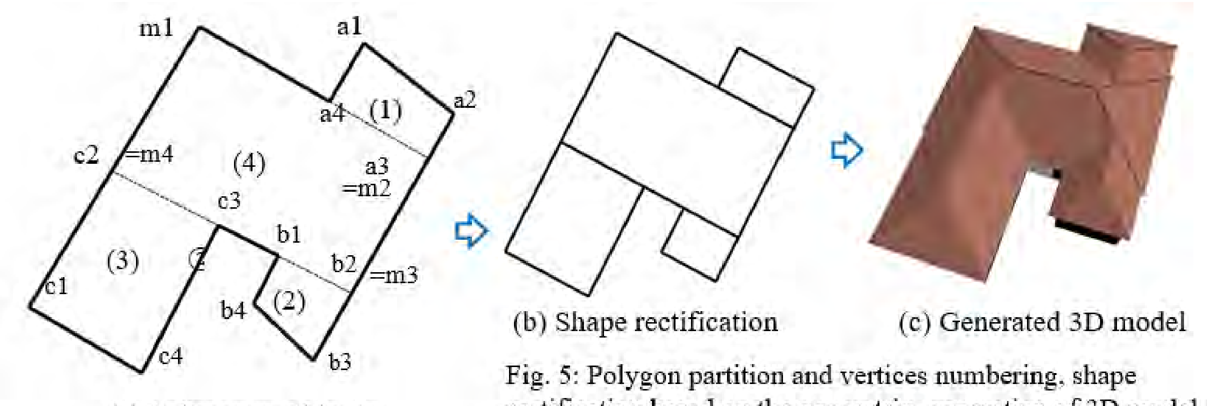
to 'L' vertex, and dividing pattern. (2) Check whether the DL is satisfying three conditions or not, by measuring the distance between the DL and other edges in the same polygon, which will be the width of the main roof. (3) If the DL satisfies the conditions and is given the highest priority, then the position of the intersection between the DL and edges is calculated. (4) Set the erase flags for the vertices of the branch that are cut off from a body polygon, and a new vertex that is the intersection will be included by the body polygon. (5) Measure the edge length and inner angle of the polygon's vertices, and acquire edges' Right and Left turns expression (RL expression).

This partitioning procedure continues until the number of the vertices of the body polygon is four. In Fig.4 (2) in upper row, branch quad is divided by DL1 which is a Forward Dividing Line (FDL) in terms of polygon vertices numbering (clockwise). In Fig.4 (3) in upper & middle row, branch quad is divided by DL2 which is a Backward Dividing Line (BDL) drawn in the opposite direction (counter-clockwise). The dividing pattern is defined by this FDL or BDL.

A branch quad divided by DL1 in Fig.4 (2) in lower row is given the highest priority for partitioning, since this partition reduces the number of the vertices of the body polygon by four. A branch quad divided by DL1 in Fig.4 (2) in upper & middle row are given the less priority for partitioning, as these partition reduces the vertex number by two. Thus, the system is giving each DL the degree of priority for partitioning, and the partitioning by the DL of the highest priority will be executed. Two DLs satisfying first two conditions can be drawn from the same vertex, such as 'A', shown in Fig.4 (2) in lower row. But, the third condition excludes the longer DL, since condition third demands a DL whose vertices are not shared by another DL, which will prevent unnecessary dividing. A shorter DL is selected for partitioning. After remaining body polygon's vertex number is four, the shape rectification begins by transforming the remaining polygon into a rectangle, as shown in Fig.4 (5). An active branch quad will start to search for an adjacent quad in reverse order from the last divided branch. The active quad will find a neighboring quad by using quad's vertices position of before rectification. Therefore, each quad instance has double vertices positions of before and after rectification. When forming the branch rectangle and branch roof rectangle, the system is using quad's vertices position of after rectification.

4.3 SHAPE RECTIFICATION

Specifically, the rectification procedure is implemented to the polygon shown in Fig.5, which shows the process of polygon partition and shape rectification, automatic 3D modelling. Before polygon partitioning, all edge length and edge inclination of the polygon are measured, and the length of all edges are sum up according to the snapped angle of all edge inclination. Then, the angle for a longest sum up edge length can be adopted as the 'main angle' of the polygon, which will be then used as the inclination of all partitioned rectangles. After GIS module measuring the length and inclination of all edge of the partitioned polygon, i.e., a quadrilateral ('quad' for short), the edges are categorized into a long edge (w_L or edge12) and a short edge (w_S or edge23). A partitioned quad (quadrilateral) is numbered clockwise with the start point of a longest edge facing right as pt1 (a1, b1,..) or with the start point of a longest edge facing left as pt3 (a3, b3,..) as shown in Fig.5 (a).



(a) Polygon partitioning

(b) Shape rectification

(c) Generated 3D model

Fig. 5: Polygon partition and vertices numbering, shape rectification based on the generatrix, generation of 3D model

When a quad is cut off, the dividing pattern and which edge of the quad is cut off (active edge i.e. DL: Dividing Line) is saved at the quad. During the searching stage, an active quad will search for an adjacent quad by locating which quad the checking point on the active edge contains, and then checking on which edge of the adjacent quad the checking point is. In case of quad (1) in Fig.5 (a), DL (a3a4) will be an active edge, and search for an adjacent quad. After searching and having found out the adjacent quad is quad (4) and the adjacent edge is m1m2 of quad (4), the mutual vertex is a3(=m2), which the rectification procedure uses as a 'standard position (generatrix)' for rectification, since this vertex is shared by two quads and could be an origin of local coordinates.

The rectified positions of the vertices of quad (1) are calculated as follows.

a1.x=m2.x + w_S*cosθ- w_L*sinθ

a1.y=m2.y + w_S*sinθ+ w_L*cosθ

$a2.x=m2.x + w\_S*\cos\theta$: $a2.y=m2.y + w\_S*\sin\theta$

$a4.x=m2.x - w\_L*\sin\theta$: $a4.y=m2.y + w\_L*\cos\theta$

where θ is the main angle and w_S is the average length of two short sides of the rectangle, and w_L is the average length of two long sides of the rectangle. In case of quad (3), the mutual vertex is c2(=m4), which the rectification procedure also uses as a standard position for rectification. The rectified positions of the vertices of quad (3) are calculated as follows.

$c1.x=m4.x - w\_L*\cos\theta$: $c1.y=m4.y - w\_L*\sin\theta$

$c3.x=m4.x + w\_S*\sin\theta$: $c3.y=m4.y - w\_S*\cos\theta$

$c4.x=m4.x - w\_L*\cos\theta+ w\_S*\sin\theta$

$c4.y=m4.y - w\_L*\sin\theta- w\_S*\cos\theta$

The rectified positions of the vertices of a branch quad in other cases are calculated likewise according to the dividing pattern and which edge of the branch quad is cut off.

5. FUNCTIONALITY OF GIS MODULE

As shown in Fig.1, the CG module receives the pre-processed data that the GIS module exports, generating 3D building models. The pre-processed data includes the following data; the number of partitioned rectified quads, vertex coordinates of rectified building body quads and rectified roof quads, lengths and inclinations of the long and short edge of the quads (w_L, w_S), attributes linked with building polygon consisting of the number of storeys, the image code of roof, wall and the type of roof (flat, gable roof, hipped roof, oblong gable roof, gambrel roof, mansard roof, temple roof and so forth). Depending on these data, a CG module generates 3D building models. Fig.6 shows the generation process of a hipped roof house model by CG module.

As mentioned earlier, the GIS module partitions and rectifies approximately orthogonal building polygons into a set of rectangles, and the CG module places rectangular roofs and box-shaped building bodies on these rectangles, depending on the front view and ground plan such as Fig.7 and Fig.8. The vertices of the rectangle are numbered clockwise with the upper left vertex of a long edge being numbered ‘pt1’ as shown in Fig.8, ‘ground plan’ of a gable roof. The length of edge12 and edge23 are w_L and w_S respectively.

In 3ds Max used for the creation of 3D models, each building part or primitive has its own control point (‘cp’) and local coordinates that control its position and direction. The position of a ‘cp’ is different in each primitive. As shown in Fig.8, the top of a gable roof consists of two roof boards (two thin boxes). Since the ‘cp’ of a box lies in a center of a base, it is placed on the point that divides the line through pt12 and pt34 at the ratio shown in ground plan. The height of the ‘cp’s of two roof boards is shown in the front view of a gable roof (Fig.7).

The CG module’s generation process for modeling a hipped roof house is as follows.

(1) Generation of primitives of appropriate size, such as boxes, prisms that are the parts of the house: For example, the length and width of a box as a house body are decided by the rectangle partitioned and rectified in GIS module. As shown in Fig.8, the length of a box will be w_L and the width of a box will be w_S. Also, the length of a thin box as a roof board is decided by the rectangle partitioned while the width of a roof board is decided by the slope of the roof given as a parameter, as shown right in Fig.7.

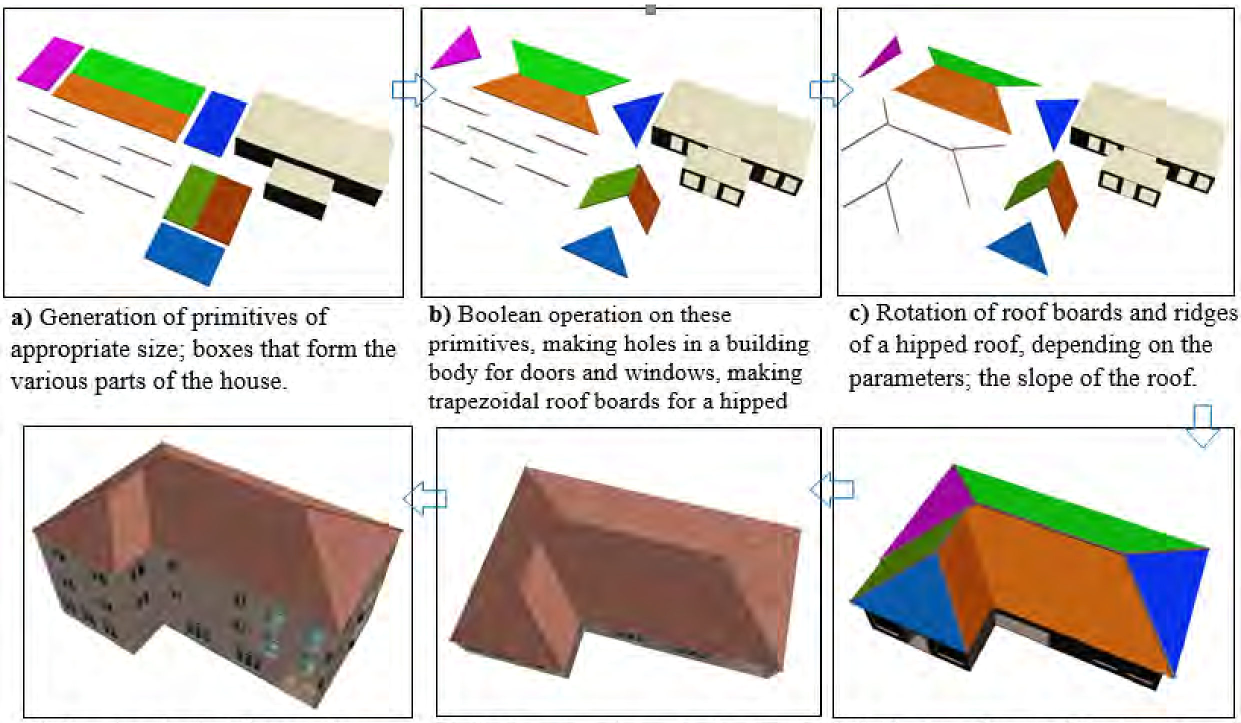
(2) Boolean operation on these primitives to form the shapes of parts of the house: for examples, making holes in a house body doors and windows, making trapezoidal or triangular roof boards for a hipped roof. The size and position, number of the holes are decided by the given parameters.

(3) Rotation of parts of the house: Parts of the house are rotated depending on the direction of the rectangle partitioned. The roof boards are rotated so as to align them according to, respectively, the slopes of the roofs.

(4) Positioning of parts of the house: Parts of the house are placed depending on the position of the rectangle partitioned. For example, the control points of roof boards are placed as shown in Fig.7 and Fig.8.

(5) Texture mapping onto these parts according to the attribute data, such as image code of wall and roof, stored and administrated at GIS application.

(6) Copying the 2nd floor to form the 3rd floor or more in case of building higher than 3 storeys according to the attribute data, the number of storeys as shown in Fig.6 (f).



a) Generation of primitives of appropriate size; boxes that form the various parts of the house.

b) Boolean operation on these primitives, making holes in a building body for doors and windows, making trapezoidal roof boards for a hipped

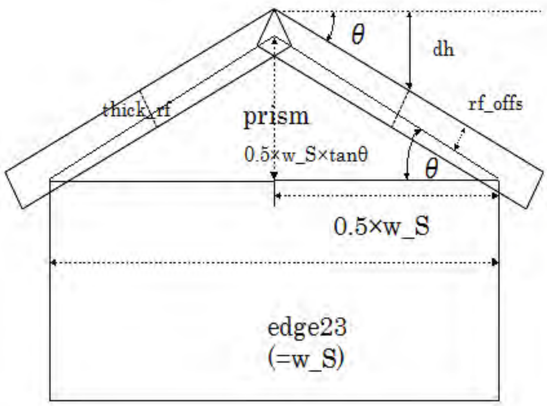
c) Rotation of roof boards and ridges of a hipped roof, depending on the parameters; the slope of the roof.

f) Copying the 2nd floor to form the 3rd floor or more in case of buildings higher than 3 storeys.

e) Texture mapping onto these parts according to the attributes: image code of roofs and walls.

d) Placing of parts of the house, according to the location of the parts calculated at GIS module.

Fig.6: Generation process of a 3D building model in CG module



The width of a roof board is as follows.

$wid\_rfb = side23L + eaves23 + rf\_offs \times \tan\theta$

Here, $side23L = 0.5 \times w\_S \times \sqrt{1 + \tan^2\theta}$

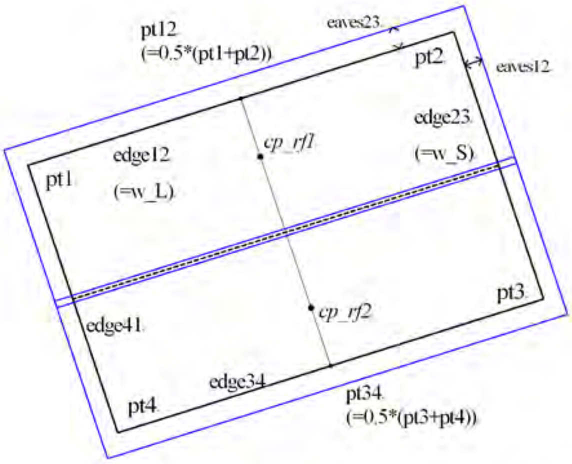
The height of a roof board is as follows.

$hei\_rf = st\_heit - 0.5 \times (side23L + eaves23 + rf\_offs \times \tan\theta) \times$
$- thick\_rf \times \cos\theta + rf\_offs \times \cos\theta + 0.5 \times \tan\theta \times w\_S$

Here, 'st_heit' is start height as follows.

st_heit= (floor-to-floor height)×(the number of sto

Fig.7: Front view of a gable roof



$$ratio\_s = 0.25 - \frac{0.5 \times (eaves23 \times \cos\theta + rf\_offs * \sin\theta)}{w\_S} + \frac{thick\_rf \times \sin\theta}{w\_S}$$

$$cp\_rf1 = (1.0 - ratio\_s) \times pt12 + ratio\_s \times pt34$$
$$cp\_rf2 = ratio\_s \times pt12 + (1.0 - ratio\_s) \times pt34$$

Here, 'thick_rf' is a thickness of a roof board. 'eaves23' is the length of eaves in a direction of edge23. θ is an angle of a roof slope with a horizontal plane. 'rf_offs' is the offset of a roof board from a prism as shown Figure 12.

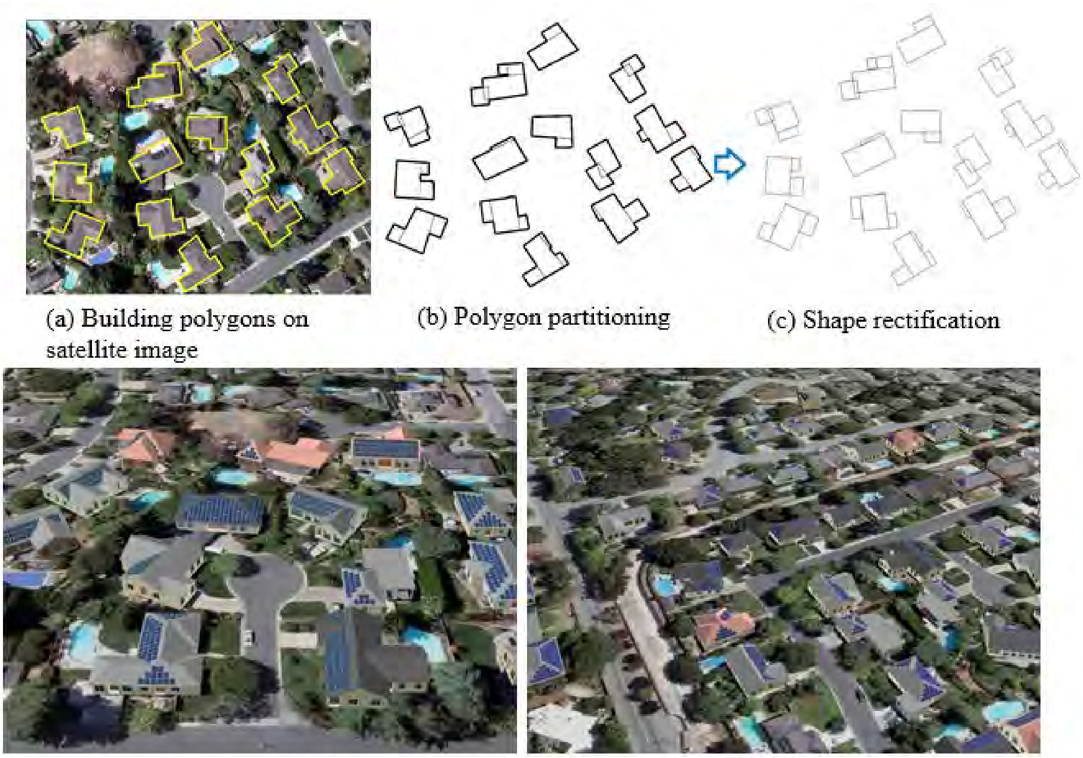
Fig.8: Ground plan and parameters of a gable roof

6. EXAMPLES and CONCLUSIONS

Here are the examples of rectification of approximately orthogonal building polygons and an automatically generated 3D urban model in Fig.9. At map production companies, technicians are drawing building polygons manually with digitizers, depending on aerial photos or satellite imagery as shown in Fig.9 (a), not all building polygons are precisely orthogonal. However, creating 3D building models are expected to be orthogonal. When placing a set of boxes as building bodies for creating the buildings, there may be gaps or overlaps between these boxes if building polygons are not precisely orthogonal.

In our system, since approximately orthogonal building polygons are partitioned into a set of rectangles and rectangles' adjacencies are revealed, one can build a 3D building on each rectangle individually, knowing which rectangle is adjacent to.

In our proposal, the new methodology is proposed for rectifying the shape of building polygons and generating 3D building models without any gap and overlap. After approximately orthogonal building polygons are partitioned into a set of mutually orthogonal rectangles, each rectangle knows which rectangle is adjacent to and which edge of the rectangle is adjacent to, which will avoid unwanted intersection of windows and doors when



(a) Building polygons on satellite image (b) Polygon partitioning (c) Shape rectification

(d) Automatically generated 3D urban model (e) Automatically generated 3D urban model

Fig.9: Application of the System: Polygon partition and shape rectification, generation of 3D urban model

building bodies combined for automatic generation of 3D building models.

Our future work includes extension of geometric primitive types to more shapes, such as elliptic cylinders or spheres.

7. REFERENCES

Aliaga G. Daniel, Rosen A. Paul ,and Bekins R. Daniel (2007). “Style Grammars for interactive Visualization of Architecture”, Visualization and Computer Graphics, IEEE Transactions on Volume:13, 786 - 797

Bekins R. Daniel ,and Aliaga G. Daniel (2005). “Build-by-number: rearranging the real world to visualize novel architectural spaces”, Visualization, 2005. VIS 05. IEEE, 143 – 150.

Carlos, V. A., Daniel, A. G., andr Bedřich, B. (2010). “Building reconstruction using Manhattan-world grammars”, Computer Vision and Pattern Recognition (CVPR), 2010 IEEE Conference on: 358 – 365

Nianjuan, Jiang, Ping, Tan, and Loong-Fah, Cheong (2009). “Symmetric architecture modeling with a single image”, ACM Transactions on Graphics - TOG, vol. 28, no. 5

O. Aichholzer, F. Aurenhammer ,and D. Alberts, B. Gärtner (1995). “A novel type of skeleton for polygons”, Journal of Universal Computer Science, 1 (12): 752–761.

Pascal Mueller, Peter Wonka, Simon Haegler, Andreas Ulmer, Luc Van Gool. (2006). “Procedural modeling of buildings”, ACM Transactions on Graphics 25, 3, 614–623.

Sugihara Kenichi (2005). “Automatic Generation of 3D Building Model from Divided Building Polygon”, ACM SIGGRAPH 2005, Posters Session, Geometry & Modeling, CD-ROM.

Sugihara Kenichi (2006). “Generalized Building Polygon Partitioning for Automatic Generation of 3D Building Models”, ACM SIGGRAPH 2006, Posters Session Virtual & Augmented & Mixed Reality & Environments, CD-ROM.

Sugihara, K. and Kikata, J.(2012). “Automatic Generation of 3D Building Models from Complicated Building Polygons”, Journal of Computing in Civil Engineering, ASCE (American Society of Civil Engineers), DOI: 10.1061/(ASCE)CP.1943-5487.0000192

Tom Kelly, Peter Wonka (2011). “Interactive Architectural Modeling with Procedural Extrusions”, ACM Transactions on Graphics (TOG) 30 (2), 14, 2011. 41, 2011.

Vanegas A. Carlos, Aliaga G. Daniel ,and Beneš Bedřich (2010). “Building reconstruction using Manhattan-world grammars”, Computer Vision and Pattern Recognition (CVPR), 2010 IEEE Conference on: 358 - 365

Yoav I. H. Parish, and Pascal Müller (2001). “Procedural modeling of cities”, Proceedings of ACM SIGGRAPH 2001, ACM Press, E. Fiume, Ed., New York, 301–308.

MODELING URBAN TECHNOLOGY ACCEPTANCE: FACTOR ANALYSIS APPROACH

Sharifeh Sargolzaei[1], Samad M.E. Sepasgozar[2] & Mohammad Mojtahedi[2]

[1]Faculty of Urban Planning, University of Art of Isfahan, Iran

[2]Faculty of the Built Environment, University of New South Wales, Australia

ABSTRACT: *Advanced technologies such as sensing and visual technologies potentially improve the efficiency of urban management systems. Modern technologies such as web-based intelligent and positioning systems by different applications are used extensively by the urban planners and are accessed by the technology users. However, studies about factors affecting the users' decision (e.g. urban experts, managers, and citizens) to use new technologies are scarce. Therefore, the purpose of this study is to develop a novel model to predict the acceptance of new urban technologies (including transportation and urban management systems) in metropolises. The proposed model includes 13 factors affecting the users' decision such as 'ease of use', 'performance', and 'perceived empathy'. The model was cross-validated by the result of a survey including 52 independent variables such as cost reduction, ease of use, time saving, and comparative advantage. Confirmatory factor analysis technique was employed to identify key factors, and the data prioritization technique was also utilized to determine the effect of the technology attributes (e.g. the technology usefulness and productivity). The factors also ranked by participants from three metropolises and discussed. The results show that the five key factors have a high impact on the technology acceptance. the proposed Metropolitan Technology Adoption Model (MTAM). This study considers transportation and urban technologies to predict technology acceptance. The MTAM enables local governors to predict the user's behaviors in the acceptance or rejection of the technology before they invest in a modern technology at a metropolitan-wide. It also assists innovators to understand users' interest and behavior when developing a new technology.*

KEYWORDS: *Urban Technology, Metropolitan, Acceptance Model, Factor, Urban user, Adoption.*

1. Introduction

New technologies have become increasingly an important tool to enhance the efficiency of urban management systems. A great amount of data is required for urban policy makers to make agile decisions for transportation and any types of city services. While utilization of new technologies is identified crucial across many disciplines, the investigation of the technology adoption process for urban management systems is totally ignored. In addition, far too little attention has been paid to the urban technology adoption barriers and users' attributes, the perception of the technology advantages and technology usefulness. Technology adoption has been investigated from different perspectives such as socio-economic perspective, psychological perspective, management systems in information and communication systems. Most studies in the field of urban technology have only focused on developing and utilizing urban technologies to solve current urban problems. However, the present paper focuses on the relationship between critical factors that may influence the trend of urban technology. In this case, it's expected that by using more technologies, urban management systems can become smarter and urban user's quality of life will be improved. The results of this study are important for managers and urban planners because these results would assist them to predict the rate of urban technology acceptance. In addition, understanding drivers and barriers to the urban technology adoption will assist policy makers and decision makers to make realistic decisions about the application of different types of technologies in cities.

This paper is organized in five parts. First, the relevant literature is reviewed to identify the research gap and develop the initial urban technology adoption model. Next, the conceptual model is discussed including key factors. Then, the research method is designed and Confirmatory Factor Analysis (CFA) is chosen to analyze the quantitative data. Next, the developed technology adoption model is validated and limitations are discussed.

2. Theorizing Urban Technology Adoption Process

Technology Acceptance Model (TAM) (Venkatesh, Morris, Davis, & Davis, 2003) suggests key factors that may influence users' decision to use a new technology. This model is based on a psychological theory which is called the theory of planned behavior (Ajzen, 1991). In addition, Reasoned Action Theory (Fishbein & Ajzen, 1975) is used to explain the behavior of persons. This theory states that most social behaviors, are under voluntary control, therefore their behavior are predictable from their intent. TAM is known as one of the most useful theories in information systems and cited by scholars in different disciplines considerably. Two main factors of TAM are perceived ease of use and perceived usefulness. Perceived ease of use refers to "the degree to which a person believes that using a particular system would be free of effort" (Davis, 1989). Also perceived usefulness factor is defined as "the degree to which a person believes that using a particular system would enhance his or her job performance (Davis, 1989). The other theory which discusses technology adoption by urban users is Diffusion on Innovation Theory (Rogers, 1995). This theory is a socioeconomic model based on individuals' social relations. The most important factor of this theory is compatibility with other technologies which currently being used by the users. This element offers an understanding of the innovation consistent with existing values, beliefs, experiences and needs of its merchants (Sargolzaei, Sepasgozar, & Moradi, 2015). Main models are presented in Figure 1.

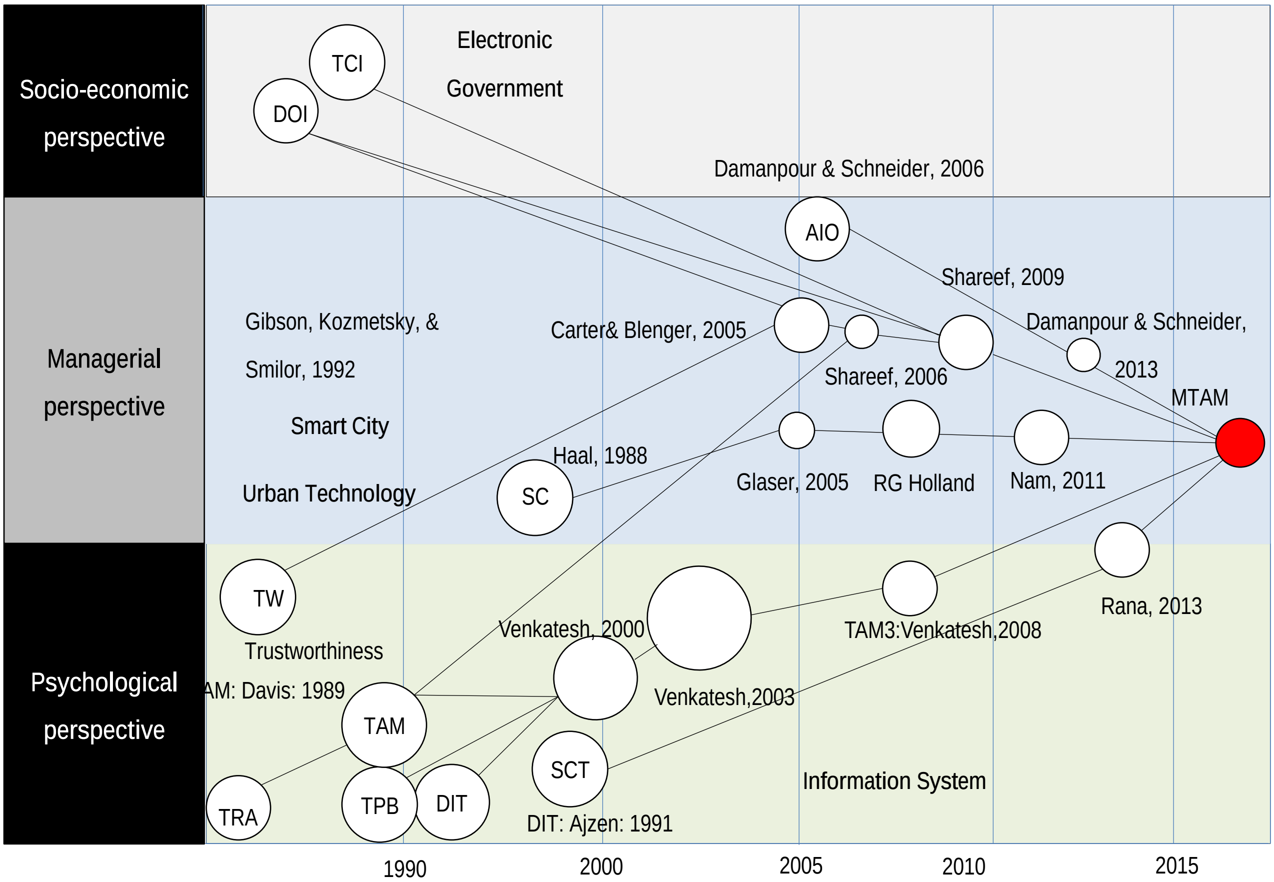


Fig 1: Visual representation of common models

Transaction Cost Analysis (Williamson, 1981) examined the economic burden and tried to explain why companies exist, and what companies expand. This theory also contributes to understanding of the reasons why companies need to employ new technologies from a cost perspective. The main factor extracted from this theory that has been used in his research, ‘cost reduction’ factor, which is expected to reduce the cost according to user expectations to save on running costs (Chiu, Hsu, & Wang, 2006). In addition, Social Cognitive Theory (Bandura, 1986) offers useful and appropriate constructs for understanding individual behavior towards technology adoption. In fact, this theory examines the social effects on individual behavior. This theory includes three main factors: self-efficacy, expectations and applicability of the technology. Since users are a part of a social network, factors of the social cognitive theory are adopted in the present paper such as self-efficacy and work facilitation related to self-efficacy, cost reduction ،energy saving ،time-saving related to expectations of applications, and low-quality services related to the concerns of applications. Self-efficacy refers to the efficient user to ensure his personal performance and also work facilitating factor refers to doing things the way they are now preferred over deals done (Karimi & Niknami, 2011). Energy saving factor may be considered an important factor and it refers to the advantages of the technology use to prevent the circumstances that resulted in the loss of time (Chiu et al., 2006). Low quality service is also considered as an important factor in social cognitive theory referring to the poor quality of service (Bandura, 1989).

Trustworthiness theory is defined as a set of beliefs about the other party that facilitates willingness. Drawing on the theory of reasoned action (TRA), researchers have explored the critical role of trustworthiness (trusting beliefs) in consumer decision making because trusting beliefs (trustworthiness) lead to trusting attitude (consumer trust), which result in trusting intentions or behavior (Akter, D'Ambra, & Ray, 2011). Perceived Security factor and Perceived Reliability factor are selected to represent this theory. Perceived Security refers to understand about a person's financial and personal abuse feel safe focuses on online networks. Perceived Reliability refers to understand the trust and confidence of the technical function of the site is correct and accurate services that promise is given in the notes (Carter & Belanger, 2005).

From a management perspective, Damanpour and Schneider (2013) discusses organizational factors which may affect the process of technology adoption in local governments. This theory is known as Adoption of Innovation in Organization and examines a series of factors such as technology relative advantages, organizational factors and operation. Relative advantages refer to the understanding of innovation as a superiority and priority compared to their previous conditions (Rogers, 1995). The operation also refers to the awareness of citizens to take advantage of modern technology to facilitate daily works (Sargolzaei et al., 2015). To clarify the psychological, administrative or economic factors of technology adoption, an initial structure of the model is developed in Figure 2.

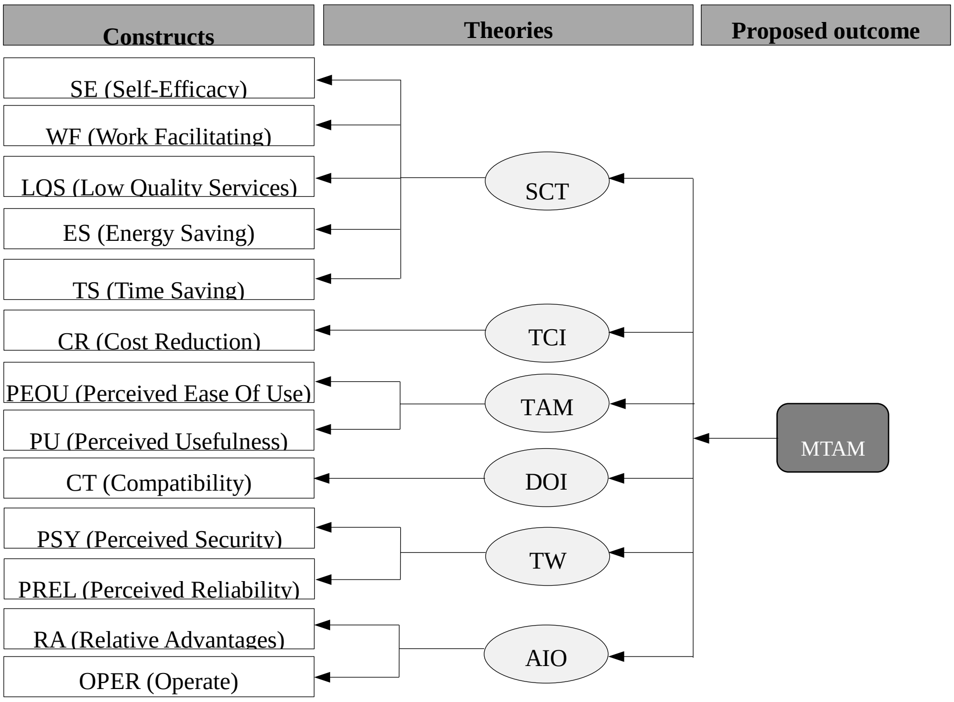


Fig 2: Extracted constructs from used theories in this research

The proposed model is based on an extensive literature review including the theory of planned behavior, diffusion of innovation, technology adoption model, and social cognitive theory as discussed above. Then a questionnaire was designed to test the basic model including proposed factors, and the data were collected accordingly. Figure 3 shows proposed a sequential framework to validate technology adoption by citizens who are using Metropolitan Urban Technology Adoption Model (MTAM).

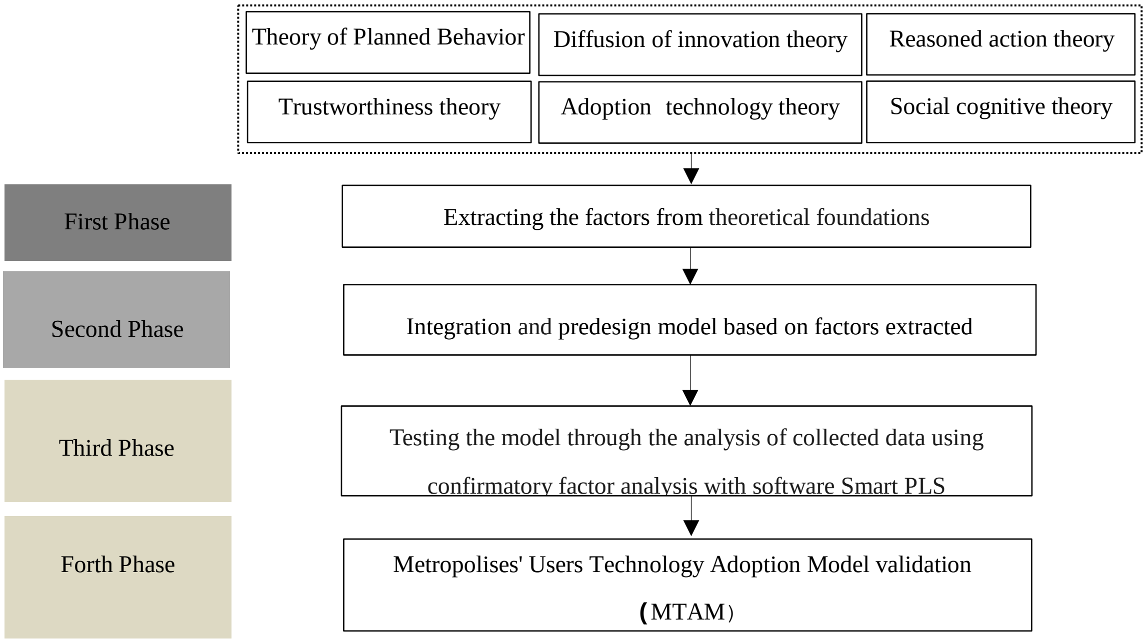


Fig. 3: Metropolises' Users Technology Adoption flowchart

3. Research Methodology

The aim of the study is to identify the main factors influencing user decision to select and use new urban technologies and systems. The confirmatory factor analysis technique was selected to investigate the user's technology adoption model that are living in metropolitans and use new technologies. In total, 315 questionnaires containing 52 questions covering 13 factors were distributed. Some of factors which are asked in the questions covers self-efficacy (SE), work facilitating (WF), operate (OPER), perceived ease of use (PEOU). Based on the proposed factors, the participants are randomly selected and were asked to complete the questionnaire in a hard copy format. For example, it is asked the participants to describe if the utilization of e-service systems is useful. How ease of use is to work with the e-service systems.

The survey is conducted by the first author in the case cities by distributing hard copies of the questionnaire. The respondents were selected randomly from the citizens who are familiar with the current online services. These participants are important to the study, because they experienced at least one of online services provided by city councils and their opinion is important to the urban management systems. The survey response rate was overwhelming; 0.75%, 91%, and 95% for three metropolitans. The sample includes a variety of people in terms of education and gender to make. Smart PLS software was utilized to perform and validate the structural equation model.

.4 Analytical Framework

The measurement models and the final quality of model must be evaluated by utilizing the confirmatory factor analysis in the structural equation modeling. The results of the analysis are provided in the following section.

In this part, the questions related to each factor are called items. Loading factor coefficients corresponding to each factor in this research are shown in table 1. For reliability purposes and covering the designed questions a test is conducted which is based on measuring the factor loadings. Accordingly, any factor loading on a related item should be greater than the optimal amount 0.7 (Ringle, Wende, & Will, 2005). Thus, as it can be seen in Table 1, the factor loading for any factors are more than 0.7 and so it is desirable, and this shows the factor loadings of each related item is acceptable. Reliability refers to the accuracy and precision of a measurement procedure.

Reliability may be viewed as an instrument's relative lack of error. In addition, reliability is a function of properties of the underlying construct being measured, the test itself, the groups being assessed, the testing environment, and the purpose of assessment. Reliability answers the question, how well does the instrument measure what it purports to measure? . Cronbach's alpha, composite reliability and convergent validity are three various methods for measuring the reliability of indicators. Cronbach's alpha coefficient shows the internal consistency reliability of each factor and questions. The Cronbach's alpha value is closer to 1; the reliability a questionnaire is greater. But the appropriate Cronbach's alpha is 0.7 (Cronbach, 1951) . In this study, only energy saving factor has Cronbach's alpha coefficient less than 0.7.

There are another criterion called composite reliability or ρ Dillon-Goldstein in CFA method performed by the smart PLS software. This means that the reliability of each factor is evaluated separately; as a result, the composition can be more reliable.

Table 1: Load Factor for each item on its associated structures

CR		ES		OPER		PREL		RA	
CR1	0.769	ES1	0.923	OPER3	0.904	PREL6	0.865	RA1	0.828
CR2	0.884	ES2	0.756	OPER4	0.821	PREL7	0.819	RA2	0.901
CR3	0.832	WF		PEOU		PSY		RA3	0.818
CR4	0.751	WF1	0.923	PEOU1	0.906	PSY1	0.871	RA4	0.797
CT		WF2	0.881	PEOU2	0.901	PSY2	0.853	TS	
CT1	0.789	WF3	0.917	PEOU3	0.791	PSY3	0.886	TS1	0.81
CT2	0.763	LQS		PEOU4	0.902	PSY4	0.836	TS2	0.915
CT3	0.867	LQS1	0.844	PREL		PU		TS3	0.848
CT4	0.821	LQS2	0.868	PREL1	0.705	PU1	0.887	TS4	0.888
SE		LQS3	0.895	PREL2	0.735	PU2	0.89		
SE1	0.92	OPER		PREL3	0.764	PU3	0.868		
SE2	0.929	OPER1	0.897	PREL4	0.802	PU4	0.888		
SE3	0.898	OPER2	0.865	PREL5	0.715	PU5	0.782		

To obtain composite reliability (Dillon-Goldstein coefficient) if its value is more than 0.7 (Nunnally, 1978), the block is one dimensional. To diagnose whether the block is one dimensional or not, Dillon-Goldstein coefficient has better indicator towards Cronbach's alpha coefficient. That's because the Cronbach's alpha is based on variables equivalence. It's supposed that all of the observed variables are as important as other variables, but Dillon-Goldstein coefficient had different assumption and been computed according to results of loading factors and its model. As shown in the third column of table 2, this coefficient is more than 0.7, and this matter confirms that blocks are one-dimension.

Table 2. Value of coefficients, *t* definitional course and specified variance of any factor

Factor	Cronbach's alpha coefficient	Dillon-Goldstein coefficient	AVE
Cost Reduction	0.82	0.88	0.66
Compatibility	0.83	0.88	0.66
Self-Efficacy	0.9	0.94	0.84
Energy Saving	0.62	0.83	0.71
Work Facilitating	0.89	0.93	0.82
Low Quality Services	0.84	0.9	0.76
Operate	0.89	0.93	0.76
Perceived Ease Of Use	0.9	0.93	0.77
Perceived Reliability	0.89	0.91	0.6
Perceived Security	0.88	0.92	0.74
Perceived Usefulness	0.91	0.93	0.75
Relative Advantages	0.86	0.9	0.7
Time Saving	0.89	0.92	0.75

In PLS modeling, one of the suitable criterions to evaluate an external model is that the factor should have most common variance with its own items towards its sharing with other factors in one determined model. To accomplish this evaluation, average variance extracted (AVE) is suggested to be tested. It refers to the average of common variance between the factor and its items. This criterion that is justifiability indicative of measurement tools, it's supposed that the aimed factor have more common variance with determined items towards of any other factor. Researchers suggest values 0.5 or more of average variance extracted, it means aimed structure specifies its marker variances about 50% or more (Fornell & Larcker, 1981). This value is shown in fourth column table 2. All of the discussed criterions about factors reached to a suitable value, reliability situation and convergent justifiability of research model are assorted.

According to Table 2 error value of 0.01 is meaningful for all courses among the factors of the present research, so structures have enough validity. As discussed above, specified value of variance for any factor shows importance rate and the role of that factor or agent. So, based on the table 2 priority of agent could be classified.

In next step, the value of the indicator of suggested overall evaluation of model must be surveyed. Computing method of indicator of general practice of model (GOF) is explained:

$$GOF = \sqrt{\overline{Communalities} \times \overline{R^2}}$$

Reached values of $\overline{\text{Communalities}}$, is obtained from average of communal values of all structures and value of R^2 is obtained from value of R Square of all structures of the model. Therefore, value of GOF for discussed model will attain by:

$$GOF = \sqrt{\overline{Communalities} \times \overline{R^2}} = \sqrt{0.72 \times 0.67} = \sqrt{0.482} = 0.69$$

Wetzels and his teammates recommended three values of 0.01, 0.25 and 0.36 as weak, normal, and strong values for GOF (Wetzels, Odekerken-Schröder, & Van Oppen, 2009) and obtaining the value of 0.69 for GOF about present research model, is suitable confirmation of general model practice. In fact, confirmatory factor analysis of this research shows that items of aimed questionnaire can specify the determined factors (Wetzels et al., 2009).

5. Discussion

The purpose of this study was to develop a model to anticipate metropolitans' users' modern technology adoption. The theories and technology adoption models were studied in the literature review. Second, for representing a suitable model according to Iranian urban residents a prior model has been tested. In this model 13 factors in confirmatory factor analysis were studied. So explained variance for each of them refers to the importance and role of each factor in the model. The results from analyzing collected data in Smart PLS software was presented in the figure 4. This priority for MUTAM factor model is in accordance with Table 3. From urban residents questioned perspective, among the factors of the model, Self-efficacy factor, Operate factor, Work Facilitating, Relative Advantages and Compatibility factor are prioritized from first to fifth. But the scores of these factors are very close to each other based on the urban resident visions. Hence, they can be considered significant. These results show urban residents questioned understand the importance of modern technology adoption for living in a successful urban life according to the terms of developments in the world. After five first factors, perceived reliability factor is prioritized in sixth with not so much difference in the score from the previous factors.This indicates that after the adoption of operation of the modern technology is important for urban users, understanding the reliability of the technology for users is an important position, so that they could rely on technology to do things in a better way. The similar score between this factor and the next forth factors which are included Perceived Usefulness, Perceived Ease of Use, Time Saving, and Cost Reduction shows urban users to facilitated the tasks and reduce the direct and indirect costs of living in metropolitans are willing to use the technology. Finally, the last factors which are at the end of prioritized list of factors are Low-Quality Services, Perceived Security, and Energy Saving. It can be because of the small importance of energy conservation in culture and social futures of respondents. The abundant energy resources in the country on the one hand and the relatively low cost of energy on the other hand, low cost of fossil fuels for energy, especially compared to other current costs of living such as rent of housing, is another factor to reduce the importance of this factor among questioned urban user. Totally, urban users do not pay attention to economize in energy conservation.

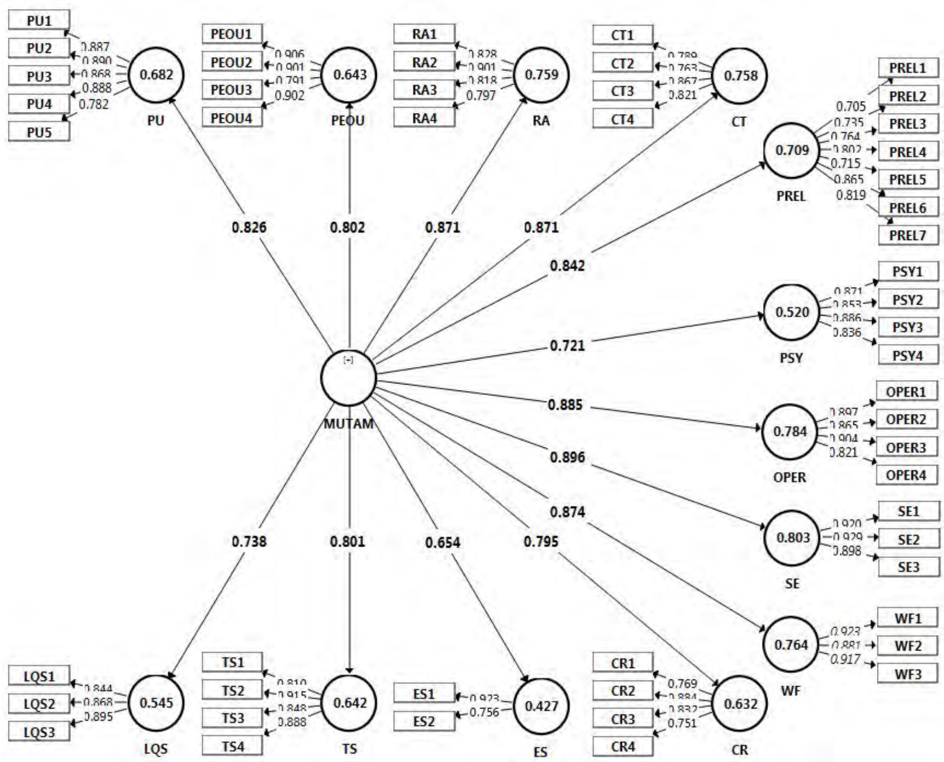


Fig 4: Output of Smart PLS software, the conceptual structure model in this research

Table 3: prioritise factors in the analysis of the models reviewed

prioritize factors	prioritize factors in the analysis of MUTAM	Extracted variance
1	Self-Efficacy	0.803
2	Operate	0.784
3	Work Facilitating	0.762
4	Relative Advantages	0.759
5	Compatibility	0.758
6	Perceived Reliability	0.709
7	Perceived Usefulness	0.682
8	Perceived Ease Of Use	0.671
9	Time Saving	0.642

10	Cost Reduction	0.633
11	Low Quality Services	0.545
12	Perceived Security	0.52
13	Energy Saving	0.427

6. Conclusion

The purpose of this study was to develop a model for predicting urban technology adoption. In order to achieve this, an extensive literature review has been done, and the initially the Metropolitan Technology Adoption Model was proposed. A quantitative method was employed to examine and validate the model including 13 proposed factors. A total of 415 questionnaires were collected from different urban technology users who are randomly recruited and answered to 53 questions each referring to a specific variable. The conformity factor analysis method was employed and analyzed using Smart PLS program. The results show that 13 factors are reliable and the questions measuring each factor are meaningful. The Cronbach's Alpha coefficient was lower than 0.7 only in the case of 'Energy Saving'. The results from the analysis assisted the researchers to prioritize factors based on their importance to each group of participants in different metropolitans. In this prioritizing process, five factors such as self-efficacy, operate, work facilitating, relative advantages and compatibility are positioned from one to fifth, where their scores are too close to each other. The result shows that technology users are interested in taking advantage of modern technologies as a part of modern urban services. The model provides an important tool for urban planners to predict and evaluate the process of technology acceptance for the technology they are planning to use in their organizations.

REFERENCES

Ajzen, I. (1991). The Theory of Planned Behavior. *Organizational behavior and human decision processes, 50*(2), 179-211.

Akter, S., D'Ambra, J., & Ray, P. (2011). Trustworthiness in mHealth information services: an assessment of a hierarchical model with mediating and moderating effects using partial least squares (PLS). *Journal of the American Society for Information Science and Technology, 62*(1), 100-116.

Bandura, A. (1986). *Social foundations of thought and action: A social cognitive theory*: Prentice-Hall, Inc.

Bandura, A. (1989). Human Agency in Social Cognitive Theory. *American psychologist, 44*(9), 1175.

Carter, L., & Belanger, F. (2005). The Utilization of E-Government Services: Citizen Trust, Innovation and Acceptance Factors. *Information systems journal, 15*(1), 5-25.

Chiu, C.-M., Hsu, M.-H., & Wang, E. T. (2006). Understanding knowledge sharing in virtual communities: An integration of social capital and social cognitive theories. *Decision Support Systems, 42*(3), 1872-1888.

Cronbach, L. J. (1951). Coefficient alpha and the internal structure of tests. *psychometrika, 16*(3), 297-334.

Damanpour, F., & Schneider, M. (2013). Characteristics of innovation and innovation adoption in public organizations: Assessing the role of managers. *Journal of public administration research and theory, 19*(3), 495-522.

Davis, F. D. (1989). Perceived Usefulness, Perceived Ease of Use, and User Acceptance of Information Technology. *MIS quarterly*, 319-340.

Fishbein, M., & Ajzen, I. (1975). *Belief, Attitude, Intention and Behavior: An Introduction to Theory and Research*.

Fornell, C., & Larcker, D. F. (1981). Evaluating structural equation models with unobservable variables and measurement error. *Journal of marketing research*, 39-50.

Karimi, M., & Niknami, S. (2011). Self-efficacy and perceived benefits/barriers on the AIDs preventive behaviors. *Journal of Kermanshah University of Medical Sciences (J Kermanshah Univ Med Sci), 15*(5).

Nunnally, J. (1978). Psychometric methods: New York: McGraw-Hill.

Ringle, C., Wende, S., & Will, A. (2005). Smart PLS 2.0 M3, University of Hamburg.

Rogers, E. M. (1995). Diffusion of Innovations: Modifications of a Model for Telecommunications. *Die Diffusion von Innovationen in der Telekommunikation, 17*, 25-38.

Sargolzaei, S., Sepasgozar, S. M. E., & Moradi, M. (2015). *Intention to Use New Technologies in Urban Management: An Application and Extension of the Technology Acceptance Model for* Paper presented at the international conference on research in science and technology, kualalumpur-malaysia.

Venkatesh, V., Morris, M. G., Davis, G. B., & Davis, F. D. (2003). User Acceptance of Information Technology: Toward a Unified View. *MIS quarterly*, 425-478.

Wetzels, M., Odekerken-Schröder, G., & Van Oppen, C. (2009). Using PLS path modeling for assessing hierarchical construct models: Guidelines and empirical illustration. *MIS quarterly*, 177-195.

Williamson, O. E. (1981). The Economics of Organization: The Transaction Cost Approach. *American journal of sociology*, 548-577.

Ajzen, I. (1991). The Theory of Planned Behavior. *Organizational behavior and human decision processes, 50*(2), 179-211.

Akter, S., D'Ambra, J., & Ray, P. (2011). Trustworthiness in mHealth information services: an assessment of a hierarchical model with mediating and moderating effects using partial least squares (PLS). *Journal of the American Society for Information Science and Technology, 62*(1), 100-116.

Bandura, A. (1986). *Social foundations of thought and action: A social cognitive theory*: Prentice-Hall, Inc.

Bandura, A. (1989). Human Agency in Social Cognitive Theory. *American psychologist, 44*(9), 1175.

Carter, L., & Belanger, F. (2005). The Utilization of E-Government Services: Citizen Trust, Innovation and Acceptance Factors. *Information systems journal, 15*(1), 5-25.

Chiu, C.-M., Hsu, M.-H., & Wang, E. T. (2006). Understanding knowledge sharing in virtual communities: An integration of social capital and social cognitive theories. *Decision Support Systems, 42*(3), 1872-1888.

Cronbach, L. J. (1951). Coefficient alpha and the internal structure of tests. *Psychometrika, 16*(3), 297-334.

Damanpour, F., & Schneider, M. (2013). Characteristics of innovation and innovation adoption in public organizations: Assessing the role of managers. *Journal of public administration research and theory, 19*(3), 495-522.

Davis, F. D. (1989). Perceived Usefulness, Perceived Ease of Use, and User Acceptance of Information Technology. *MIS quarterly*, 319-340.

Fishbein, M., & Ajzen, I. (1975). *Belief, Attitude, Intention and Behavior: An Introduction to Theory and Research*.

Fornell, C., & Larcker, D. F. (1981). Evaluating structural equation models with unobservable variables and measurement error. *Journal of marketing research*, 39-50.

Karimi, M., & Niknami, S. (2011). Self-efficacy and perceived benefits/barriers on the AIDs preventive behaviors. *Journal of Kermanshah University of Medical Sciences (J Kermanshah Univ Med Sci), 15*(5).

Nunnally, J. (1978). Psychometric methods: New York: McGraw-Hill.

Rogers, E. M. (1995). Diffusion of Innovations: Modifications of a Model for Telecommunications. *Die Diffusion von Innovationen in der Telekommunikation, 17*, 25-38.

Sargolzaei, S., Sepasgozar, S. M. E., & Moradi, M. (2015). *Intention to Use New Technologies in Urban Management: An Application and Extension of the Technology Acceptance Model for* Paper presented at the international conference on research in science and technology, kualalumpur-malaysia.

Venkatesh, V., Morris, M. G., Davis, G. B., & Davis, F. D. (2003). User Acceptance of Information Technology: Toward a Unified View. *MIS quarterly*, 425-478.

Wetzels, M., Odekerken-Schröder, G., & Van Oppen, C. (2009). Using PLS path modeling for assessing hierarchical construct models: Guidelines and empirical illustration. *MIS quarterly*, 177-195.

Williamson, O. E. (1981). The Economics of Organization: The Transaction Cost Approach. *American journal of sociology*, 548-577.

BIM AND GIS INTEGRATION: AN INVESTIGATION ON ITS SCOPE IN THE U.A.E

Amreen Nizam

Heriot Watt University

Nithin Thomas

Shapoorji Pallonji International

Dr. Yasmein Nelisen & Dr. Hagir Hakim

Heriot Watt University

ABSTRACT: *The Construction Industry in the Middle East is growing at fast pace owing to the long-term commitments in infrastructure and event-driven opportunities. Taking the case of U.A.E alone, being the host of Expo2020, there are numerous transportation and tourism projects which are expected to be awarded. In the backdrop of these projects, tools such as BIM (Building Information Modelling) and GIS (Geographical Information Systems) which have revolutionized the AEC(Architecture, Engineering and Construction) industry globally are also perceived to have great potential in the U.A.E. While asset owners have accepted them independently, there are limitations for both which can be overcome by an integrated model. This research paper investigates the scope and relevance for the implementation and integration of BIM and GIS in U.A.E in the context of regular construction, historical buildings and complex projects (projects that involve a huge amount of data). These complex projects in particular, hold a lot of importance in the current scenario of having projects like GCC rail and expansion of the Dubai Metro. In this paper, the current trends and scope are discussed based on the findings of a survey conducted amongst a sample size of 60 professionals associated with the construction industry in the U.A.E. The survey indicates that BIM and GIS are still in its infancy in the U.A.E. However, the research also identified that there is great potential in its integration considering the several big projects lined up. The challenges of BIM-GIS and its integration are discussed and the paper concludes by stating that the U.A.E has great scope for BIM-GIS integration if introduced in the right manner.*

KEYWORDS: *BIM, GIS, Integration, Complex projects.*

1. INTRODUCTION

1.1 BIM and GIS – A Brief

Digital technology has brought about revolution all around the world. With remarkable transformation in the retail, transport, financial and manufacturing industry, digital technology is changing the way we build, plan and use our infrastructure. However, the construction industry has always been slow to embrace new technology and innovative concepts (Stewart et al., 2002). Innovation in construction projects and its approaches has led to fragmentation in the industry as there is now a diverse range of stakeholders involved right from designers/engineers to the vendors/supplier(Kent and Becerik-Gerber, 2010).These stakeholders generate a wide range of information which forms part of the project document. However, this information from various stakeholders tends to be left unregulated which can lead to complexities (Rezgui and Zarli, 2006).

BIM and GIS have gained popularity as digital tools that have great potential to transform the AEC industry (Ebrahim et al., 2015) and offer solutions to reduce the above said fragmentation (Succar, 2009). Taking the case of U.A.E too, BIM and GIS are revolutionizing the way companies are planning, designing, delivering and managing assets. Despite the fact that both BIM and GIS have been embraced by asset owners independently, a lot of the information they hold is stored in separate databases that do not interoperate with each other leading to the duplication of effort and complex management of separate workflows (AECOM, 2015).This in turn has paved way for the researches, studies and attempts to generate an integrated BIM-GIS model. While such arguments mainly apply to new buildings/construction, very little work has been done in the area of historical buildings. Historical buildings have large amount of architectural details which cannot be surveyed by traditional techniques and hence the application of digital technology like BIM and GIS can be beneficial (Dore and Murphy, 2012).Another area where BIM and GIS have indispensable contribution is “Complex” projects. They are those done by companies like CERN (European Council for Nuclear Research) and Crossrail and have a significant amount of data and complexity involved. In case of these projects, BIM and GIS are inevitable tools offering invaluable benefits to these projects as compared to the traditional CAD (Whyte et al., 2016). The Middle East is seen to be the most lucrative landscape for BIM owing to the enormous amount of rail and transportation projects that is happening within the region. Taking the case of U.A.E too, with the advent of the projects like the Dubai Metro and GCC rail which are indeed complex projects, the scope for the use of BIM and GIS remains large. A notable point is the BIM mandate adopted by the Dubai Municipality. Despite the fact that the mandate is more focused towards the consultants rather than a full life-cycle approach, this can still be perceived as the first step towards pioneering the adoption of BIM in the U.A.E. However, the focus on an integrated BIM-GIS approach still remains limited (Thomas and Al-Hajj, 2014). Arguably, in the recent years, some projects in Dubai such as the Expo Village Development require an integrated BIM-GIS application in the project specifications and such projects could pave the way for other asset owners to adopt an integrated BIM-GIS approach.

Based on the above discussions, this paper investigates the current trends of BIM and GIS in the U.A.E, the scope for its integration and also looks at the barriers affecting a full-fledged integration.

1.2 Research Methodology

In order to clearly understand the implementation of BIM and GIS on a global scale, a literature review was carried out. A break-up of the publications reviewed is as outlined in the following table:-

Table 1: Chronological sorting of publications referred

Sno	Years	Client
1	2016 - 2010	22

2	2009 - 2001	6
Total		28

After the literature review, it was imperative that a proper assessment of the local industry was done. In order to do it in the most comprehensive manner, a survey was thought to be best at reaching a large crowd rather than carrying out personal interviews. Based on the findings of the literature review, the survey was electronically circulated to professionals in the U.A.E industry and was completed by a total of 60 respondents, with details as follows:-

Table 2: Details of survey respondents

Years of experience	**Architects**	**Consultants**	**Contractors**	**Quantity Surveyor**	**GIS Specialist**	**Client**
0-2	1	4	5	0	-	-
2-5	6	7	10	2	-	1
5-10	2	-	2	2	1	-
10-15	1	3	1	2	-	-
15-20	-	4	4	0	-	-
Above 20 years	-	1	1	0	-	-
Total	10	19	23	6	1	1

The following section of this paper reviews BIM and GIS (and their integration) during the different stages of a "regular" project lifecycle. "Regular" in this paper means projects such as buildings, hydraulic structures, highway projects and pipelines. Section 3 discusses on the applicability of BIM-GIS for historical buildings taking the examples of case studies conducted by researchers. Section 4 outlines the efficiency of BIM-GIS for complex projects and section 5 points out the challenges. The literature of all the above said sections is reviewed in Section 6 where the authors conclude the paper with the discussions of their findings and the scope for future study.

2. ROLE OF BIM AND GIS IN THE AEC INDUSTRY

2.1 The essential similarity and difference between BIM and GIS

Essentially, BIM derives its principles from CAD and can be used for all stages of the project lifecycle. BIM as defined by NBIMS (National BIM Standard) is

'*Building Information Modelling is digital representation of physical and functional characteristics of a facility creating a shared knowledge resource for information about it and forming a reliable basis for decisions during its life cycle, from earliest conception to demolition*.'-(NBIMS)

With the advent of Computer Aided Design (CAD), industry practitioners have long been able to visualize a project even before it is constructed. BIM has also been successful in proving its visualization capabilities, but it's implications are going much further than CAD. GIS has shown unmatched potential in handling spatial data and has been used for various disciplines in construction such as transportation, water resources, hydrologic systems, irrigation, drainage, facilities management, urban planning and for outdoor planning tasks like site selection, job-site planning, emergency evacuation etc. (Zhang et al., 2013). While BIM is used mainly for new construction, GIS is used to represent existing buildings (Isikdag and Zlatanova, 2009). BIM and GIS deliver the same function i.e. to create digital representations of the real world, there are differences between the two in terms of 3D visualization and geospatial data analysis

2.2 Application of BIM and GIS in construction projects.

Research has, for some time identified the application of BIM and GIS during various stages of the project lifecycle such as the design phase, pre-construction phase, construction phase and the operations phase. Beginning with site selection, Kumar and Bansal (2016) have pointed out that GIS has great capabilities in site selection as there is a need of the geospatial data such as location of utility and service lines when selecting a site. Moving over to the design aspect, Azhar et al. (2011) pointed out that BIM that has shown unmatched functionalities owing to its visualization capabilities and moreover, value engineering proposals can also be done.

During the pre-construction phase, cost-estimation is one of the key tasks that are encountered. It is a very important task as it is from this cost estimation that the entire project budget is fixed which is then linked to the succeeding stages of a project such as construction and operation. BIM can be effectively used for Quantity Take Offs (QTO's) and BIM based QTOs are more detailed and accurate thereby reducing errors in cost and valuation. However, BIM based QTOs can be developed only by BIM experts as it requires an in-depth understanding of the dynamics of the application because extracting the information depends upon the way it is modeled and how the parameters have been defined. BIM does not completely disassociate estimators of their jobs as cost estimation can be done only by associating the material, labor and equipment costs to the QTO generated by BIM. Moreover, intangibles such as site conditions, indirect costs can be done only by estimators (Monteiro and Poças Martins, 2013).On the other hand, the most important and crucial of all stages in the project life-cycle is the construction stage. Time and cost constraints play an important part during this stage. In order to ensure safety in construction, Zhang et al. (2013) presented an automated rule based system for BIM in safety analysis using algorithms to present the Occupational Safety and Health Administration (OSHA) rules. However, Zhang et al. (2013) say that this method has certain limitations, and the first one being that as the environment of the construction site keeps changing and because BIM environment lacks spatial data, it cannot be used to cover all unsafe conditions and second being that the manual effort in forming the algorithms and rules is tedious.

Moving over to the context of GIS, Bansal (2011) points out that regarding safety planning, there are various factors like environmental conditions, site topography, thermal comforts and access route planning which cannot be modeled with BIM makes it less efficient for construction safety planning. GIS on the other hand, has a spatial database, where all construction drawings, lay-outs and blue prints are maintained and a non-spatial database where all data related to safety is maintained. Bansal (2011) also developed a safety database in GIS which was successfully implemented in building the MBA block for NIT Kurukshetra. However, Bansal (2011) identified that this database cannot be used during the operations stage of a project as it is necessary to show equipment, workers, materials and temporary structures so as to see their interaction in order for safety planning.

And lastly, during the operations phase, studies done by various researchers have identified BIM for FM (Facilities Management) is a tool and a way forward for a whole life cycle approach. However, the usage of GIS in Facilities Management is limited due its restrictive visualization capabilities.

2.3 Current trends in the AEC industry

As per a report published by AECOM in 2015, it is seen that U.A.E has been perceived to have the highest growth market in the Middle East. On a back of strong performance over the last few years, the U.A.E market is expected to grow with remarkable projects such as the Expo2020,Al Maktoum International Airport and other related attractions (AECOM, 2015).

On the basis of the survey carried out by the authors, the following key findings have been identified for the U.A.E construction industry on the role of BIM and GIS: -

A. 50.94% respondents used BIM in their projects whereas in the case of GIS usage, it narrowed down to a 33.96%. It was seen that Architects (66.67%) and Engineers (69.23%) were the heaviest users of BIM whereas Quantity surveyors used BIM the least.

B. In the case of GIS, again, Architects (55.56%) were the heaviest users whereas all the quantity surveyor respondents answered that they do not use GIS in their workplace at all.

C. Respondents identified that Revit to be the most commonly used BIM platform and GIS platforms like QGIS, ArcGIS etc. were seen to be least used and restricted to use only by GIS specialists.

D. It was also noted that 96.23% agreed that adopting BIM and GIS could revolutionize the construction industry.

In the U.A.E, BIM has been successfully used in many projects such as the Midfield Terminal and Dubai Opera House. GIS has not been linked with BIM yet but has been used independently for projects such as the “Makani”; an initiative by the Dubai government where almost 1000 buildings are mapped digitally with GPS co-ordinates and Masdar City for smart city planning (ConstructionWeekOnline, 2016).The Abu Dhabi government has also introduced a common co-ordinate system based on the WGS84 datum which is also a step taken by the government in GIS implementation (SDI, 2009).

2.4 Integration of BIM and GIS in construction projects

Integration of BIM and GIS is a topic that has been gaining interest. An integrated BIM-GIS platform can help to combine the benefits of both BIM and GIS in one platform and literature shows that numerous attempts have been done for the same. Cheng and Yang (2001) in their research developed a GIS-based tool called Material Plan which is basically a combination of GIS and CAD and can be used for generating material take-offs and Bill of Materials (BOM).The selection of optimal location for tower cranes is an important task in construction planning. A shortfall or surplus amount in the number of cranes can increase the construction costs considerably. GIS-BIM can be used effectively for this selection where GIS is used in the analysis of the spatial data. The output of this would generate the locations of the tower cranes which are then integrated with the BIM structural model. A clash detection is run and clashes, if any, are corrected by changing the locations in GIS (Irizarry and Karan, 2012). The efficiency of integrating BIM-GIS for construction supply chain (material, equipment and personnel) management was studied by Irizarry et al. (2013) and they developed an integrated BIM-GIS model for the same. This model uses BIM for material take-off and GIS for the analysis of spatial data (warehousing and transporting).The potential of BIM to produce the material take-off reduces the time required for the same by manual methods. Moreover, the graphical alerts generated by BIM are much more efficient and comprehensive than statistical reports for the material status. GIS in this model, helps to reduce the logistical issues monitoring and mapping all supply chain activities and data like the location of suppliers and transportation. The disadvantage that Irizarry et al. (2013) point out in their model is the task of manual entry if there is an incidence of having to quantify an element that does not exist in the BIM model or when the quantity needed from an element cannot be calculated from the component properties.

The following are the key findings from the authors’ survey regarding the integration of BIM-GIS in the U.A.E construction industry: -

A. It was seen that a majority (70%) of the respondents felt that there is a need for integrating BIM and GIS for projects happening in the Middle East. Moreover, almost three fourth of the respondents agreed that adding GIS information to BIM model would increase the overall functionality.

B. In the project life-cycle, the design phase was identified to be benefited the most by the integration of BIM and GIS. This was then followed by the pre-construction phase, construction phase and the operations phase which is illustrated by the following figure:

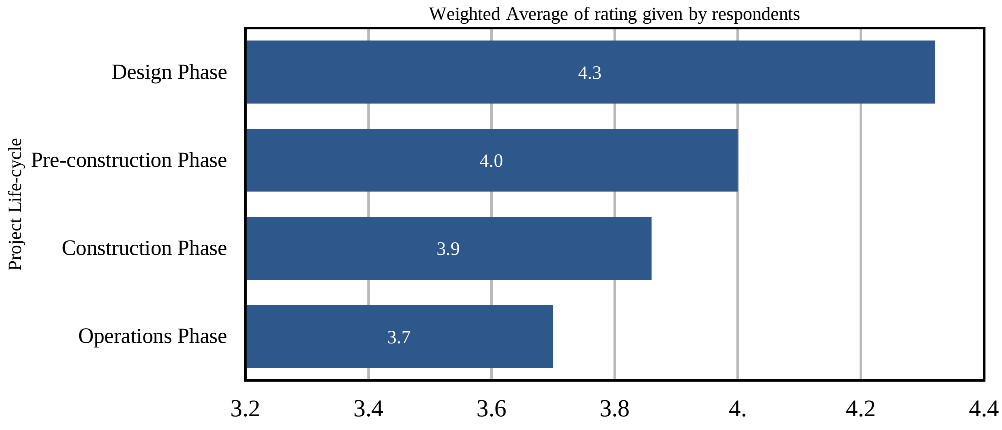


Figure 1: Effectiveness of BIM-GIS integration in the project life-cycle (as per results of the authors' survey)

C. Respondents of the survey conducted by the authors were asked to rate the following projects based on the benefit they would achieve by the integration of BIM and GIS. All the respondents agreed that Infrastructure projects are benefitted the most with a weighted average of 4.5 which is closely followed by road and transportation projects (4.44),followed by residential projects (4.18),stadium projects (3.92) and lastly by commercial projects (3.84).

3. BIM-GIS FOR HISTORICAL BUILDINGS

Historical buildings have a large amount of architectural details which had made the recording of these buildings difficult with the traditional survey methods. However, the development of 3D models for historical heritage buildings has been gaining momentum in the recent years (Dore and Murphy, 2012).

Saygi et al. (2013) argued that despite the fact of BIM having enhanced 3D capabilities, its potential and the use in the case of historical buildings is limited. This is because historical buildings have a great diversity in the architectural features of each element (e.g. column, beam, and floor) which are not covered in the BIM "standard families" due to which the creation of new component families (or parametric families) becomes a very tedious task. In this context, Murphy et al. (2009) points out that HBIM (Historical Building Information Modelling) can be used applied for historical buildings as it has a library of parametric architectural objects designed from historic manuscripts ranging from Vitruvius to 18th century architectural pattern books. HBIM employs reverse engineering. i.e., the details of architectural parametric elements are mapped onto the survey data collected by laser scanning and photogrammetric methods to generate the 3D model. This can then be integrated into a 3D GIS for further analysis. Saygi et al. (2013) compares GIS and BIM and concludes that GIS has great potential to analyze spatial and non-spatial data and can easily integrate new data but has limited 3D functionality. As BIM and GIS are distinct in functionalities, (Baik et al., 2014) suggests in his paper that with the integration of BIM and GIS, the issues can be resolved. They conducted a case study where a historical building was modeled using HBIM and this was then integrated into a GIS platform (using Autodesk Infraworks) so as to create a semantically rich model incorporating benefits of both BIM and GIS.

Although the U.A.E does not have much scope in historical buildings as compared to its European counterparts, almost half (59.18%) of the respondents from the authors' survey agreed that BIM and GIS integration could be used effectively for the recording of historical buildings in the U.A.E.

4. BIM-GIS FOR THE DELIVERY OF COMPLEX PROJECTS

There are organizations such as CERN (European Council for Nuclear Research), Airbus, Crossrail and other similar companies that deliver very complex projects. Complex projects are those which are have a high level of technological data, require a very high capital and collaboration of multiple firms for the project delivery. Some of these projects are vital to the industrial growth and modern economy (Whyte et al., 2016). The projects delivered by these firms range from the manufacture of aircrafts and developing railway infrastructure to very complex particle accelerators.

Taking the case of CERN, the delivery of the Large Hadron Collider, which is a 27 km long circular tunnel situated at about 100 meters below the ground, had a design phase of 20 years. The amount of data involved is significant in the sense that the whole project involves 100 million components out of which there are 1.5 million documents and drawings. Moreover, around 7000 drawings and documents are created in a month. The documents are variant with bill of materials, simulations, technical specifications, equipment codes, test procedures, radiation procedures, recycling and waste management details. Similar is the case for Crossrail where the delivery of railways is managed by a large amount of data.1 million in drawings and documents and 0.25 million GIS records. For each of these projects, the contribution of BIM and GIS is invaluable (Whyte et al., 2016)

A very significant point to put forward is that CERN has appointed Arup (A leading multi-national engineering firm) in order to carry out the design study of the FCC (Future Circular Collider).As discussed; these particle accelerators are massive and complex projects which involves significant quantities of data. The proposed accelerator has a circumference of about 100 kms and is expected to be at least four times the size of the present Large Hadron Collider. In this regard, Arup has developed a web-based GIS application which integrates all the spatial data and incorporates this with the tunneling and particle collider system constraints. Also, another notable point is the use of BIM in order to assess the feasibility, risk and cost factors associated with the particle accelerator (ARUP, 2014)

"*Using BIM this early on in the design process is invaluable. It allows us to make critical decisions using data that can be easily visualized, enabling the team to make decisions with a clear overview of the multiple, highly complex components of this ground breaking project. We're delighted to be working with such a far-sighted client and strong project team to help CERN achieve its objective to break new boundaries in particle physics research*."

— (Matt Sykes, Project Director, Arup)

Complex projects rely heavily on digital technologies like BIM and GIS without which the project delivery can be very much time-consuming and tedious. According to MEED (Middle East Economic Digest) estimates, it is the transportation industry which is at the fore-front of development and growth. In the Middle East, large-scale transportation projects valued at a total of 270 billion USD are expected to be awarded within the next two years.

Taking the case of U.A.E, the current backdrop of being the Expo2020 host has given a boost to the transport and tourism industry with projects like The Expo2020 Dubai Metro Route Expansion and the GCC rail (which is set to link all the GCC countries) lined up. A great majority (93.88%) of the respondents from the authors' survey strongly agreed that an integrated BIM-GIS platform would be beneficial for the delivery of complex projects.

5. CHALLENGES

5.1 Challenges facing the implementation of BIM and/or GIS

Taking the case of BIM and GIS, there are various factors that limit its implementation and integration in the construction industry. A closer examination of these barriers and recommendations for its resolution are outlined in the succeeding paragraphs.

A. Change in the level of granularity: BIM and GIS are tools that work on entirely different platforms and so there is a change in the level of granularity; BIM models are usually very fine grained as compared to CityGML(City Geography Mark-up Language) models and the transformation of BIM model into CityGML can make the resulting model to look fine grained and vice versa. Moreover, While IFC (Industry Foundation Classes) models use CSG (Constructive Solid Geometry), Sweeping and BRep (Boundary Representation) methods for representing geometry, Geospatial models use BRep methods. When transferring these models from IFC to CityGML, the CSg and Sweep appear different which would then require manual means to be updated. Numerous researches and studies are being done so as to alleviate this problem. (El Meouche et al., 2013).

B. Lack of mandate and regulation: On an industrial level, this can be managed by setting up mandatory industrial requirements. On the other hand, BIM and GIS can be offered as valued added service to owners and clients. Another point to be noted is that Dubai is only city in the Middle East to have set up a BIM mandate. This mandate was introduced in the year 2013 (circular 196) but superseded in 2015 by circular 207 which pertains to the use of BIM in construction projects by all stakeholders ranging from project owners to engineers, contractors and governmental departments (ConstructionWeekOnline, 2015)

C. Lack of expertise among professionals: This is also considered one of the major challenges that the industry faces. Majority of the BIM and GIS professionals claim that they are self-trained and this in any manner would not substitute formal training. For this reason, there is any for setting up training centers and certifications which again goes by the fact that there is need for industrial standards (AECOM, 2015).

D. Legal and contractual issues: Due to the lack of industrial standards, there is an issue regarding the ownership of BIM/GIS data. As the owner pays for the design, the owner may feel entitled to own it but since there are other stakeholders such as engineer, contractor and facility managers etc. who would put in their proprietary information which would need to be protected as well .This disagreement over copyright issues can be only managed with proper contractual documents stating the rights and responsibilities of each party (AECOM, 2015).

E. Cost: The high initial cost in BIM/GIS is another major barrier that withholds the stakeholders from investing in it. These stakeholders need to look at the return on investing in BIM/GIS rather than just looking at its initial cost as studies show that investing in BIM/GIS not only reduces the overall cot but also helps in delivering projects on time and with greater efficiency (AECOM, 2015).

F. Lack of client knowledge on BIM/GIS: Many a times, it is due to the client's lack of awareness on BIM/GIS that it is not implemented in projects. As discussed in the above-said reasons, a lot of owners/clients perceive BIM/GIS to be costly, interoperable etc. This can be managed only with training sessions and talks on BIM/GIS in the industry (AECOM, 2015).

Based on the findings of the survey conducted by the authors, the following table shows the ranking of the different barriers in the implementation and integration of BIM and GIS based on its significance; (1 being most significant and 7 being the least significant).

Table 3: Ranking of barriers in BIM/GIS integration and/or implementation (from results of authors' survey)

Ranking	Barrier	Weighted average by respondents
1	Change in the level of granularity when transferring BIM information into GIS and vice versa	2.58
2	Lack of standards in BIM and/or GIS	2.46
3	Legal and contractual issues regarding ownership of BIM/GIS data	2.42
4	Interoperability issues	2.38
5	Lack of client knowledge in BIM and/or GIS	2.13
6	Lack of expertise on BIM/GIS	1.98
7	High initial investment cost associated with BIM/GIS	1.88

5.2 BIM-GIS adoption around the world

On a global level, the adoption of BIM is mixed, due to a combination of the above-said barriers. However, the following table provides a list of countries where BIM/GIS is already mandated or is soon to be mandated.

Table 4: BIM/GIS adoption around the globe (Buildingsmart, 2014)

Country	**Enforcement Level**
Australia	Still in its infancy but not yet mandated and framework has not been established yet
G.C.C	Dubai is the only city to have introduced the BIM mandate. Qatar is moving towards standardization. Other countries such as K.S.A, Bahrain and Kuwait, BIM is being used and is gaining popularity.
Hong Kong	Strict requirement by the Hong Kong housing authority
Netherlands	Required by the Ministry of Interior for large building projects. ARCADIS Netherlands has been involved in the integration of Geospatial into design process.
Norway, Denmark, Finland	Strong requirement by some authorities like the Defense Construction Service in Denmark and the Senate Properties in Finland.
Singapore	The BCA (Building Construction Authority) implemented the world's first BIM electronic submissions
South Korea, Japan	The South Korean Public Procurement Service made BIM compulsory for all public sector projects and private sector projects valued higher than 50 million USD. CIM is being advocated in Japan
U.K, France, Germany	Has introduced the BIM mandate in 2016 which requires BIM to be used in all major construction projects. France and Germany have been using BIM for construction projects but not yet mandated.
U.S.A	BIM has been actively used in many construction and maintenance projects. BIM-GIS integration is also gaining popularity one such example being the Milwaukee Metropolitan Sewerage District

On the basis research findings, it was noticed that a large majority (75%) of the respondents believed that the U.A.E industry is mature enough to adopt the integration of BIM-GIS. Also, when asked to evaluate the GCC countries in terms of the effectiveness in adopting BIM and GIS, our respondents rated U.A.E to be the most effective, followed by Qatar, K.S.A, Kuwait, Bahrain and lastly Oman.

Parsons Brickerinhoff, which is a part of the global construction firm Balfour Beatty, has been at the forefront in applying 3D,4D and even 5D for construction projects. They have also been successful in combing geospatial data into design process. For example in the case of highway projects, they have successfully updated the BIM model in a geospatial environment to have a gaming technology, wherein public can drive on highways in a virtual environment before construction so as to be familiar with the detours which may be required during construction (Zeiss, 2013).

6. CONCLUSION

While a large proportion of the Middle East market is dependent mainly on the public works sector, U.A.E is an exception. Event-driven commitments have paved the way to large scale developments in infrastructure, transport and tourism projects such as the EXPO 2020, Dubai Metro Route Expansion, GCC Rail and other theme parks to name a few. A significant point to be noted is that Dubai is the only city to have introduced a BIM mandate in the GCC, several other GCC countries are now following suit with mandates and directives towards BIM implementation. The survey findings also rank U.A.E as the most effective country for BIM and GIS adoption. However, on a global scale, the U.A.E is behind other countries where there are strict requirements for the use of BIM-GIS. With large amounts of money being invested on showcase events such as FIFA 2022 (Qatar) and EXPO 2020 (U.A.E), the world is anticipating whether these projects will be delivered using the latest and most efficient and engineering and construction methods. It is imperative for stakeholders to have understanding of benefits of BIM and GIS which can help in an effective project delivery. The authors' survey findings indicate a vast majority (94%) of the respondents feel that BIM and GIS have a huge potential in its integration in the U.A.E, However, change in the level of granularity and lack of standards in BIM and GIS are the major barriers hindering the full-fledged implementation. The other major barriers that tools such as BIM and GIS though still gaining popularity have great potential in its implementation. Lack of skills, lack of client knowledge, high initial investment cost, interoperability issues and lack of expertise were noted as the other barriers. The authors also feel the need to have more researches, awareness and training among industry professionals and asset owners in order to have the effective implementation and integration of BIM/GIS. Undoubtedly, it is the asset owners who would benefit mostly out of this implementation and integration.

The limitation of this research is that most of the respondents are based in the U.A.E and there is a possibility that some of the responses may be biased. Future studies could include reviewing a practical case study of a pilot project approach towards BIM and GIS integration, which could pave the way for further research.

From the authors' primary and secondary research, it can be summarized that there is an increasing demand for BIM and GIS application in several parts of the world with certain developed countries driving the process with full-fledged application. Nevertheless, in the case of U.A.E, BIM application was found to be ahead of GIS. The visionary development of U.A.E has a considerable number of infrastructure projects lined up. These, in turn with the survey findings have led the authors to identify that the U.A.E industry is a strong contender to drive BIM and GIS application. However, the identified barriers that hinder a full-fledged development have to be addressed by government mandates and or client-driven innovation.

7. REFERENCES

AECOM (2015). Middle East Handbook 2015. AECOM.

ARUP (2014). Arup develops BIM tool for future particle accelerator at CERN. *In:* ARUP (ed.).

Azhar, S., Carlton, W. A., Olsen, D. & Ahmad, I. (2011). Building information modeling for sustainable design and LEED® rating analysis. *Automation in Construction,* 20**,** 217-224.

Baik, A., Alitany, A., Boehm, J. & Robson, S. (2014). Jeddah Historical Building Information Modelling" JHBIM"-Object Library. *ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences,* 2**,** 41.

Bansal, V. K. (2011). Application of geographic information systems in construction safety planning. *International Journal of Project Management,* 29**,** 66-77.

Buildingsmart (2014). Standards Overview. *In:* Petrie, R. (ed.). Buildingsmart.

Cheng, M.-Y. & Yang, S.-C. (2001). GIS-Based Cost Estimates Integrating with Material Layout Planning. *Journal of Construction Engineering and Management,* 127**,** 291-299.

ConstructionWeekOnline (2015). Revealed: Dubai Municipality's updated BIM mandate. *In:* Bhatia, N. (ed.).

ConstructionWeekOnline (2016). Special Report – BIM development. *In:* Zendera, Y. (ed.).

Dore, C. & Murphy, M. Integration of Historic Building Information Modeling (HBIM) and 3D GIS for recording and managing cultural heritage sites. *Virtual Systems and Multimedia (VSMM), 2012 18th International Conference on*, 2012. IEEE, 369-376.

Ebrahim, M. A.-B., Mosly, I. & Abed-Elhafez, I. Y. (2015). Building Construction Information System Using GIS. *Arabian Journal for Science and Engineering***,** 1-14.

El Meouche, R., Rezoug, M. & Hijazi, I. (2013). Integrating and managing BIM in GIS, software review. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences,* 2**,** W2.

Irizarry, J. & Karan, E. P. (2012). Optimizing location of tower cranes on construction sites through GIS and BIM integration. *Journal of Information Technology in Construction,* 17**,** 351-366.

Irizarry, J., Karan, E. P. & Jalaei, F. (2013). Integrating BIM and GIS to improve the visual monitoring of construction supply chain management. *Automation in Construction,* 31**,** 241-254.

Isikdag, U. & Zlatanova, S. (2009). Towards Defining a Framework for Automatic Generation of Buildings in CityGML Using Building Information Models. *In:* Lee, J. & Zlatanova, S. (eds.) *3D Geo-Information Sciences.* Berlin, Heidelberg: Springer Berlin Heidelberg.

Kent, D. C. & Becerik-Gerber, B. (2010). Understanding construction industry experience and attitudes toward integrated project delivery. *Journal of construction engineering and management,* 136**,** 815-825.

Kumar, S. & Bansal, V. K. (2016). A GIS-based methodology for safe site selection of a building in a hilly region. *Frontiers of Architectural Research,* 5**,** 39-51.

Monteiro, A. & Poças Martins, J. (2013). A survey on modeling guidelines for quantity takeoff-oriented BIM-based design. *Automation in Construction,* 35**,** 238-253.

Murphy, M., McGovern, E. & Pavia, S. (2009). Historic building information modelling (HBIM). *Structural Survey,* 27**,** 311-327.

Rezgui, Y. & Zarli, A. (2006). Paving the Way to the Vision of Digital Construction: A Strategic Roadmap. *Journal of Construction Engineering and Management,* 132**,** 767-776.

Saygi, G., Agugiaro, G., Hamamcioglu-Turan, M. & Remondino, F. (2013). Evaluation of GIS and BIM roles for the information management of historical buildings. *ISPRS Ann. Photogramm. Remote Sens. Spat. Inf. Sci,* 2**,** 283-288.

SDI (2009). Common Co-rodinate System based on WGS84 Datum for AD & U.A.E. *In:* Western Region Muncipality, T. P. D. (ed.).

Stewart, R. A., Mohamed, S. & Daet, R. (2002). Strategic implementation of IT/IS projects in construction: a case study. *Automation in Construction,* 11**,** 681-694.

Succar, B. (2009). Building information modelling framework: A research and delivery foundation for industry stakeholders. *Automation in Construction,* 18**,** 357-375.

Thomas, N. & Al-Hajj, A. BIM Implementation and the Construction Industry. *The 1st International Conference of the CIB Middle East & North Africa Research Network* 2014 Abu Dhabi, U.A.E.

Whyte, J., Stasis, A. & Lindkvist, C. (2016). Managing change in the delivery of complex projects: Configuration management, asset information and 'big data'. *International Journal of Project Management,* 34**,** 339-351.

Zeiss, G. 2013. (Building on BIM). Available: http://www.geospatialworld.net/article/building-on-bim/.

Zhang, S., Teizer, J., Lee, J.-K., Eastman, C. M. & Venugopal, M. (2013). Building Information Modeling (BIM) and Safety: Automatic Safety Checking of Construction Models and Schedules. *Automation in Construction,* 29**,** 183-195.

SUSTAINABLE SMART CITIES: EVALUATION OF AUSTRALIAN PRACTICE

Fahim Ullah* & Muhammad Jamaluddin Thaheem

*Department of Construction Engineering and Management, School of Civil and Environmental Engineering, National University of Sciences and Technology, Pakistan. *Email: fahimullah@nit.nust.edu.pk*

Samad M.E Sepasgozar

Faculty of the Built Environment, University of New South Wales, Sydney, Australia, Email: samad.sepasgozar@gmail.com, Phone: +60 (2) 9385 6528

Abstract: The rapidly expanding cities and unparalleled level of urbanization throughout the world have opened ways for smart cities. Cities of tomorrow not only need to be smart but also incorporate the ever increasing demand of sustainability. In this context, Australian cities are evaluated in terms of their social, economic and environmental sustainability factors since they provide expensive and assessable practices. To assess the sustainability performance, this paper evaluates six most populated Australian cities and compares them for smartness. It identifies key factors and their sub factors which contribute to sustainable smart cities and influence their success in terms of economic and environmental sustainability. The identified factors are divided into two groups: socio-economic and environmental and four sub-groups: governance, retrofitting, land use and environment. The findings reveal that Australian cities rely highly on governance, followed by land use, environmental management and least on retrofitting. This implies that the role of government is most significant in achieving the smart city goals. Fortunately, the policy making and regulatory authorities seem aware of this responsibility. The paper provides useful insight into the Australian smart cities, the key sustainability factors of which can be adopted by the developing countries.

KEYWORDS: *smart cities; sustainability; review; Australian cities; success factors; futuristic development*

1. INTRODUCTION

The concept of urbanization is increasing throughout the world. Around 10 percent of the world population lives in top 30 metropolises (Dobbs et al., 2011). On average, almost half of the world population lives in cities. Hence the world is at an unparalleled level of urbanization (Dirks et al., 2010). Such speedy growth requires a challenging imperative for sustainable development and better lifestyle leading to the introduction of smart cities. Smart City represents a community which is technologically advanced, sustainable and interconnected, secure, comfortable, and attractive (Lazaroiu and Roscia, 2012). The rapid expansion of cities and their conversion to smart cities face various challenges. The problems arising due to the rapid urbanization lead to loss of basic functionalities needed for comfortable living. Some of the problems are health concerns, air pollution, solid waste, traffic congestion, resource scarcity, disintegration of existing and new technologies, and aging and deteriorating infrastructure (Washburn et al., 2009). These issues present various risks of new variety and magnitude that the world had no idea about previously. Other problems are organizational and social, physical, technical or material. The ever growing concerns associated with multiple stakeholders, higher interdependency, and social and political complexity are additional sources of risk leading to mismanagement of these cities and often resulting in failure (Weber and Khademian, 2008).

More than 80 percent Australian population lives in cities. In addition to administrative and management problems, these cities are responsible for producing nearly 75 percent greenhouse gases either directly or indirectly. Such issues make the operation and design of these cities a critical challenge for urban and regional development authorities. The failure or success of transformation of these cities over the next 20-30 years will determine the fate of future generations and will be a key legacy (Kymlicka, 2013). Along with meeting these challenges, a new challenge on rise is the existing infrastructure going out of date. According to Adams (2009) by 2030, as much as over 80 percent of existing Australian urban infrastructure would be 20 years or even more older. Hence the transformation cannot simply be dealt with as rebuilding infrastructure or retrofitting it, but will also require the rationalization and enhanced utilization of the existing infrastructure as a whole. In this regard, the roads, parks, rails, buildings, waterways, distribution systems and energy infrastructure need to be looked into with open minded, new and up to date ways. Aye and Fujiwara (2014) and Adams (2009) also warned for worse if the traditional out of date methods are stuck to which are already showing failures and shortcomings. So, this increased need of smart cities and conversion of existing smart cities into sustainable ones is the call of the day especially for the Australian cities. The argument is not limited to economy only as it used to be traditionally but about the holistic capacity development to withstand the pressures of meeting increased globalization demand, the challenges of global warming, outdated operation modes and ever increasing population. In order to meet the sustainability requirements, various studies have been carried out. The purpose of this study is to identify the key factors of sustainable smart cities and compare top six Australian cities on their basis. Using the published literature, it gathers the success factors, divides them into two main domains i.e. socio-economic and environmental sustainability factors and studies the complex relations of these factors at four sub-group levels: retrofitting, governance, land use and environmental management.

2. LITERATURE REVIEW

Smart city is a developed urban area that ensures and facilitates sustainable economic development and enhanced life quality by excelling in multiple key areas: economy, people, mobility, living, environment and government. This is achieved through strong social and human capital, and/or ICT infrastructure (Dameri, 2013). Smart cities are also termed as resilient cities which are a sustainable network of human communities and physical systems. These physical systems are natural and constructed components of a city. These components include but are not limited to buildings, roads, built environment, infrastructure, energy facilities, communications, waterways, geology, topography and other natural systems (Godschalk, 2003). Smart cities have been studied from various aspects such as urban logistics, ICT and governance. For example, Morfoulaki et al. (2016) studied the city of Serres, Greece, evaluated the specific policy measures for promoting sustainable urban logistics and formulated a plan for evaluating the city using multi criteria decision making. Webb et al. (2016) developed the governance plan for cities using sustainable energy in their case study for UK. However, the environmental, retrofitting, governance and land use components are not fully explored. The relative newness of smart cities and the boom of sustainability in the world calls for sustainable smart cities. The three key pillars for sustainable smart cities as identified by Söderström et al. (2014) are economic, social and environmental. In this regards, the work of Shen et al. (2011) provides a detailed study of the environmental and economic sustainability indicators and their measurement mechanism along with the comparison of various managerial practices. Similarly, other sustainable indicators for smart cites as identified by Jedliński (2014) are socio-economic development, climate change, sustainable transport, sustainable consumption and production, natural resources, public health, social inclusion, demographic changes, global partnership and good governance. The current study integrates their work and studies Australian cities in two contexts: socio-economic and environmental. The first context is further divided into retrofitting, governance and land use.

In Australian context, smart cities have been in focus since long. The concept of smart cities was initially merged with compactness of the cities in the early 1970's. Factors such as squandering of virgin land, economic policies and decisions, transport, and cultural priorities were among the earliest identified success or failure factors for smart cities (Newman, 1992). The success of smart city is determined by the use of its technology, learning opportunities of its residents and the integration of governance and policy making (Nam and Pardo, 2011).Yiftachel and Hedgcock (1993) formulated three groups for imparting and measuring the smartness of cities: (1) Equity, (2) Community, and (3) Urbanity. Australia has the honor of coming up with one of the two initial smart cities, the other being Malaysia. The Multifunction Polis (MFP), an autonomous smart city, was introduced in 1994 near Adelaide and is believed to be one of the first smart cities in the world (Söderström et al., 2014). The term 'smart' was used for MFP due to its usage of ICT and latest technology for decision making and city management. Moriarty (2002) stressed on environmental sustainability of Australian cities. Odendaal (2003) compared Brisbane and Durham, and stressed the use of ICT and technology for good governance. Kenworthy (2006) used the words eco-city and its associated concepts for top 10 transportation and planning factors to induce sustainability in Australian cities. Similarly, Baum et al. (2006) reviewed the sustainability of health systems for 18 years for Australian cities. More recently, the emergence of the six most populated Australian cities as smart cities is another feather in the hat for Australian planning and management teams. These include Sydney, Perth, Melbourne, Brisbane, Adelaide and Gold Coast. In this context, the studies of Yigitcanlar (2010) for knowledge based development, Chourabi et al. (2012) for understanding smart cities, and more recently Motlagh et al. (2015) for knowledge mining the Australian smart cities grid are useful. In current study, the smart city endeavors have been studied under two groups and four sub-groups as previously mentioned and shown in Table 1.

Table 1: Groups and sub-groups

Groups	Subgroups	Definition	Reference
Socio- economic	Retrofitting	Addition of new features or re-modification of the existing system to fit the latest requirements and needs	(Cetiner and Edis, 2014)
	Governance	Management, decision making and the implementation of decisions	(Ramaswami et al., 2016)

	Land use	The optimum utilization of the available land to provide better life style and healthy environment	(Yamagata and Seya, 2013)
Environmental		Better utilization and conservation of natural resources, protection of habitants and hazard control.	(Chourabi et al., 2012)

3. METHODOLOGY

This paper follows a multi-stepped methodology. In first step, relevant literature was systematically chosen and reviewed in accordance with Siddiqui et al. (2016). In this step, a total of 60 papers published on smart cities in Australia were reviewed. The search engine used consisted of Google Scholar, SCOPUS, ASCE, Taylor & Francis, Emerald and Science Direct libraries. For searching the relevant literature, keywords of 'smart cities', 'smart cities in Australia' and 'success factors of smart cities' were used. Later on keeping in view the trends from retrieved papers, keywords of smart city of 'Perth', 'Sydney', 'Melbourne', 'Adelaide', 'Brisbane' and 'Gold Coast' were added and searched. Efforts were made to retrieve at least 5 research papers for each city. As a result, in total 60 relevant papers were retrieved out of which at least 30 focused on the six mentioned cities. From these papers, success factors were highlighted for Australian smart cities and were classified into the two categories. The factors are both positive and negative in terms of their effects on the two groups and their details are shown in Table 2.

Table 2: Positive and negative factors for cities

City	**Factors**			
	Socio-economic		**Environmental**	
	Positive	**Negative**	**Positive**	**Negative**
Perth	32	9	10	7
Sydney	44	9	21	5
Gold Coast	20	7	2	3
Brisbane	36	4	2	1
Melbourne	42	9	9	9
Adelaide	20	7	11	2

In the second step, the identified factors were distributed into groups and subgroups previously established. Hertzog (2008) recommends that a group of 10 or more experts must be involved in a study in order for it to produce useful results. Hence this study involved 11 experts whose details are shown in Table 3. The experts were selected based on their specific expertise in fields of Construction Engineering and Management, Architectural Engineering, and Urban and Regional Planning as well as their knowledge of smart cities. They had a minimum experience of 3 years in their respective fields and were contacted either online or in person. Moreover, six experts selected from academia and five from industry to have an insight from both streams of knowledge. Overall, out of the eleven experts, 2 were from Australia and 9 were from Pakistan.

Table 3: Experts profile

Category	Education	Count	Expertise	Affiliation	Min Experience
Academia	PhD	3	Construction Engineering and Management = 2	1 each from NUST Pakistan and UNSW Australia.	
			Architectural Engineering =1	UniMelbourne Australia	
	MS	3	Construction Engineering and Management = 2	NUST Pakistan	
			Urban and Regional planning = 1	NUST Pakistan	
Industry	MS	3	Civil Engineering = 2	Top City Pakistan	3 years
			Urban and Regional Planning = 1	DHA green Pakistan	
	BSc	2	Civil Engineering =1	DHA green Pakistan	
			Architectural Engineering =1	Top City Pakistan	

All the experts helped in 2 important tasks. Firstly, to divide the success factors into the previously defined two groups. Then, to distribute these factors into the four selected process criteria. Lastly, to help in assessing the effect of each success factor on the criteria: low, medium and high. The experts were asked to assign values to each factor on a Likert scale: 5 for high, 3-4 for medium, 1-2 for low and 0 for no effect, corresponding to their effect on the smartness of cities.

4. CASE STUDY ANALYSIS

A total of six most populated Australian smart cities were chosen for highlighting their sustainability and smartness features. Each case is investigated in terms of their governance, retrofitting, land use and environmental aspects to identify key factors that may affect their socio-economic and environmental features.

4.1 Sydney

Sydney, the state capital of New South Wales, is the most populous city of Australia. It is located at the east Australian coast and surrounds the world’s largest natural harbor. The city due to its large population is facing several issues in fulfilling its sustainability dreams. These are but not limited to governance, retrofitting, greenhouse gas emissions, etc.

4.2 Melbourne

Melbourne is the state capital of Victoria and is the 2nd most populated city of Australia. Its metropolis is largely located on the Philip Bay and consists of 31 municipalities. The population of Melbourne is more than 4.5 Million.

4.3 Brisbane

Brisbane is the most populous city of Queensland, the 3rd most populous city in Australia and is the capital of the state. It has a population of around 2.3 million. Situated at the southeast corner of Queensland, it is centered along the Brisbane River. Its metropolitan area spreads along the Moreton Bay: in north from Caboolture to Beenleigh in the south.

4.4 Perth

Perth is the capital of the state of Western Australia and is the 4th largest Australian city following Sydney, Melbourne and Brisbane. Due to much reduced rainfall and substantial urban growth for last 30 years, serious questions have been raised over its continuous sustainability and is currently focused by both researchers and policy makers at large. Further, it houses almost three quarters of the western state's population within a span of less than 1% of its total area which further creates problems for decision and policy makers (Kennewell and Shaw, 2008).

4.5 Adelaide

Adelaide is the capital city of state of Southern Australia. It has a population of more than 1.3 Million and is the 5th most populous city of Australia. Adelaide houses more than 75% of over 1.7 Million state population. It is situated on the Adelaide Plains at the north of the Fleurieu Peninsula and between the low-lying Mount Lofty Ranges and Gulf St. Vincent.

4.6 Gold Coast

Gold Coast is located in South East Queensland and is a coastal city on the eastern coast of Australia. Though it is a non-capital city, it is the 2nd most populous city in the state and 6th most populous urban area in Australia. Its northern part is located at a distance of 42 kilometers south-east of the Brisbane and the metropolitan area extends towards New South Wales. Its metropolitan area converges with that of Greater Brisbane and contributes into a population of over 3 million people.

5. RESULTS

In light of the methodology, the effects of factors were observed for the mentioned cities. These effects where High, Medium and Low corresponds to the impact, are shown in Table 1. Both positive and negative factors were inquired. For the sake of clarity, negative factors are shown in italics. Table 4 shows the distribution of factors into socio-economic success factors.

Table 4: Socio-economic success factors and their distribution

City	Subgroup	Group: Socio-economic
Perth	**Retrofitting**	**HIGH:** future viability; strategic redevelopment*; residential density; compact;*
		MEDIUM: continual development; cohousing; network city;
		LOW: decentralized concentration; overheated rental market; *minimal road capacity increases;*

(Yiftachel and Hedgcock, 1993; Curtis, 2008; Kennewell and Shaw, 2008; Moriarty, 2002; Forster, 2006; Kenworthy, 2006)	**Governance**	**HIGH:** community-oriented; vision-oriented and reformist thinking; decision making; *changes to planning practice; political instability;* **MEDIUM:** business interests; policy context and supporting initiatives; *low income;* **LOW:** democratic sustainability framework; human-oriented centers; priority to the development of superior public transport systems; social relation; equity; community; retail activity; *increasing real estate prices; complex employment opportunities*;
	Land use	**HIGH:** strength of the planning system; **MEDIUM:** office development; parking provision; accessibility; land use-transport integration; activity corridors; transport corridors; low density development; home ownership; mixed-use urban form; well-defined higher-density; conditions for non-motorized modes; *poor transportation planning;* **LOW:** activity centers; ethnic and cultural diversity;
Sydney (Dowling et al., 2014; Yigitcanlar, 2010; Bulkeley, 2000; Moriarty, 2002; Forster, 2006; Low et al., 2003; Dodson and Sipe, 2008)	**Retrofitting**	**HIGH:** Retrofitting needs; building and health controls; **MEDIUM:** multinuclear construction; urban regeneration projects; *home ownership; high residential density;* **LOW:** *dwelling type;*
	Governance	**HIGH:** government collaboration and partnerships; risk management; socio-economic needs; public transport; localized sustainable development; *high automobile dependence; political interference; lack of resources;* **MEDIUM:** governance framework; education; power of authorities; conduct; sociotechnical systems; new initiatives; performance measurement; knowledge based urban development; strategic planning; central business districts; local government; small scale decisions; education and traffic management; cost reduction; job density; human needs; intergenerational and intra-generational equity; education and civilization; *institutional barriers*; *occupants behavior; commercialization;* **LOW:** branding; ethnic groups; national communication; service provision; jurisdictional limitations; general competence powers; ; socio-economic diversity; life style; learning;
	Land use	**HIGH:** land-use planning; housing attraction; *population concentration;* **MEDIUM:** coastal management; connectivity; *geographical proximity;* **LOW:** energy supply infrastructure; centrality; high to medium rise house; transportation; *spatial distribution;*
Gold	**Retrofitting**	**HIGH:** modal splits; *density and diversity;* **MEDIUM:** None **LOW:** None

Coast (Yigitcanlar et al., 2015; Yigitcanlar et al., 2008)	**Governance**	**HIGH:** government policy; economic forces; technology; retail activities; **MEDIUM:** tourism urbanization; travel behavior; social and behavioral trends; infrastructure design; *the level of motorization; traffic congestion; car dependency;* **LOW:** None
	Land use	**HIGH:** integration; accessibility; transportation sustainability; land use planning; *rapid urbanization; urban density;* **MEDIUM:** educational uses; mobility; parking supply in employment centers; life style; automated people movers; community profiles; *transport trends;* **LOW:** pedestrian friendliness;
Brisbane	**Retrofitting**	**HIGH:** asset management; centrality; *home ownership;* **MEDIUM:** None **LOW:** None
(Odendaal, 2003; Yigitcanlar et al., 2008; Yigitcanlar, 2010; Forster, 2006; Partridge, 2004)	**Governance**	**HIGH:** central business districts; SMEs; cyber initiatives; E- government; knowledge based urban development; socio-economic perspective; *strategic planning; complex employment opportunities;* **MEDIUM:** stable economy; inclusive; technology region; knowledge-based Industries; high- to medium-tech manufacturing; business services; financial services; health and education services; cultural and recreational services; knowledge **LOW:** self-efficacy; international transport services; high-tech services; life style; branding; learning; technology application/ ICT; socio- cultural; community organizations; community learning hubs; digital divide; psychological perspective; community precincts;
	Land use	**HIGH:** Infrastructure development; accessibility; connectivity; normal residential density; *population concentration;* **MEDIUM:** affordable access; **LOW:** None
Melbourne	**Retrofitting**	**HIGH:** retrofitting and redevelopment; heritage preservation; **MEDIUM:** adaptability; *dwelling type;* **LOW:** strategic redevelopment; *home ownership;*

(Yigitcanlar, 2010; Yigitcanlar et al., 2008; Adams, 2009; Forster, 2006; Moriarty, 2002; Newton, 2012; Low et al., 2003)	**Governance**	**HIGH:** strategic planning; central business districts; ICT; socio-technical transitions; *car dependency; institutional barriers;* **MEDIUM:** knowledge based urban development; high-quality public realm; activity centers; increased employment opportunities; public transport; knowledge-based industries; high- to medium-tech manufacturing; high-tech services; business services; financial services; health and education services; international transport services; knowledge community precincts; social inclusion and equity; *household behavior*; *electrical systems failure;* **LOW:** life style; branding; learning; cultural and recreational services; local character; mixed use; transport corridors; knowledge economy; supply-side responses; competitiveness and productivity; job density; *fire threats;*
	Land use	**HIGH:** centrality; infrastructure management; multinuclear construction; *high density development;* **MEDIUM:** transportation; rail systems faulty design; productive suburbs; normal residential density; housing attraction; **LOW:** connectivity; *lower per capita road provision*;
Adelaide (Forster, 2006; Moriarty, 2002; Haughton, 1999; Baum et al., 2006)	**Retrofitting**	**HIGH:** strategic redevelopment; **MEDIUM:** adaptable model; *home ownership;* **LOW:** None
	Governance	**HIGH:** recognition of goals; links between academia and industry; *regulatory failures;* **MEDIUM:** public transport policy development; social justice; retailing; main trade orientation; economic growth; technology; mixed use; community involvement; *externality costs; complex employment opportunities;* **LOW:** value system; engagement; inspirational leadership;
	Land use	**HIGH:** reducing car dependence; *higher residential densities;* land use planning; **MEDIUM:** community land trusts ; strong social health vision; *high automobile dependence; travel distance;* **LOW:** competing demands;

Table 4 shows the socio-economic factor distribution and their impacts. In case of Perth, Sydney and Melbourne, their distribution is quite balanced pointing to high studies in these cities on the smartness factors. A few anomalies observed are in case of Gold Coast and Brisbane, which seem to stress really high on the retrofitting issues indicating a lack of policies and a focus towards other factors (Odendaal, 2003; Yigitcanlar et al., 2015). On the other hand, almost all the cities give a balanced pattern for governnace factors pointing to their importance and attention given by policy makers. Table 5 shows the distribution of factors into environmental group.

Table 5: Environmental success factors and their distribution

City	**Environmental**

Perth	**HIGH:** spatial planning; energy use; protection of the city's natural areas; green streets **MEDIUM:** nature of development; food-producing capacity; *pollution and emissions; convivial climate; areal expansion; lesser rainfalls; air pollution; disproportionately high amount of the energy, materials and waste production; ecological justice concerns;* **LOW:** environmental costs; environmental degradation; growth management; urbanization;
Sydney	**HIGH:** eco-environmental integration; environmental impact assessment; going solar; land care and coast care; environmental policy; *resource consumption;* **MEDIUM:** environmental education programs; energy efficiency; greenhouse policy; cities for climate protection; waste management; vegetation retention and land management; dynamic environmental factors; wastage and sewerage water management; ecological sustainability; minimal use of non-renewable resources; *air pollution; environmental costs; more energy cost;* **LOW:** ecological footprint; less water consumption; biological diversity; low carbon; emissions reduction;
Gold Coast	**HIGH:** *storm water;* spatial patterns; *pollution;* **MEDIUM:** *climate change;* **LOW:** air quality;
Brisbane	**HIGH:** environmental considerations; **MEDIUM:** spatial planning; *geographical proximity;* **LOW:** None
Melbourne	**HIGH:** urban regeneration projects; ecological sustainability; *unsustainable resource consumption; environmental costs;* **MEDIUM:** geographical proximity; livability; environmental sustainability; water management; *pollution; water consumption trebling*; *soil moisture felling below acceptable levels; climate change; high household energy; more energy costs;* **LOW:** waste management; livability–sustainability nexus; energy management; *spatial distribution;*
Adelaide	**HIGH:** light green to deep green approach; eco-city; *more energy costs;* **MEDIUM:** spatial distribution; urban regeneration projects; energy efficiency; green spaces; ecological consciousness; bio regional development; utilization of solar energy; environment preservation; *pollution;* **LOW:** public open spaces;

Similar to Table 4 for socio-economic factors, Table 5 for environmental factors also shows a more balanced distribution of factors for Sydney, Perth and Melbourne and lesser for Gold Coast and Brisbane. Also Gold Coast show more negative factors comparatively due to the threats posed by storm water and its locality. After highlighting the success factors and their distribution into the two groups, individual cities are discussed below in terms of their smartness and sustainability features. The individual factor count for each of the four processes is taken into consideration in accordance with Tables 4 and 5, and the frequency is normalized into percentages to show the importance and considerations given to various processes by the city management. Table 6 reports the percentage influence of various sub-groups of factors in the six cities being studied as a comparative matrix.

Table 6: Comparative matrix

Subgroups	**Perth**		**Sydney**		**Gold coast**		**Brisbane**		**Melbourne**		**Adelaide**	
	Count	%	Count	%	Count	%	Count	%	Count	%	Count	%
Retrofitting	11	18.6	7	8.6	2	6.2	3	7.1	6	9.1	3	7.5
Governance	14	23.7	38	46.9	11	34.3	32	76.1	32	48.4	16	40
Land use	17	28.8	10	12.3	14	43.8	4	9.6	9	13.6	8	20
Environmental Management	17	28.8	26	32.1	5	15.6	3	7.1	19	28.8	13	32.5
Total Factors	**59**		**81**		**32**		**42**		**66**		**40**	

5.1 Discussion

Table 6 highlights both strengths and challenges for Australian smart city endeavor. The city of Perth displays balanced factors for all the four processes. With the land use and environmental management factors leading with a percentage of 28.8 each, followed by governance with 23.7 and retrofitting with 18.6. The city's strength lies in its strategic redevelopment and future planning and viability for the retrofitting process. In case of governance, the key success influencers are its vision oriented reformist thinking, the solid decision making and community oriented democratic sustainability framework. These attributes counter the challenges of governance up to a certain extent. The strength of the general planning system enhances the potential land use of this city and helps in land use management. Lastly, for environmental management, the city has potentials in the form of spatial planning, energy use, green street concepts and city's natural areas protection. Some balancing factors for this city highlighted by the current study are residential density and compactness for retrofitting process. Political instability, low income and associated rising real estate prices, and potential changes to planning system emerge as threats to its governance. Moreover, the potential threat to land use is the weaker transportation planning system leading to heavier car dependency. Lastly, the environmental threats include both natural and artificial. The former including convivial climate and lesser rainfalls whereas the later includes areal expansion, pollution and poor waste management systems.

Sydney displays a clear dominance of the governance process factors. With a portion of almost 50%, the city's focus is clearly on the governance as shown in Table 6. It is followed by environmental management factors with 32% and the remaining two with less than 15% influence. This governance issue, as previously highlighted, is due to population challenge. Having the largest population, the management becomes even more challenging. As a result, the city's main focus is on governance in which it has adopted good environmental management policy such as greenhouse gases reduction and 'Cities for climate protection' initiative as highlighted by Bulkeley (2000). However, more action is still required. As per Tables 4 to 6, the strength of Sydney lies in its good risk management strategies and successful implementation for governance, building and health control checks for retrofitting, better land use planning and a better environmental policy. While this is a positive side of the city planning, a few negative factors or threats are worth mentioning. The first and foremost threat is posed by the population itself in the form of higher residential densities, making the governance and associated retrofitting difficult as highlighted by Dowling et al. (2014). High automobile dependence, lack of resources, political influence and institutional barriers make the governance even more difficult. The geographical proximities pose a threat to the land use planning whereas the resource consumption, pollution and associated costs of their management are a few sources of threats to environment.

In case of Gold Coast, a clear dominance of land use process factors can be seen. The land use leads the remaining processes with a percentage influence of 43% followed by governance, with a score of 34%. The remaining two are less than 16%. It is due to its population concentration and the management issues due to the city lying on coastal regions. A few issues of rising sea levels claiming its land and that of storm water causing land handling issues are major threats to the city. Similarly, the city's economy is highly reliant upon its tourism whose sustainability is in question these days due to the management problems and occupant's interaction which is often neglected by the city planners. A few positive factors for this city's sustainable smartness endeavors are those of natural model splits for retrofitting, retail activities, economic forces and policies for governance, accessibility, transportation sustainability and land use planning for better management, and the natural spatial patterns and good air quality for environmental management. Similarly, a few threats posed to this city are density and diversity to its retrofitting, the level of motorization, transportation and sustainable tourism to its governance, rapid urbanization and associated densities to land use and the storm water, pollution and climatic change to the environmental management policy makers. Also, the migration of whales and the need to preserve these natural species is another challenge faced by city administration. Food insecurities, urban agriculture and land use planning are some other issues needing to be taken care of if the authorities are to make the sustainability dream a reality.

In case of Brisbane just like Sydney and unlike Perth and Gold Coast, planning and development revolve around city's governance. Almost 76% of factors fall into the governance stream and the remaining are even less than 10% individually. One of the key factors of this concentration is that of population. But unlike Sydney, the governance of Brisbane is heavily influenced by positive factors and hence becomes its strength. Especially the socio-economic perspective, the establishment of Small and Medium Enterprises (SME) and the technology usage components add considerable strength into the elements of Brisbane's governance. Similarly, knowledge based urban development and the cyber initiatives add further value to the city's governance. In terms of land use, the strength of Brisbane lies in its accessibility, connectivity and well spread residential density. To add to the good management, the city also has a development program for environmental considerations. Unlike the previously mentioned cities, Brisbane displays a very less number of negative factors or threats to its management and hence the achievement of sustainability goals is much nearer if the current pace of development and associated considerations are followed. In case of retrofitting, the city faces an issue of home ownership as the increasing population's individual home ownership demands cannot be met explicitly which if met will also make the associated retrofitting a tough ask. Similarly, in case of governance a few threats are the lack of strategic planning and complex employment opportunities. Be it the lack of strategic planning for supply side at homes or the social factors and health issues, a few planning glitches do exist in Brisbane. Lastly, in case of land use and environmental management, the only reported issues to deal with are the population concentration and geographical proximity.

For Melbourne, the focus largely lies on the governance factors which is similar to that of Sydney as both are the most populated cities of Australia. The governance factors are reported as high as 48% followed by environmental process factors with 29% and the remaining two with less than 15% each. The city's strength in terms of retrofitting and preservation of its architecture lies in the heritage preservation. Unlike the previously mentioned cities, Melbourne has a strong strategic planning coupled with its socio-technical transitions and technology usage, thus helping its governance. Moreover, in case of land use, the city has a normal residential density that is well spread along with a better infrastructure and transportation management systems. Finally, for environmental management, the city has a good ecological sustainability system, urban regeneration projects and the water management systems. The city, just like Brisbane, faces the threat of home ownership by all the inhabitants which is practically impossible for a population of this magnitude. A few threats to governance are the improper household behavior of inhabitants, institutional barriers, provision of electricity and the increased car dependency. In case of land use, the city faces threats of lower per capita road provision, high density development and faulty rail system design. Mitigating these issues will require a handsome amount of money and resources. Similarly, a few environmental concerns for this city are trembling water consumption, unsustainable resource consumption, soil moisture falling below acceptable levels, pollution, energy management and the associated costs.

In case of Adelaide, there is dominance of governance factors for the city like Sydney, Melbourne and Brisbane. The reason is the high concentration of population. Almost 40% of the success factors are associated with governance followed by 32.5% for environmental management and so on. The city has a good adaptable and strong strategic redevelopment model. In terms of governance, as most of the population of the southern region is concentrated in this city, there are strong ties between the academia and industry leading to better recognition of goals and social justice. The city despite being heavily populated has a better transportation policy and good use of technology helping the governance. As a result, it has successfully reduced its car dependence as opposed to the previously mentioned cities and has a better land use policy. In addition to these, the city has one of the best and aware environmental management policies. This includes but is not limited to the light to deep green approach, the concept of eco-city, utilization of solar energy, ecological consciousness, open public spaces and green spaces. While this is a positive side of the city, it also faces certain challenges. Most of these challenges are associated with the higher population concentration such as home ownership issues like Sydney and Melbourne. The increased travel distance for jobs and associated complexities in job and employment opportunities. While the city has one of the best environmental management systems in Australia, a few of the environmental concerns do exists such as pollution and the cost associated with energy management.

6. CONCLUSION AND RECOMMENDATIONS

The aim of this paper was to identify the factors contributing to managerial success of Australian smart cities. The results of the comparative analysis show that the most of the six cases give high regards to governance due to their higher population densities. These not only give rise to housing concerns but also influence other key areas like transportation and travel. On the other hand, Gold Coast and Perth seem to be more inclined towards their land use management with a percentage score of 43.8 and 28.8 respectively. The reasons are mainly their population concentration and the land being damaged by storm water or other environmental challenges especially in case of Gold Coast. Except Perth giving 18.6% weightage to the retrofitting factors, none of the city seems much concerned about the retrofitting related factors and is focusing on other initiatives thus assigning a score of as low as 10% and below. Perth, Sydney, Melbourne and Adelaide give a respectable portion of attention to their environmental management factors as evident from their percentage scores while Gold Coast and Brisbane seem less focused towards the environmental management issues which is a matter of concern especially for Gold Coast with its deteriorating environment both in the form of storm water disasters and climate change. Brisbane on the other hand having a solid in place environmental management policy is concerned about other key factors of sustainability.

Summarizing the findings, it can be safely said that most of the Australian cities are inclined towards better governance and associated factors. In order to achieve the goals of sustainable smart cities, governance is a very important factor. Thus the thrust is positive and in right direction. The paper also highlighted a few concerns for each city and mitigation of these negative influencers is necessary for achieving the sustainability dream and building a better Australia. In this regards, the paper provides a new direction for further study on the possible improvements later on. It further, highlights the key success factors currently being focused or otherwise needing to be focused by the policy makers and city management that provides the policy makers with information on the dimensions needing attention such as reduction of political influence in Sydney, managing household for Melbourne, reducing car dependence for Perth, strategic planning for Brisbane, storm water management for Gold Coast and pollution reduction for Adelaide. In this context, a comprehensive sustainability framework development is required for each of the six studied cities which will ensure better resource utilization and management of the key success factors as highlighted by this study. Hence, the policy makers can have a quick idea about the positives or negatives of the existing cities and build upon this work, a comprehensive management policy for achieving the sustainable smart cities dream whereas the researchers can carry this work forward and focus on each of the identified and highlighted success factor for in depth analysis and imprints on the city's sustainability. It must be noted that the paper is not all-inclusive and is restricted by the specific searching and sampling criteria being used. Therefore, the retrieved papers and sustainability factors are not exhaustive and can be improved in future. Also the study can be repeated in future for the very concepts of smart cities such as flexi city, knowledge-based city, electronic communities, cyber ville, intelligent city, digital city, telicity, information city, wired city, MESH city, etc.

7. REFERENCES

Adams, R. 2009. Transforming Australian cities for a more financially viable and sustainable future: Transportation and urban design, *Australian Economic Review,* 42, 209-216.

Aye, N. N. and Fujiwara, T. 2014. Application of option-games approach to the irreversible investment for a new energy industry in Myanmar by simple one-stage strategic model: Focused on potential of smart house, *Global Journal of Flexible Systems Management,* 15, 191-202.

Baum, F., Jolley, G., Hicks, R., Saint, K. and Parker, S. 2006. What makes for sustainable Healthy Cities initiatives?—a review of the evidence from Noarlunga, Australia after 18 years, *Health Promotion International,* 21, 259-265.

Bulkeley, H. 2000. Down to earth: local government and greenhouse policy in Australia, *Australian Geographer,* 31, 289-308.

Cetiner, I. and Edis, E. 2014. An environmental and economic sustainability assessment method for the retrofitting of residential buildings, *Energy and Buildings,* 74, 132-140.

Chourabi, H., Nam, T., Walker, S., Gil-Garcia, J. R., Mellouli, S., Nahon, K., Pardo, T. A. and Scholl, H. J. Understanding smart cities: An integrative framework. *In System Science (HICSS), 2012 45th Hawaii International Conference on*, ed.^eds. 2012. IEEE, 2289-2297.

Curtis, C. 2008.Planning for sustainable accessibility:the implementation challenge,*Transport Policy,*15,104-12.

Dameri, R. P. 2013. Searching for Smart City definition: a comprehensive proposal, *International Journal of Computers & Technology,* 11, 2544-2551.

Dirks, S., Gurdgiev, C. and Keeling, M. 2010. Smarter cities for smarter growth: How cities can optimize their systems for the talent-based economy, *IBM Institute for Business Value*.

Dobbs, R., Smit, S., Remes, J., Manyika, J., Roxburgh, C. and Restrepo, A. 2011. Urban world: Mapping the economic power of cities, *McKinsey Global Institute*.

Dodson, J. and Sipe, N. 2008. Shocking the suburbs: urban location, homeownership and oil vulnerability in the Australian city, *Housing Studies,* 23, 377-401.

Dowling, R., Mcguirk, P. and Bulkeley, H. 2014. Retrofitting cities: local governance in Sydney, Australia, *Cities,* 38, 18-24.

Forster, C. 2006. The challenge of change: Australian cities and urban planning in the new millennium, *Geographical research,* 44, 173-182.

Godschalk, D. R. 2003. Urban hazard mitigation: creating resilient cities, *Natural hazards review,* 4, 136-143.

Haughton, G. 1999. Searching for the sustainable city: competing philosophical rationales and processes of'ideological capture'in Adelaide, South Australia, *Urban Studies,* 36, 1891-1906.

Hertzog, M. A. 2008. Considerations in determining sample size for pilot studies, *Research in nursing & health,* 31, 180-191.

Jedliński, M. 2014. The position of green logistics in sustainable development of a smart green city, *Procedia-Social and Behavioral Sciences,* 151, 102-111.

Kennewell, C. and Shaw, B. J. 2008. Perth, Western Australia, *Cities,* 25, 243-255.

Kenworthy, J. R. 2006. The eco-city: ten key transport and planning dimensions for sustainable city development, *Environment and urbanization,* 18, 67-85.

Kymlicka, W. 2013. Multiculturalism: Success, Failure, and the Future, *Washington DC: Transatlantic Council on Migration. Accessed,* 20.

Lazaroiu, G. C. and Roscia, M. 2012. Definition methodology for the smart cities model, *Energy,* 47, 326-332.

Low, N., Gleeson, B. and Rush, E. 2003. Making believe: institutional and discursive barriers to sustainable transport in two Australian cities, *International Planning Studies,* 8, 93-114.

Morfoulaki, M., Kotoula, K., Stathacopoulos, A., Mikiki, F. and Aifadopoulou, G. 2016. Evaluation of specific policy measures to promote sustainable urban logistics in small-medium sized cities: the case of Serres, Greece, *Transportation Research Procedia,* 12, 667-678.

Moriarty, P. 2002. Environmental sustainability of large Australian cities, *Urban Policy and Research,* 20, 233-244.

Motlagh, O., Foliente, G. and Grozev, G. 2015. Knowledge-mining the Australian smart grid smart city data: A statistical-neural approach to demand-response analysis. *Planning Support Systems and Smart Cities.* Springer.

Nam, T., & Pardo, T. A. 2011. Conceptualizing smart city with dimensions of technology, people, and institutions. In *Proceedings of the 12th Annual International Digital Government Research Conference: Digital Government Innovation in Challenging Times* (June 12-15). ACM. MD, USA. pp. 282-291

Newman, P. 1992. The compact city: an Australian perspective, *Built Environment (1978-)*, 285-300.

Newton, P. W. 2012. Liveable and sustainable? Socio-technical challenges for twenty-first-century cities, *Journal of Urban Technology,* 19, 81-102.

Odendaal, N. 2003. Information and communication technology and local governance: understanding the difference between cities in developed and emerging economies, *Computers, Environment and Urban Systems,* 27, 585-607.

Partridge, H. L. 2004. Developing a human perspective to the digital divide in the'smart city'.

Ramaswami, A., Russell, A. G., Culligan, P. J., Sharma, K. R. and Kumar, E. 2016. Meta-principles for developing smart, sustainable, and healthy cities, *Science,* 352, 940-943.

Shen, L. Y., Ochoa, J. J., Shah, M. N., and Zhang, X. 2011. The application of urban sustainability indicators–a comparison between various practices, *Habitat International*, 35(1), 17-29.

Siddiqui, S. Q., Ullah, F., Thaheem, M. J. and Gabriel, H. F. 2016. Six Sigma in construction: a review of critical success factors, *International Journal of Lean Six Sigma,* 7, 171-186.

Söderström, O., Paasche, T. and Klauser, F. 2014. Smart cities as corporate storytelling, *City,* 18, 307-320.

Washburn, D., Sindhu, U., Balaouras, S., Dines, R., Hayes, N. and Nelson, L. 2009. Helping CIOs understand "smart city" initiatives, *Growth,* 17.

Webb, J., Hawkey, D. and Tingey, M. 2016. Governing cities for sustainable energy: The UK case, *Cities,* 54, 28-35.

Weber, E. P. and Khademian, A. M. 2008. Wicked problems, knowledge challenges, and collaborative capacity builders in network settings, *Public administration review,* 68, 334-349.

Yamagata, Y. and Seya, H. 2013. Simulating a future smart city: An integrated land use-energy model, *Applied Energy,* 112, 1466-1474.

Yiftachel, O. and Hedgcock, D. 1993. Urban social sustainability: the planning of an Australian city, *Cities,* 10, 139-157.

Yigitcanlar, T. 2010. Making space and place for the knowledge economy: knowledge-based development of Australian cities, *European Planning Studies,* 18, 1769-1786.

Yigitcanlar, T., Dur, F. and Dizdaroglu, D. 2015. Towards prosperous sustainable cities: A multiscalar urban sustainability assessment approach, *Habitat International,* 45, 36-46.

Yigitcanlar, T., Fabian, L. and Coiacetto, E. 2008. Challenges to urban transport sustainability and smart transport in a tourist city: the Gold Coast, *The Open Transportation Journal,* 2, 29-46.

Part IV: BIM, VR and AR for Construction and Safety

INTEGRATING AUGMENTED REALITY AND BUILDING INFORMATION MODELLING TO FACILITATE CONSTRUCTION SITE COORDINATION

Ali Ghaffarianhoseini, Dat Tien Doan, Tongrui Zhang, Attiq Ur Rehman, Nicola Naismith, John Tookey, James Rotimi

Department of Built Environment Engineering, School of Engineering, Computer and Mathematical Sciences, AUT University, Auckland, New Zealand

Amirhosein Ghaffarianhoseini

Department of Geography, Faculty of Arts and Social Sciences, University of Malaya (UM), Malaysia

Tianming Yu, Zhentao Mu, Yicao Qi

Shenyang Huayu Architectural Design CO., LTD, China

ABSTRACT: *The construction industry has been evolving to embrace the delicate balance between buildings and the sustainable environment. This has highlighted the necessity to optimize resources to create healthier and more energy-efficient constructions. Likewise, it is vital to determine the viability of architectural design and building process. The application of relevant techniques to achieve this goal is essential. However, the lack of capabilities which immerse clients, end users, and building team members in highly detailed, fully lit environments that simulate the final structure of existing techniques could discourage the development of green buildings. Augmented Reality (AR) technology, which has advanced rapidly in the past few years, could play a key role towards onsite construction coordination. Despite within a Virtual Reality (VR) environment enabling its potential practice for simulated information sharing, this study focused primarily on the applications of AR for reviewing 3D drawings in a real-world interface based on a 2D drawing. Moreover, integration of professional models empowering the accuracy for AR presentation is an inevitable essential during sustainable construction management. The objective of this paper highlights the need for a structured methodology of fully integrating AR technology in BIM to facilitate construction site coordination. This study describes current AR research opportunities and challenges in sustainable construction management and emphasize what they can gain from the adoption of BIM. It is demonstrated that, extension to the site via the AR technology within the BIM platform can develop and visualize project designs, construction plans, schedules, and construction equipment into a real-time interactive and digitally manipulable environment.*

KEYWORDS: *Augmented Reality (AR); Virtual Reality (VR); Building Information Modelling (BIM); Sustainable Construction Management; Green buildings.*

1. INTRODUCTION

The improvement of the cost-efficiency in construction projects has a major impact on nation's gross domestic product and jobs added (Finkel, 2015; Ibrahim et al., 2010; Jaffe et al., 2016; Lu et al., 2015; MBIE, 2014). It is suggested that there is a need to optimize resources to create more and healthier energy-efficient constructions in the Architecture, Engineering and Construction (AEC) industry. In the past decades, computer aided design (CAD) was dominantly used in AEC industry (Aouad et al., 2013; Phiri, 1999), however, coordination among multiple disciplines and complex structures could reduce the effectiveness of two dimensions (2D) method (Aouad et al., 2013). Moreover, three dimensions (3D) modelling provides multi-view drawings, represents the building entities in a more complete way rather than 2D (Watson & Anumba, 1991). Therefore, AEC industry has been focusing on 3D applications for integrating all construction working documentation for projects (Cory, 2001). Although 3D methods hold the potential to deal with complex construction issues, 3D modelling requires more time and cost for training (Aouad et al., 2013; Cory, 2001). Besides, the convenience of 3D method used onsite is also important (Aouad et al., 2013; Cory, 2001). However, 3D packages are limited by the level of interoperability (Aouad et al., 2013). Based on these conditions, this study proposes an AR (Augmented Reality)-based construction drawing to improve the efficiency of onsite construction. The study provides a literature review for the state of the art of 2D and 3D digital drawings and AR technology. Then, this study will detail the technology roadmap for the solution of integrating AR and BIM for onsite coordination for the main objectives. In section 4, the application of the proposed technology into BMW Brilliance Automotive Ltd. Dadong Plant New 5 Series Construction Project Assembly Shop project is introduced, and the results are discussed and final conclusions provided.

2. LITERATURE REVIEW

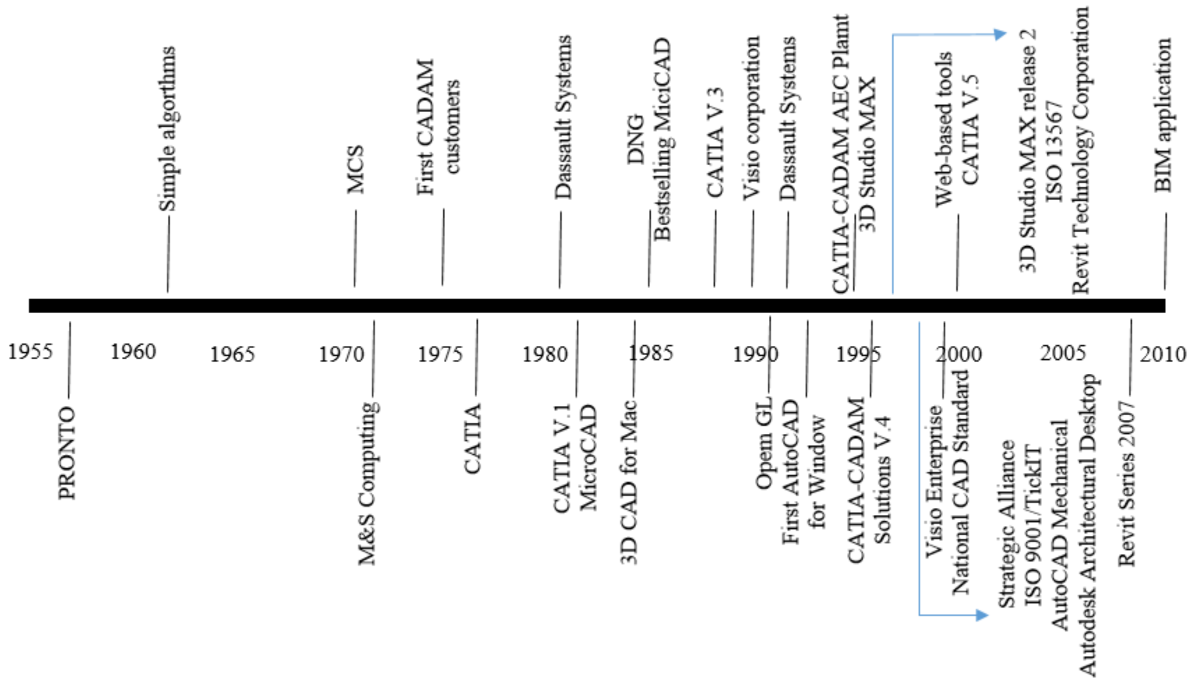
The construction industry is a vibrant and dynamic sector of any country's economy. It is responsible for a major impact on nation's gross domestic product and jobs added (Finkel, 2015; Ibrahim et al., 2010; Jaffe et al., 2016; Lu et al., 2015; MBIE, 2014). However, the sector is believed to have low levels of innovation (Loosemore, 2015; Noktehdan et al., 2015; Suprun & Stewart, 2015; Tajuddin et al., 2015). In addition, low productivity is a common pattern globally in this sector (Chalker & Loosemore, 2016; Loganathan & Kalidindi, 2015; Muhammad et al., 2015; Noktehdan et al., 2015). A breakthrough in technology could play an important role to change these issues as advanced technology could improve the character and nature of the construction industry (Noktehdan et al., 2015; Teo et al., 2015).

2.1 Digital drawing in construction industry

An important adopted innovation technology was the introduction of digital drawing (see Figure 1). It began with the PRONTO development, the first commercial numerical-control programming system, by Dr. Patrick J. Hanratty in 1957 (Martin-Dorta et al., 2013). The first CAD programs could display patterns of the lines initially in 2D in 1962 (Aouad et al., 2013). However, the general method of design remained largely unchanged much until the mid-1990s; engineering had described their works by simple tools such as pen, paper, and ruler (Yan & Damian, 2008). In 1991, stereolithography was used as a feasible method for digital fabrication (Naboni & Paoletti, 2015). 1992 marked the point at which digital model was applied in a large project, fish-shaper pavilion (Naboni & Paoletti, 2015). The structural analysis was performed by the digital surface model (Naboni & Paoletti, 2015). It directed the production and assemblage of the full-scale structural components (Naboni & Paoletti, 2015). The first complete book, "Computer-Aided Architectural Model Building", which describes the digital fabrication in the architectural design process was published in 1996 (Streich & Weisgerber, 1996).

Fig. 1: Milestones in CAD (Adapted from Aouad et al. (2013))

These developments established the foundations for CAD interface used currently, which has expanded drawing possibilities and simply transfer the information among construction stages, leading to the rapidly process



(Stephenson, 1996).

2.2 2D and 3D modelling

CAD is useful in the construction industry, which is related to a high degree of repetition as well as the wide variety of different work disciplines that need to be completed quickly and accurately (Aouad et al., 2013). Saving time could bring a significant benefit in terms of profits to construction projects (Phiri, 1999). With the popularisation of computer and the characters of the industry, CAD drawings have been used frequently (Phiri, 1999). The design of projects could be assessed for cost, buildability or compliance with Building Regulations by the integration of

CAD and analytical applications (Aouad et al., 2013).

2.2.1 2D

2D has been the principal means of communicating design information in the construction industry since round the beginning of the 20th century (Schantz, 1989). It is undeniable that it has generated a number of advantages with few of disadvantages (Cory, 2001).

Figure 2 shows nine advantages and three disadvantages of adopting 2D CAD. Adopting 2D CAD provides facilities for the input and manipulation of basic graphics (Watson & Anumba, 1991). Different facilities with the abilities to erase, copy, move, alter (extend/trim, rotate, mirror, etc.) could be exploited for a series of stacked plans (Phiri, 1999). In addition, symbol libraries in which frequently occurring standard components or symbols are stored could enhance the efficiencies of drafting (Aouad et al., 2013; Watson & Anumba, 1991). Moreover, 2D CAD drafting can be altered quickly and is secured by saving in uneditable formats (Aouad et al., 2013).

In terms of the disadvantages, it only provides individual views which sometimes require interpretation (Cory, 2001). Regarding to the interoperatbility, 2D CAD will most likely enhance collaboration and information among stakeholders (Aouad et al., 2013). However, adopting different softwares could reduce the interoperability due to the different digital formats of 2D files which are uneditable (Aouad et al., 2013).

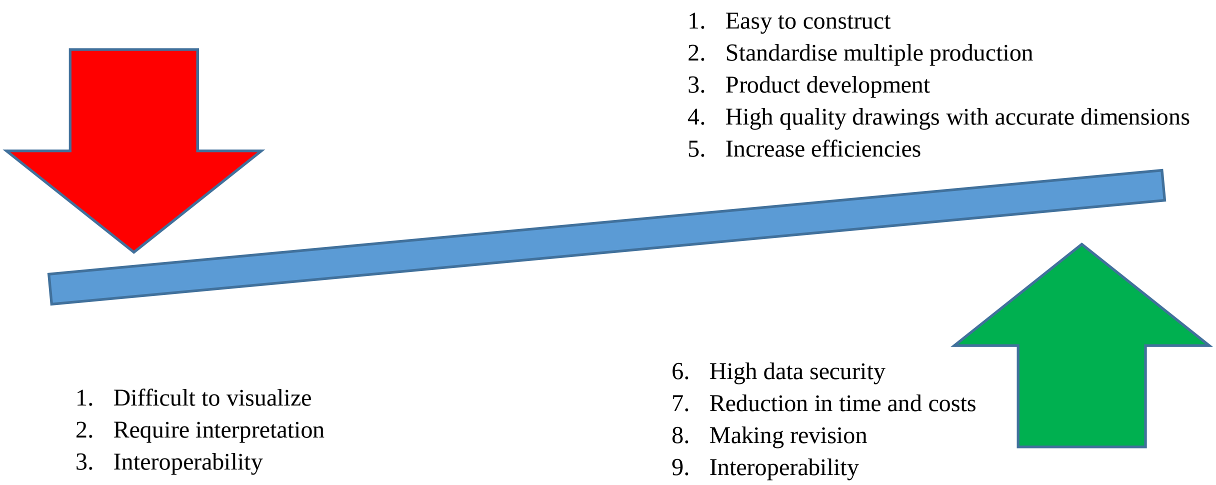


Fig. 2: Advantages and disadvantages of 2D CAD

2.2.2 3D

3D modelling, which provides multi-view drawings, represents the real world in a more complete way rather than 2D (Watson & Anumba, 1991). Therefore, AEC industry has been focusing on utilizing 3D models to generate all construction working documentation for projects (Cory, 2001).

Compared to 2D, 3D offers numerous benefits, indicated in Figure 3. It increases the productivity by the flexible modification of the designs at different levels (Watson & Anumba, 1991). Changes that are made will be immediately reflected in all the available views of those models (Phiri, 1999). It generates a computer copy of the proposed real-life projects which can be analysed automatically to generate plans and elevations; extract volumetric information, and predict its response to different environmental conditions (Aouad et al., 2013). It also enhances competitiveness in bidding for different forms of contracts due to the 3D visualization, ranging from simple block modelling at the early design stage to full rendered images for final stage, which is persuasive in communication ideas (Phiri, 1999). The exploded views could also reduce the potential design errors and checking time (Cory, 2001). Moreover, architects, engineers, and clients could earn benefits with facilities for 3D modelling and easily understood printouts as they clearly transfer the information exchanges among stakeholders, leading to the minimization in costs of site alterations and other expenditures (Aouad et al., 2013; Cory, 2001; Phiri, 1999).

Although many benefits can be achieved with 3D model use, it has a number of disadvantages including. 3D modelling requires an extremely high learning curve which requires substantial time and cost for training (Aouad et al., 2013; Cory, 2001). Besides, completing models with full properties declarations for entire structures and materials involves the cooperation among stakeholders (Cory, 2001). However, the level of interoperability among 3D packages is limited which considerably reduces the success of projects (Aouad et al., 2013).

1. Time
2. Upfront cost
3. Interoperability

1. Productivity
2. Prototyping attribute of 3D models
3. Enhanced competitiveness
4. Visualization
5. Error and time reduction
6. Interoperability

Fig. 3: Advantages and disadvantages of 3D CAD

2.2.2 2D and 3D overview

Both 2D and 3D bring considerable benefits to the construction industry. Depending on the characteristics of the project and the capability of organizations, the decision to choose either 2D or 3D will be made. Although 3D is encouraged and has become popular in construction projects, the final design output required on the site is a set of 2D drawings (Paterson et al., 2015). This is because 2D drawings are still the conventional means of communication among engineering staff (Cheng, 2013).

3D modelling is known as a compliance of drawings which improves the coordination between stakeholders which could reduce project conflicts. While 2D drafting still plays an important role at the final output of the design process, integration between 2D and 3D is necessary to maximum their potential benefits.

2.3 AR

Using the AR technique integration between 2D and 3D could be achieved. With the 2D drawing outputs, virtual objects could be created from 3D BIM model using the mobile-device AR.AR is referred as an integrated technique of image processing and display system of complex information which generates virtual objects over real objects to produce a mixed world (Irizarry et al., 2013; Jiao et al., 2013; Yang et al., 2013). According to Azuma et al. (2001), it could combine real and virtual objects in a real environment, run interactively in real time, and align with each other. AR has been developed since the 1960s with the introduction of the ultimate display to present 3D graphics (Azuma et al., 2001; Yang et al., 2013). In 1968, simple wireframe drawings could be displayed in real time with the use of an optical see-through head-mounted display and one of two different 6 Degrees of Freedom trackers (Yang et al., 2013).

In the late 1990s, several conferences on AR were organized such as the International Workshop and Symposium on Augmented Reality, the International Symposium on Mixed Reality, and the Designing Augmented Reality Environments workshop (Azuma et al., 2001). During this time, ARalso received more attention from well-funded orgranizations, including Mixed Reality Systems Lab in Japan and the Arvika consortium in Germany (Azuma et al., 2001). In 1997, a survey to guide and encourage further research in this area was published (Azuma et al., 2001; Azuma, 1997). In 2000s, new possibilities in the field of 3D data visualization, navigation and interaction far beyond the traditional static navigation and interaction were created by the synergy of AR (Portalés et al., 2010; Yang et al., 2013).

AR has been adopted in many fields of science and engineering. Thomas et al. (2000) carried out research on outdoor/indoor AR first person application ARQuake, an extension of the desktop game Quake. Regenbrecht and Specht (2000) investigated an approach to solve the problem of providing sufficient computational and graphics power on conventional wearable computers by AR implementation. Livingston et al. (2002) developed the Battlefield Augmented Reality System (BARS) for military operations. Birkfellner et al. (2002) presented a simple design of the modified head-mounted display for AR visualization in medicine.

AR is also considered as one of the advanced computer technologies which has potential to provide significant advantages through visualization to the AEC industry (Dunston, 2008). There are some issues in the AEC industry including a lack of information for field operators (Chi et al., 2012; Schall et al., 2009; Woodward et al., 2010), gaps between planned solutions and practical implementations (Dunston, 2008), and poor communications between related project participants (Chen & Schnabel, 2009; Hammad et al., 2009; Kim et al., 2011). AR has shown the potential to solve these issues (Chi et al., 2013). Kuo et al. (2013) stated that AR has been gaining extensive applications in the construction field, such as real-time 3D display of on-site construction progress (Woodward et al., 2010), introduction of objects assembling procedures (Behzadan et al., 2006), design and revitalization in existing built environments (Donath et al., 2001), and others. Dunston (2008) described a vision for Mixed Reality implementation, especially AR systems, for AEC industry. Golparvar-Fard et al. (2009) proposed the visualization of performance metrics to represent progress deviations through superimposition of 4D as-planned model over time-lapsed photographs in single and comprehensive visual imagery. Dunston (2009) evaluated the benefits of inspection with the ARCam versus a conventional method in AEC industry. Roberts et al. (2002) used AR to overlay locations of subsurface utility lines onto real world views to assist maintenance workers to avoide buried infrastructure and structure elements (Behzadan & Kamat, 2013).

Mobile-device AR has been researched to optimize workflows for various purposes including quality control, safety management, scheduling, mocking up spaces for clients, training workers, construction education (Irizarry et al., 2013), and in this research for construction site coordination.

3. TECHNOLOGY

The traditional method for construction coordination includes 2D-based method and BIM-based method 2D-based method holds its advantages in stakeholders' comprehension in its dimensions, while BIM-based method take advantages of its visualization for the spatial relationship of each component. However, onsite stakeholders do not fully understand the 2D drawings in some complex cases. Furthermore, not all of them are always well-skilled with BIM technology, it is suggested that this can cause the low utilization for BIM model. Therefore, a match of 2D drawings and BIM model could be of significant value. Moreover, the introduction of AR will be useful to achieve it. The process of AR-based method for construction site coordination includes steps shown in Figure 4.

Firstly, the engineers should integrate their design data in BIM model and out put the 3D model. Secondly, They should optimize their output 3D model so that different materials can be distinguished. If the 2D blueprints are not complex enough for identification and recognition, they should also be optimized in PhotoShop. Thirdly, a AR environment is needed to correlate the 3D models to the 2D drawings. Finally, the UI designers should make a friendly interface so that the workers onsite can install and use it easily.

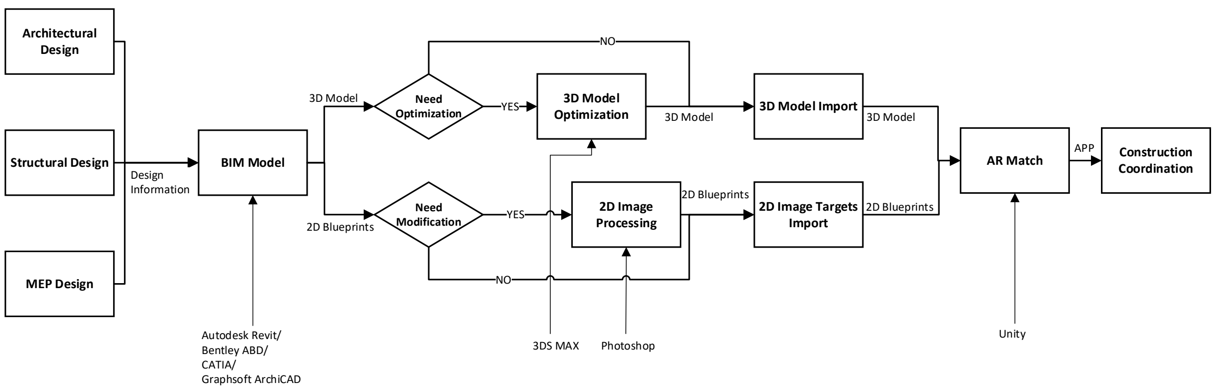


Fig. 4: The process of AR-based construction site coordination

4. CASE STUDY

To validate the effectiveness and efficiency of the technological roadmap, this study select BMW Brilliance Automotive Ltd. Dadong Plant New 5 Series Construction Project Assembly Shop as the case study. This project involves complex pipes covering multiple disciplines and the construction quality requirement is very high.

4.1 General description

BMW Brilliance Automotive Ltd. Dadong Plant New 5 Series Construction Project Assembly Shop is located at Dadong District, Shenyang, Liaoning Province of China. The project commenced 1st, May, 2014 and expected to be completed on 31th, March, 2017. With a total area of 165,000 m^2, the client requires a high standard of quality for the Mechanical, Electrical & Plumbing (MEP) installation.

4.2 Issues to be faced

This project faces three main issues:

a) Due to the complex MEP installation processes required for project, more visual methods are needed to coordinate onsite for sustainable construction management. The use of a Conventional 2D method will not successfully show the construction workers how to work successfully onsite. Furthermore, onsite workers may not have enough 3D software skills. Thus, the first issue is how to show the 3D relationship for each pipeline of this project.

b) The project would also benefit from the use of BIM to coordinate onsite. BIM can provide an nD model that provides rich information including 3D relationship data, however the conventional popular mobile BIM platforms such as BIM 360 GLUE, BIMx present the roaming of a building in shade mode, which are not easy for onsite workers to adapt. Moreover, there are not enough mobile devices onsite for mobile BIM applications. Thus, the adoption of mobile BIM applications onsite is the second issue.

c) The adoptive design document form for delivery is 2D drawings, this may not present information comprehensively, especially MEP pipelines. Meanwhile, 3D digital drawings are not currently allowed for design review. Thus the project team should provide 2D drawings which satisfy the requirements of 3D design.

4.3 Application of AR-based Onsite Coordination

a) Create the BIM models for each discipline and export the 3D models. Designers have the choice from a range ofplatforms including Autodesk Revit, Bentley AECOSim Building Designer, Graphsoft ArchiCAD, Dassault CATIA etc. to create the BIM model. Meanwhile, the design works always include architectural design, structural design, MEP design, all the designers in different disciplines will work based on the same central documents to fasten the model creation works. After all the works are finished, the designers should agree on which disciplines should be shown in the AR-based construction drawings and single discipline or the integrated one. Then, the 3D models should be exported. Figure 5 shows the BIM model of this project created in Revit 2016.

b) Generate 2D construction drawings and export them as images. Within a BIM framework, 2D construction drawings can be done by sectioning from 3D BIM models. The designers should then dimension each component and 2D generate the construction drawings.

c) Collect all the contexts, figures and videos that need to be included. Some joints are complex and it is difficult for onsite workers to understand the construction method. Thus, construction knowledge is needed to be attached by AR in the form of context, figures and videos.

d) Optimize the 3D models and distinguish different systems with standard colors. Sometime, in MEP design, there are few systems to be distinguished such as different HVAC systems. Developers create the BIM models first, then export to 3DS MAX for optimization. In 3DS MAX, standard materials should be used to distinguish each system. If they are not optimized, it will be time-consuming to change materials or colors in AR development engines.

e) Optimize the 2D images to meet the recognition requirements. There is a recognition index in each AR development engine to show how the image can be recognized. If the image full of similar patterns, it would be difficult to be recognized. Therefore, when this happens, developers should use image processing software such as Photoshop to add recognition patterns on it. Then, it is exported to image format such as .jpg, etc.

f) Transform the 2D images to image targets. Images are with image format that would not adaptable to AR required format. Thus, the developers should upload the image to certain websites such as Vuforia, etc. to transform 2D images to image targets packages.

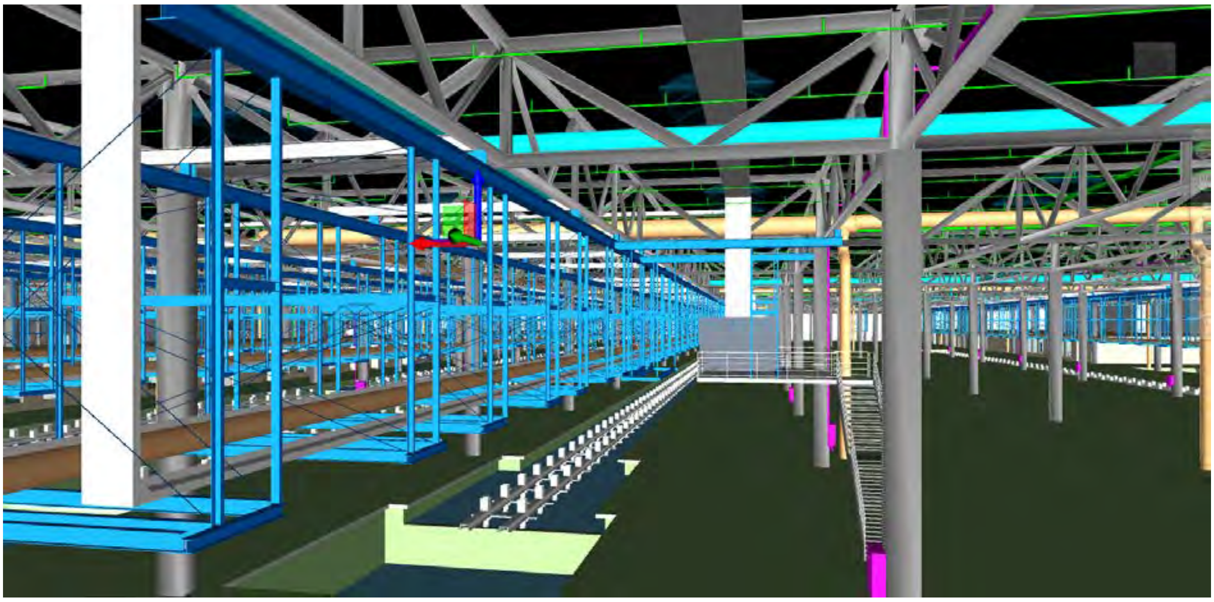


Fig. 5: The overview of BIM model for Assembly Shop.

g) Load all the require sources include optimized 3D models, image targets, contexts, images, videos in certain AR development engines. After all the sources are already collected, then the developers need to load them in AR development engines such as Unity before matching the sources in the right position with the image targets. Figure 6 has shown the relationship between image target and 3D model for a part of Assembly Shop.

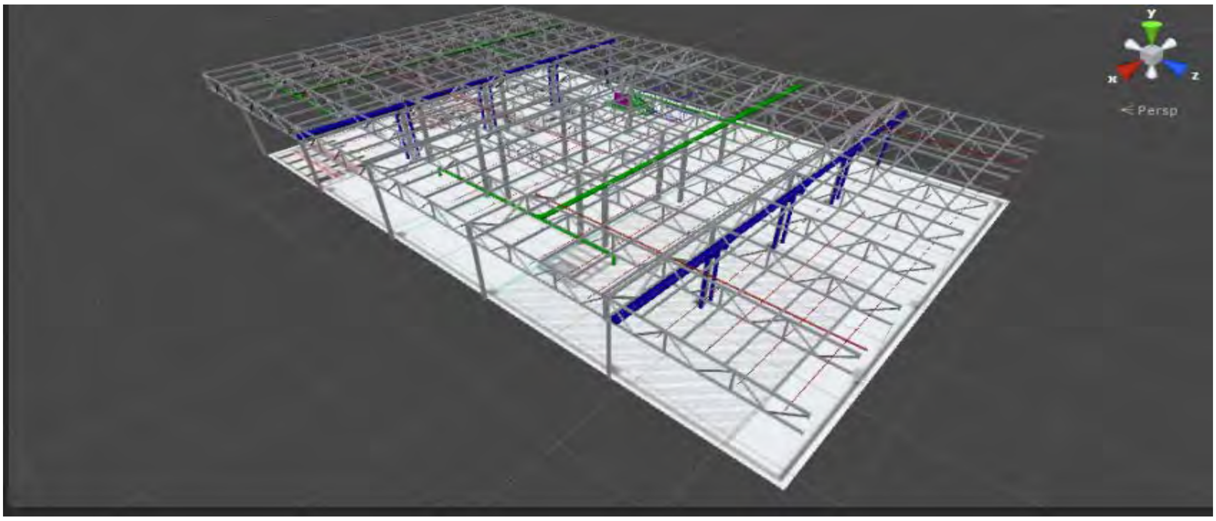


Fig. 6: The match of 3D model with 2D image target for a part of Assembly Shop.

h) Design the interfaces of the APP and the operation modes. The developers should design the interfaces of the APP and add several basic functions to it including the framework of operations, the operation modes, etc. After that, the APP for Android, ios, windows, Linus platform is published. Finally, the APP in devices and coordinate onsite will be installed. Figure 7 shows the onsite stakeholders use mobile phone to check the AR-based construction drawings. Figure 8 is the results of the APP onsite.

Above all, in this project, the onsite workers utilize the AR-based construction drawings to make 3D relationship of pipes clear. Whenever they get confused, they can refer to the AR-based 3D model to align their position. In this project, each dimension could be shown on 2D drawings and the AR-based 3D model only to show the relationship without dimensions. In case of in some complex positions where contains much more pipes it was difficult for 2D drawings to detail the dimensions, onsite workers also asked for help from BIM engineers.

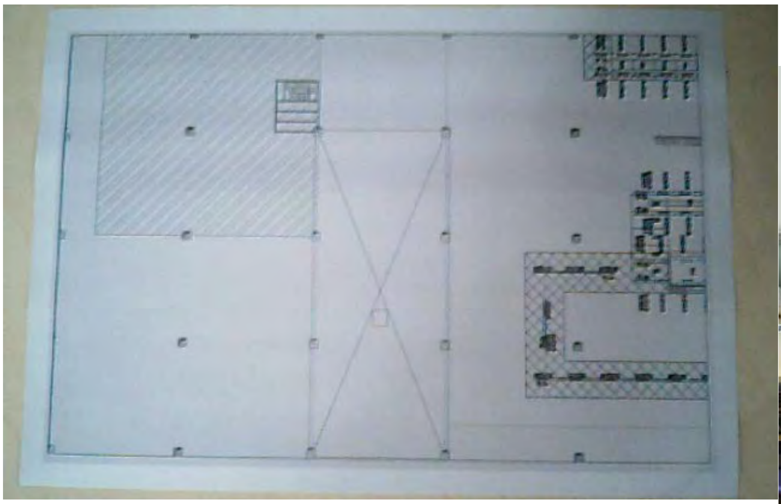


Fig 7: The application of AR-based construction drawing

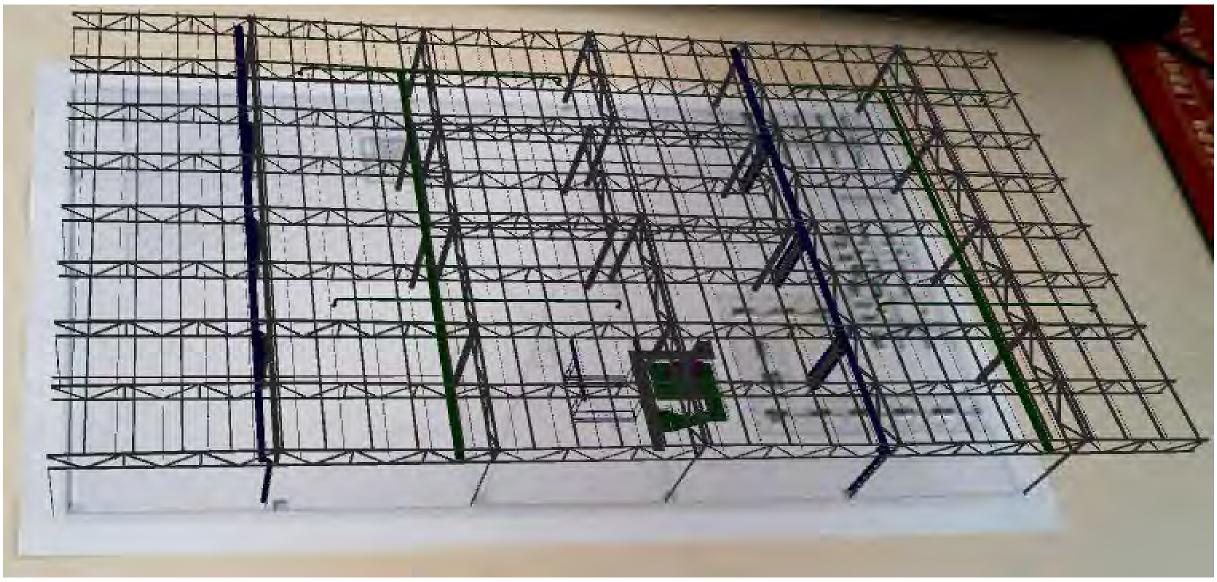


Fig 8: The result of AR-based construction drawing APP

5. DISCUSSION

This paper has presented the process of AR-based construction site coordination. The results demonstrate the applicability of the proposed technology to construction sites. It can successfully improve the performance of existing on-site management processes by providing the 3D virtually based on 2D images. The 2D outputs could be virtualized comprehensively with a mobile AR, thereby enhancing the interoperability. In addition, reducing time and errors in the projects is also achieved with this potential technology. Besides, onsite workers without knowledge concerning 3D software skills still have the ability to complete their works without attending training courses. While this paper presented the initial works toward AR-based construction drawings, several challenges remain. These challenges include that the AR-based drawings are currently set only with the presentation of the 3D models above the 2D drawings, however, the dimensions are missing, which is important onsite. In this project, the onsite workers only use 2D drawings for dimensions and 3D AR-based model for clearing the relationship between different components. Secondly, in this project, the proposed method is limited by the real-time adaptive capacity. Although the proposed method can review the 3D drawings in real time based on 2D drawings, the real-time communications among stakeholders have not been involved in this project. Finally the hardware of the mobile devices is becoming the limitation of the application of AR-based APP. The mobile phones of the onsite workers are usually with low configurations and normally can only integrate fewer 3D drawings in their mobile phones.

6. CONCLUSION

In this paper, an overview of CAD and AR, including historical developments, together with potential benefits and challenges, was presented. AR is a rapidly growing field in construction sector since late 1990s. The development of mobile computing solutions has provided a flexible and powerful environment for on-site construction management and it is expected to shift the conventional construction management practices. Mobile-device AR has been researched to optimize workflows for various purposes including quality control, safety management, scheduling, mocking up spaces for clients, training workers, construction education. This paper presented mobile AR as an advanced and innovative tool for construction site coordination, AR-based construction drawing APP. A case study involving construction of an assembly shop in China was conducted to validate the system. The case study showed that the proposed system has a high potential to achieve more sustainability, profitability, interoperability, and security in the construction sector.

This study contributed to the existing body of knowledge by demonstrating how AR mobile can improve the existing on-site construction management practices. Future studies, however, are required to encourage the involvement of mobile cloud streaming technology to solve the hardware obstacles. In addition, the development of functions such as dimension and communication related functions, etc. is also encouraged.

7. REFERENCES

Aouad, G., Wu, S., Lee, A., & Onyenobi, T. (2013). *Computer aided design guide for architecture, engineering and construction*: Routledge.

Azuma, R., Baillot, Y., Behringer, R., Feiner, S., Julier, S., & MacIntyre, B. (2001). Recent advances in augmented reality. *IEEE computer graphics and applications, 21*(6), 34-47.

Azuma, R. T. (1997). A survey of augmented reality. *Presence: Teleoperators and virtual environments, 6*(4), 355-385.

Behzadan, A. H., & Kamat, V. R. (2013). Enabling discovery-based learning in construction using telepresent augmented reality. *Automation in construction, 33*, 3-10.

Behzadan, A. H., Khoury, H. M., & Kamat, V. R. (2006). Structure of an extensible augmented reality framework for visualization of simulated construction processes*IEEE.* Symposium conducted at the meeting of the Proceedings of the 2006 Winter Simulation Conference

Birkfellner, W., Figl, M., Huber, K., Watzinger, F., Wanschitz, F., Hummel, J., . . . Ewers, R. (2002). A head-mounted operating binocular for augmented reality visualization in medicine-design and initial evaluation. *IEEE Transactions on Medical Imaging, 21*(8), 991-997.

Chalker, M., & Loosemore, M. (2016). Trust and productivity in Australian construction projects: a subcontractor perspective. *Engineering, Construction and Architectural Management, 23*(2), 192-210.

Chen, I., & Schnabel, M. A. (2009). Retrieving lost space with tangible augmented reality Symposium conducted at the meeting of the Proc. of the 14th CAADRIA Conf

Cheng, R. K. (2013). *Inside Rhinoceros 5*: Cengage Learning.

Chi, H.-L., Chen, Y.-C., Kang, S.-C., & Hsieh, S.-H. (2012). Development of user interface for tele-operated cranes.

Advanced Engineering Informatics, 26(3), 641-652.

Chi, H.-L., Kang, S.-C., & Wang, X. (2013). Research trends and opportunities of augmented reality applications in architecture, engineering, and construction. *Automation in construction, 33*, 116-122.

Cory, C. A. (2001). *Utilization of 2D, 3D, or 4D CAD in construction communication documentation*. presented at the meeting of the Fifth International Conference on Information Visualisation,

Donath, D., Beetz, J., Grether, K., Petzold, F., & Seichter, H. (2001). Augmented reality techniques for design and revitalisation in existing built environments. *Angenommener Beitrag zur ACADIA, Buffalo*.

Dunston, P. S. (2008). Identification of application areas for Augmented Reality in industrial construction based on technology suitability. *Automation in construction, 17*(7), 882-894.

Dunston, P. S. (2009). Evaluation of augmented reality in steel column inspection. *Automation in construction, 18*(2), 118-129.

Finkel, G. (2015). *The economics of the construction industry*. Abingdon, United Kingdom: Routledge.

Golparvar-Fard, M., Peña-Mora, F., Arboleda, C. A., & Lee, S. (2009). Visualization of construction progress monitoring with 4D simulation model overlaid on time-lapsed photographs. *Journal of Computing in Civil Engineering, 23*(6), 391-404.

Hammad, A., Wang, H., & Mudur, S. P. (2009). Distributed augmented reality for visualizing collaborative construction tasks. *Journal of Computing in Civil Engineering, 23*(6), 418-427.

Ibrahim, A. R. B., Roy, M. H., Ahmed, Z., & Imtiaz, G. (2010). An investigation of the status of the Malaysian construction industry. *Benchmarking: An International Journal, 17*(2), 294-308.

Irizarry, J., Gheisari, M., Williams, G., & Walker, B. N. (2013). InfoSPOT: A mobile Augmented Reality method for accessing building information through a situation awareness approach. *Automation in construction, 33*, 11-23.

Jaffe, A., Le, T., & Chappell, N. (2016). *Productivity distribution and drivers of productivity growth in the construction sector*. Retrieved from http://motu-www.motu.org.nz/wpapers/16_08.pdf

Jiao, Y., Zhang, S., Li, Y., Wang, Y., & Yang, B. (2013). Towards cloud augmented reality for construction application by BIM and SNS integration. *Automation in construction, 33*, 37-47.

Kim, B., Kim, C., & Kim, H. (2011). Interactive modeler for construction equipment operation using augmented reality. *Journal of Computing in Civil Engineering, 26*(3), 331-341.

Kuo, C., Jeng, T., & Yang, I. (2013). An invisible head marker tracking system for indoor mobile augmented reality. *Automation in construction, 33*, 104-115.

Livingston, M. A., Rosenblum, L. J., Julier, S. J., Brown, D., Baillot, Y., Swan, I., . . . Hix, D. (2002). *An augmented* *reality system for military operations in urban terrain*: DTIC Document.

Loganathan, S., & Kalidindi, S. N. (2015). A Review of Labor Productivity Research in Construction. *International Journal of Technology, 5*(2), 91-99.

Loosemore, M. (2015). Construction innovation: Fifth generation perspective. *Journal of Management in Engineering, 31*(6), 04015012.

Lu, W., Yang, H., & Langston, C. (2015). *Internationalization of the construction industry*. Abingdon, United Kingdom: Routledge.

Martin-Dorta, N., de Chaves Assef, P. G., De la Torre Cantero, J., & Rufino, G. R. (2013). IMPLEMENTING BIM TECHNIQUES FOR ENERGY ANALYSIS: A CASE STUDY OF BUILDINGS AT UNIVERSITY OF LA LAGUNA. *ENVIRONMENTAL SECURITY, GEOLOGICAL HAZARDS AND MANAGEMENT*, 61.

MBIE. (2014). *The New Zealand Sectors Report 2014: An analysis of the New Zealand economy by sector*. Retrieved from http://www.mbie.govt.nz/info-services/business/business-growth-agenda/sectors-reports-series/pdf-image-library/the-new-zealand-sectors-report-2014-main-report/New%20Zealand%20Sectors%20Report%20-%20full%20report%20-PDF%205%20MB.pdf

Muhammad, N. Z., Sani, A., Muhammad, A., Balubaid, S., Ituma, E. E., & Suleiman, J. H. (2015). EVALUATION OF FACTORS AFFECTING LABOUR PRODUCTIVITY IN CONSTRUCTION INDUSTRY: A CASE STUDY. *Jurnal Teknologi, 77*(12).

Naboni, R., & Paoletti, I. (2015). *Advanced Customization in Architectural Design and Construction*: Springer.

Noktehdan, M., Shahbazpour, M., & Wilkinson, S. (2015). Driving Innovative Thinking in the New Zealand Construction Industry. *Buildings, 5*(2), 297-309.

Paterson, G., Harty, J., & Kouider, T. (2015). *Getting to Grips with BIM: A Guide for Small and Medium-sized Architecture, Engineering and Construction Firms*: Routledge.

Phiri, M. (1999). *Information technology in construction design*: Thomas Telford.

Portalés, C., Lerma, J. L., & Navarro, S. (2010). Augmented reality and photogrammetry: A synergy to visualize physical and virtual city environments. *ISPRS Journal of Photogrammetry and Remote Sensing, 65*(1), 134-142.

Regenbrecht, H. T., & Specht, R. (2000). A mobile passive augmented reality device-mpard*IEEE.* Symposium conducted at the meeting of the Augmented Reality, 2000.(ISAR 2000). Proceedings. IEEE and ACM International Symposium on

Roberts, G. W., Evans, A., Dodson, A., Denby, B., Cooper, S., & Hollands, R. (2002). The use of augmented reality, GPS and INS for subsurface data visualization Symposium conducted at the meeting of the FIG XXII International Congress

Schall, G., Mendez, E., Kruijff, E., Veas, E., Junghanns, S., Reitinger, B., & Schmalstieg, D. (2009). Handheld augmented reality for underground infrastructure visualization. *Personal and ubiquitous computing, 13*(4), 281-291.

Schantz, H. (1989). Banking, information, and imaging standards from a users' perspective.

Stephenson, R. J. (1996). *Project partnering for the design and construction industry*: John Wiley & Sons.

Streich, B., & Weisgerber, W. (1996). *Computergestützter architekturmodellbau: CAAD-grundlagen, verfahren, beispiele*: Birkhäuser-Verlag.

Suprun, E. V., & Stewart, R. A. (2015). Construction innovation diffusion in the Russian Federation: Barriers, drivers and coping strategies. *Construction Innovation, 15*(3), 278-312.

Tajuddin, M. Z. M., Iberahim, H., & Ismail, N. (2015). Relationship between Innovation and Organizational Performance in Construction Industry in Malaysia. *Universal Journal of Industrial and Business Management, 3*(4), 87-99.

Teo, E. A. L., Ofori, G., & Tjandra, I. K. (2015). Building Information Modelling (BIM) for safety improvement in Singapore construction*CIB (International Council for Building), Delft, the Netherlands.* Symposium conducted at the meeting of the Proceedings of the 2015 CIB W099 Conference: Benefitting Workers and Society through Inherently Safe (r) Construction, Belfast, Northern Ireland, 9–11 September

Thomas, B., Close, B., Donoghue, J., Squires, J., De Bondi, P., Morris, M., & Piekarski, W. (2000). ARQuake: An outdoor/indoor augmented reality first person application*IEEE.* Symposium conducted at the meeting of the Wearable computers, the fourth international symposium on

Watson, A., & Anumba, C. (1991). The need for an integrated 2D/3D cad system in structural engineering. *Computers & structures, 41*(6), 1175-1182.

Woodward, C., Hakkarainen, M., Korkalo, O., Kantonen, T., Aittala, M., Rainio, K., & Kähkönen, K. (2010). Mixed reality for mobile construction site visualization and communication Symposium conducted at the meeting of the Proc. 10th International Conference on Construction Applications of Virtual Reality (CONVR2010)

Yan, H., & Damian, P. (2008). *Benefits and barriers of building information modelling*. presented at the meeting of the 12th International conference on computing in civil and building engineering,

Yang, M.-D., Chao, C.-F., Huang, K.-S., Lu, L.-Y., & Chen, Y.-P. (2013). Image-based 3D scene reconstruction and exploration in augmented reality. *Automation in construction, 33,* 48-60.

VIRTUAL COLLABORATIVE SAFETY TRAINING FOR CRANE OPERATIONS

Isik Ates Kiral & Semra Comu

Bogazici University, Istanbul, Turkey

Jiayu Chen

City University of Hong Kong, Hong Kong

John E. Taylor

Georgia Institute of Technology, Atlanta, GA, USA

ABSTRACT: *Tower cranes are among the most frequently used heavy equipment in the construction industry for transporting materials in vertical and horizontal directions, which creates mechanical advantages for construction companies. Despite its advantages, enhancing the safety of tower crane operation is challenging. Crane activities require both a specialized skill set to operate and also collaboration among the specialized crafts. Therefore, an advanced collaborative training method may prevent serious incidents on construction sites. However, providing collaborative safety training on-site is risky and for some tasks impracticable. For this reason, virtual environments can be utilized to provide a safe space for developing necessary skill sets which might otherwise be dangerous and risky on a real construction site. Moreover, accidents or hazardous cases can be demonstrated and tested without exposing the trainees to any real danger. In addition to developing skill sets, virtual environment-based training could also enhance the trainee's collaboration skills by supporting multiuser interaction. In this study, we aimed to develop an effective safety training tool for crane operations that involves developing collaboration skills, ensuring knowledge transfer and providing elaborate feedback. We developed a virtual safety training tool called V-SAFE (Virtual Safety Analysis For Engineering applications) which simulates and visualizes tower crane scenarios. In order to evaluate the performance of the proposed training system, undergraduate and graduate students participated in an alpha test and virtual experiment. Results indicate that V-SAFE can successfully simulate collaborative tasks in a tower crane operation. Thus, this study has the potential to provide an effective safety training method for crane operations.*

KEYWORDS: *Crane Operation, Virtual Collaboration, Virtual Safety Training*

1. INTRODUCTION

For many years, the demand for construction services has increased. Due to population around the world, the needs of communities have expanded resulting in higher demand for construction, including infrastructure projects such as power plants, high-rise buildings and transportation networks. Consequently, the construction industry has become an important economic driver for many countries around the world. For instance, the Hong Kong construction industry earns around 96 billion Hong Kong dollars (Hong Kong Census and Statistics Department, 2016a) which corresponds to 4,4% of the Hong Kong National Economy (Hong Kong Census and Statistics Department, 2016b). Similarly in the United States, construction volume is around 717 billion U.S. dollars which corresponds to more than 4% of the U.S. national economy (U.S. Bureau of Economic Analysis, 2016).

In addition the increasing demand for construction services, the technological requirements have become more complex. In order to meet the complex requirements, industrialization has become an important strategy. Off-site and mass production coupled with the use of automation technologies has increased. Consequently, production and transportation equipment have become critical capital investments for the organizations (Shapira et al., 2007).

Tower cranes are used to displace heavy materials and transport them in a vertical and lateral direction. Considering that heavy materials are above the lifting capacity of the human workforce, companies use cranes to achieve a mechanical advantage to improve time and cost effectiveness. Even though crane operations have many advantages, providing safety during lifting tasks is challenging. For this purpose, effective safety training must provide and maintain a safe work environment during crane operations. Yet, traditional safety training methods do not meet the needs of the highly complex construction projects (Ho and Dzeng, 2010). In this study, we aim to develop an effective safety training method for the crane operations by using virtual technologies.

2. BACKGROUND

Crane operations are high-risk construction activities that could cause catastrophic injuries (Shapira and Lyachin, 2009). On the other hand, most of the crane accidents are preventable (Shapira and Lyachin, 2009). For this purpose, many researchers focus on crane operation related safety issues (e.g. Shapira and Lyachin, 2009, Shapira et al. 2014) and develop methods for sustaining safe work environments (e.g. Guo et al., 2012; Lin et al., 2011; Li et al., 2012; Kıral et al., 2015). For example, Shapira and colleagues (2014) developed a laser-based model to capture the blind spots from the viewpoint of a crane operator. Accordingly, they aimed to reduce blind lifts on construction sites (Shapira et al. 2014). The quantitative analysis results show that the location of the crane and staging areas are crucial and the signal persons' position is a significant parameter in the provision of safety. Consistently, Shapira and Lyachin (2009) identified the factors of accidents as project conditions, environment, human factor and safety management and they also evaluated the degree of influence of these causes. Among all the risk factors, they found the competency of the crane operator as the most important parameter (Shapira and Lyachin, 2009). Moreover, the character and risk behavior of the operator and the superintendent together with the experience level of the signal person are the other human based factors for crane accidents (Shapira and Lyachin, 2009). Taken together, previous research (Shapira et al., 2014, Shapira and Lyachin, 2009) on the safety management of crane operations has revealed that human-based factors have a significant effect on the tower crane related accidents.

Since human factors have the greatest impact on accidents (Shapira and Lyachin, 2009), effective training is important to provide safety during crane operations. As one of the preliminary training effectiveness studies, Kirkpatrick (1979) states that an effective training method should cover *reaction*, *learning*, *behavior* and *results*. According to Kirkpatrick (1979);

i. Reaction – How well the trainees liked a particular training program. Evaluating in terms of reaction is the same as measuring the feelings of the conferees.

ii. Learning – What principles, facts and techniques were understood and absorbed by the conferees.

iii. Behavior –How the participants adjust their behaviors based on the training.

iv. Results – The success level of the participants based on the examination results.

On the other hand, Kirkpatrick (1979) did not consider the relationship between the training method and its effectiveness level. In this regard, Frese and Zapf (1994) state that, active training methods, which provide higher interaction, such as giving safety lectures and conducting interviews are more effective compared to passive techniques such as providing safety documents or videos. In other words, the method used to transfer information to the trainees is one of the most important elements of the training efficiency. Similarly, Burke and colleagues (2006) designed a safety training effectiveness model entitled as *engagement hypothesis*. They state that the effectiveness of the training is correlated with the engagement level of the trainees (Burke et al. 2006). Burke and colleagues list the interaction level of the safety training as follows: *(i) least engaging, (ii) moderately engaging and (iii) highly engaging* (2006). A precise safety training method should cover: information transfer, hands-on training, behavioral modelling, and feedback mechanism (Burke et al. 2006). Overall, many studies on safety training (Kirkpatrick, 1979; Frese and Zapf, 1994; Burke et al., 2006) highlight the need for conveying the information via hands-on practice. Moreover, since the collaboration requirement between different roles is a prerequisite in the tower crane tasks (Shapira et al., 2014), effective tower crane safety training should also cover the collaboration during hands-on training. However, hands-on practice on the construction site is risky.

Hands-on training on construction sites is not a common practice, but vital for achieving high safety performance levels. For this purpose, many researchers focus on developing off-site safety training methods, but with hands-on practice opportunity by using virtual technologies (e.g. Guo et al., 2012; Lin et al., 2011; Li et al., 2012; Kıral et al., 2015). Virtual reality technology provides an interactive relation between users and computers via visualized information flow in the virtual environment (Hoffman et al., 1996). A virtual environment "is synthesized as a collection of 3D geometrical entities… the geometrical entities are rendered in real-time, often with the help of special purpose 3D rendering engines, to provide an interactive walk-through experience" (Chen, 1995:29). Such environments have been studied extensively to examine how workers collaborate in virtual environments (e.g., Comu et al., 2013; Fruchter, 1999; Iorio and Taylor, 2014).

In addition to collaborative aspects of virtual environments, an important contribution of virtual collaboration technologies is that trainees can train themselves in a construction work space where they are in no physical danger. In this sense, virtual reality or virtual environment-based training methods are highly appropriate to provide an effective hands-on safety training for tower crane tasks. Therefore, in recent years, researchers have begun to investigate the suitability of virtual environment based safety training on the tower crane tasks (Lin et al., 2011; Guo et al., 2012; Li et al., 2012; Kıral et al., 2015). Guo and colleagues (2012) developed a virtual environment based training method to improve the safety training effectiveness of tower crane operation. The study shows that serious gaming technologies improved the training efficiency during construction plant operations. In the same vein, Lin and colleagues (2011) developed a virtual safety education tool that involves crane operations. Study results indicate that the performance of the trainees improved. Lin and colleagues' (2011) contribution is supported by another study (Li et al. 2012) that evaluates the tower crane dismantlement activities via virtual reality based safety training. Similarly, Kıral and colleagues (2015) found that virtual reality-based safety training has a great potential to provide highly interacting safety training proposed by Burke and colleagues (2006). Taken together, studies related to virtual safety training highlight the suitability of using virtual technologies to train workers for tower crane operations. In light of these several studies (Guo et al., 2012; Lin et al., 2011; Li et al., 2012; Kıral et al., 2015) about virtual construction safety training, we aim to develop a highly interactive virtual platform called V-SAFE (Virtual Safety Analysis For Engineering applications).

3. RESEARCH METHODOLOGY

3.1 Motivation of Using Virtual Environment

In this study, we aim to develop a simulation-based virtual environment that emulates tower crane operations. In the very first step, the tool simulates an example of crane lifting operation in a three-dimensional (3D) virtual environment. The environment involves the main features of the simulation such as collision detection technology, reality integration and crane operation functions. The main reasons for using these features are to provide a realistic, safe workspace for the users and to enable their exposure against potential accidents occurring on construction sites. Thus, users could enhance their knowledge about safety procedures during tower crane tasks. In addition, we also aim to establish a base for the trainees to learn from their mistakes and face potential consequences of these mistakes. With this way, users could adjust their behavior when they experience the catastrophic outcomes of the accidents in a risk free virtual environment. Moreover, another major importance of the virtual training could be considered as providing a repeatable practice opportunity. Due to the reasons listed above, virtual environments are appropriate for the safety training of tower crane operations.

3.2 V-SAFE Development

V-SAFE was developed using the Unreal Engine 4. Unreal Engine is an open source game engine developed by Epic Games for high-end games on PCs, game consoles, and virtual reality (Unreal Engine Official Website, 2016). Not only for PC gaming, the Unreal Engine is also used for other purposes such as education, training, transportation, movie storyboard and simulation. Warner Bros., Sony, and Amazon are licensees of the product (Unreal Engine Official Website, 2016). The main advantage of the Unreal Engine 4 over its competitors is its graphical fidelity. Also, 3D walk-throughs and architectural visualization projects can be easily built by using blueprints in the Unreal Engine 4. In short, high end graphics, using blueprints, and open source are some of the reasons why we chose the Unreal Engine 4 for developing the V-SAFE.

3.2.1 V-SAFE Model Framework

The model framework of V-SAFE involves five major stages. In the first phase, the tool generates the 3D models necessary for the simulation such as; buildings, bricks, personal protective equipment. In addition to that, the models in the surrounding environment such as clouds, trucks, walls, are also developed. Thus, users could monitor a realistic construction workspace in a 3D environment. Secondly, users enter into the environment by creating their own avatars on the server (Figure 1) and select one of the roles in the crane operation simulation; (i) crane operator, (ii) pointer and (iii) brick layer. In the third stage, when the all users select their role, they start the training by entering to the warehouse and they select the correct personal protective equipment (Figure 2).

Fig. 3: An Avatar with Personal Protective Equipment

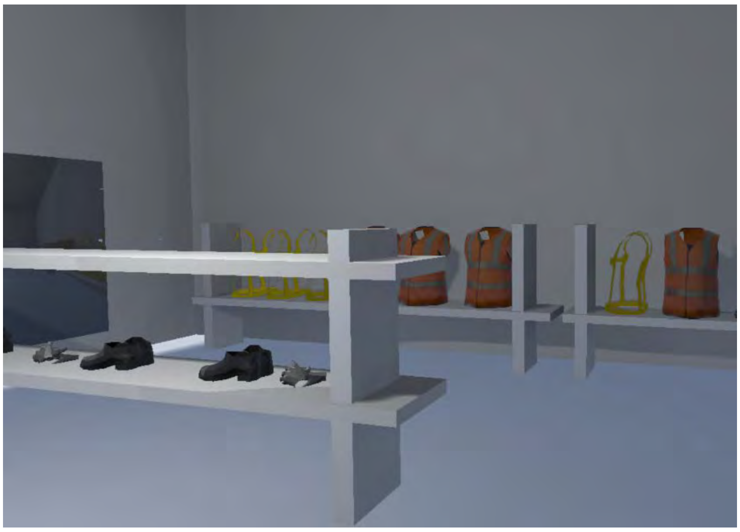


Fig. 2: Personal Protective Equipment Selection in the Warehouse

As the fourth step, the trainees start interacting with the models (e.g. crane, lift, rope, etc.) and other trainees in the virtual environment. Based on their behavior, decisions and collaboration, their performance is analyzed and they receive a written feedback at the last stage of the training session.

3.2.2 V-SAFE Training Procedure

The main procedure of the training consists of three stages. First of all, we evaluated the potential hazards of tower crane tasks defined by Shepherd and colleagues (2000). In addition, we evaluated and defined the causes of tower crane accidents listed by Shapira and Lyachin (2009). We integrated the major following accident causes to the virtual media: (i) blind lifts, (ii) type of load, (iii) wind, (iv) weather conditions, (v) operator proficiency, (vi) operator character and (vii) signal person behavior. Later, we investigated the major precursors and the potential impacts of these accidents (Shepherd et al., 2000). By the systematic analysis based on accidents, we proposed a feedback criteria that evaluates: (i) the safety knowledge and behavior of the trainees, (ii) collaboration skills and (iii) the level of conveying the safety information. Subsequently, we associated these hazards into the virtual objects in the virtual environment of V-SAFE. Finally, we defined three different roles as a crane operator, pointer, and bricklayer. Crane operators' main duty is to move the load from ground level to the second floor of the building, without causing any safety errors. Pointers' main responsibility is to guide the crane operator during the transportation of the load, especially on the blind spots. The brick layer is responsible for loading and unloading processes.

3.3 Experimental Setting

In the virtual experiment, we utilized graduate and undergraduate students as surrogate workers. Initially, we provided the necessary safety management information and the tutorial of the software to the trainees. We recorded a video supported by PowerPoint presentations. All the trainees watched the same video related to their role. In this way, we ensured that all the trainees received the same information which is crucial to sustain a controlled environment for the experiments. Before conducting the virtual experiments, we also ran several alpha tests with students and researchers to ensure that the features of the software work properly. Alpha test results show that, all the features of the V-SAFE, which are collision detection, modeling the surrounding environment, user-user and user-virtual object interaction, are precisely functioning.

After the completion of the alpha tests, we conducted the virtual experiments with 12 students. During the experiment, users had to fulfill both their individual and collaborative duties in the virtual environment. Based on their decisions and safety behavior, trainees could be subjected to potential accidents such as falling from height, struck by the objects, etc. During the experiments, trainees used joysticks, gamepads, keyboard, mouse and monitors (Figure 3 & 4).

Fig. 3: Interaction of the Trainee as a Pointer Using Gamepad.

Fig. 4: Interaction of the Trainee as a Crane Operator Using Joysticks.

Users could monitor the surrounding environment based on the first person point of view and they could orient their avatar by using the keyboard, mouse or gamepad. In addition, crane operators use joysticks to orient the movement of the tower crane, which makes the simulation environment more realistic.

4. ANALYSIS RESULTS

Based on the performance of the trainees during the virtual experiments, the results are illustrated in the following tables (Table 1, 2 and 3).

Table 1: Performance Evaluation of the Crane Operator Role on the V-SAFE Training Platform.

		User 1	**User 2**	**User 3**	**User 4**
Personal protective equipment selection.	Taking all the necessary personal protective equipment and walky-talky.	✓	✓✗	✓✗	✓✗
Pre-test of the tower crane functions	Checking all the movement functions of the tower crane before loading.	✓	✓	✓	✓
	Checking the audio warning system before loading.	✓	✓	✗	✗
Selection of the rope type	Checking the weather condition and wind speed on the crane control screen.	✓	✓	✗	✓
	Learning the dimensions and weight of the load from brick layer.	✓	✓	✓	✓
	Selecting the correct rope type based on the weather condition, wind speed, load dimension	✓	✓	✗	✓

	and weight information.				
Movement of the load	Activating the audio warning system during movement, loading and unloading.	✓	✗	✗	✗
	Moving the hook close to the load based on the guidance of the pointer and loading process.	✓	✓	✓	✓
	Moving the load for approximately 10 centimeters up for ensuring the load points are correct.	✓	✓	✓	✗
	Moving the hook to the 2nd floor safely.	✗	✗	✗	✗
✓✗: Symbol represents that the objective was partially completed by the trainees.					

Table 2: The Performance Evaluation of the Pointer Role on the V-SAFE Training Platform.

		User 1	**User 2**	**User 3**	**User 4**
Personal protective equipment selection.	Taking all the necessary personal protective equipment and walky-talky.	✓✗	✓✗	✓	✓
Guiding the crane operator before and during loading.	Guiding the crane operator, during the movement of the hook to the load.	✓	✓	✓	✓
	Checking the loading points based on the center of the gravity	✓	✓	✓	✗
Guiding the crane operator before and during loading.	Guiding the crane operator, after the loading process.	✗	✗	✗	✗
	Putting on the safety belt on the 2nd floor.	✗	✗	✗	✗
✓✗: Symbol represents that the objective was partially completed by the trainees.					

Table 3: The Performance Evaluation of the Brick Layer Role on the V-SAFE Training Platform.

		User 1	**User 2**	**User 3**	**User 4**
Personal protective equipment selection.	Taking all the necessary personal protective equipment and walky-talky.	✓	✓	✓✗	✓✗
Guiding the crane operator before and during loading.	Informing the crane operator about the weight and dimensions of the load.	✓	✓	✓	✓
	Loading the materials to the hook on the ground floor.	✓	✓	✓	✓
Unloading process.	Putting on the safety belt on the 2nd floor.	✗	✗	✗	✗

	Unloading the load from the tower crane and piling the load on the 2^{nd} floor adequately.	×	×	×	×
✓×: Symbol represents that the objective was partially completed by the trainees.					

5. DISCUSSION

A wide variety of construction heavy machinery is operating on construction sites, which makes construction jobs quicker and easier. However, ensuring safety on construction sites with heavy machinery operations is extremely challenging. Several recent studies highlight that human-based issues (Shapira and Lyachin, 2009) and inadequate safety training (Shapira et al., 2014) are some of the major causes of accidents in the construction industry. In light of these issues, we aimed to develop and test an effective safety training method for tower crane operations, which is a commonly utilized type of heavy equipment in the industry.

In this study, we began with an inquiry on which safety training features should be involved by an effective safety training method and how these could be integrated into a virtual safety training context. For this purpose, we conducted an extensive literature review to identify the key issues of providing an effective safety training. Many studies in the literature (e.g. Kirkpatrick, 1979; Frese and Zapf, 1994; Burke et al., 2006) have emphasized the importance of the hands-on practice and the method used for information transfer. Moreover, Shapira and colleagues (2014) highlight the importance of collaboration during tower crane activities. As a result of this systematic review, we developed an Unreal Engine 4 based safety training program, entitled V-SAFE. We tested V-SAFE in two stages; an alpha test and an experiment, in order to evaluate the effectiveness of the tool during potential tower crane scenarios that could occur on real construction sites.

By hands-on practice in a risk free virtual environment, we aimed to enable an experiential learning where knowledge is created through the transformation of experience (Kolb, 1984). In other words, in experimental learning, “knowledge results from the combination of grasping and transforming experience” (Kolb, 1984: 41). Our analysis results highlight the importance of experiential learning in terms of the tower crane operations. Table 1 shows that none of the users with the tower crane operator role succeeded to move the load to the 2^{nd} floor without causing any accidents. Frese and Zapf (1994) highlight that importance of conveying the safety information through hands-on practice has a significant effect on the effectiveness of the training. In that case, the failure of the users during a movement task could be a good example about the importance of the safety information conveyance. Despite the users learning about crane movement, they were not capable of orienting the load safely in their initial trial.

Second, Shapira and Lyachin (2009) highlight that lack of hazard identification is an important cause of accidents related to tower crane activities. For example, crossing under the loads is one of the most common causes of accidents during tower crane tasks (Shapira and Lyachin 2009). Yet, none of the trainees crossed under the load since they could easily identify the risk in the virtual environment. In general, hazard identification stage in construction projects is completed through the investigation of the 2D materials such as drawings, architectural designs, site photographs, etc. On the other hand, all of these methods fail to address the third dimension integration, therefore, spatial cognition capacity of the trainees is quite limited. Just like other virtual environments, the V-SAFE reduced this gap by integrating third dimension and providing spatial awareness. The analysis results show that the V-SAFE has a high potential to improve the hazard identification level.

Another important issue of the effective training could be considered as the level of the information transfer provided by the training method (Kirkpatrick, 1979; Burke et al, 2006). As an important part of our analysis, we evaluated the decisions of the trainees about the selection of rope type and personal protective equipment. During the rope selection, we noticed that, nearly all trainees selected the correct rope, while only one user has mistaken about the rope selection by selecting a stronger rope. In that case, improper rope selection, which is one of the major causes of accidents during crane tasks, is successfully prevented by using the virtual training method. Moreover, personal protective equipment selection, which is merely based on information transfer, was successfully achieved by using the V-SAFE. In other words, we could improve the self-learning capabilities of the trainees.

Just like self-learning and safety information transfer, we also aim to integrate the collaborative learning into the V-SAFE. As shown in the Table 1, Table 2, and Table 3, many activities require collaboration among different roles. During the load movement tasks, there is a collaboration requirement among all the trainees. Table 2 presents that, all the pointers successfully guided the crane operators on the blind spots. Moreover, From Table 2 it could be seen that the crane operators successfully gathered the load dimensions from the brick layer and loading is successfully achieved. Moreover, some users warn other users about selecting the correct personal protective equipment. As a result, we noticed that, the V-SAFE establishes a base for the users to learn from each other. Hence, all the users could improve their safety knowledge, therefore they are able to improve their safety performance.

On the other hand, there are several limitations of this study. An important limitation of this study could be considered as the lack of comparative analysis between the traditional safety training methods and V-SAFE. Further research with a higher number of sample spaces is also needed to compare the effectiveness of conventional safety training methods and virtual environment based training.

6. CONCLUSION

Providing a safe construction site is an ongoing global concern and tower crane tasks constitute an important contributor to accidents. In order to ensure safety in tower crane operations, literature highlights the importance of safety training. In this study, we developed and examined the features of V-SAFE. We focused on the essentials of effective safety training, and evaluated the suitability of the virtual safety training method in an experiment. The results highlight that V-SAFE could provide an effective and low risk safety training for tower crane operations. In addition, V-SAFE successfully achieved the core elements of effective safety training, such as knowledge transfer, information transfer, providing elaborate feedback, behavioral modeling and collaboration. In brief, utilizing virtual technologies is appropriate for construction companies in order to improve the efficiency of the safety training process.

7. ACKNOWLEDGEMENT

This material is based in part upon work supported by Bogazici University Scientific Research Projects (BAP) under Grant No. 7902. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of Bogazici University Scientific Research Projects (BAP).

8. REFERENCES

Beavers, J. E., Moore, J. R., Rinhart, R., and Schriver, W. R. (2006). “Crane-related fatalities in the construction industry.” J. Constr. Eng. Manage., 132(9), 901–910.

Burke, M. J., Sarpy, S. A., Smith-Crowe, K., Chan-Serafin, S., Salvador, R. O., Islam, G. (2006). Relative effectiveness of worker safety and health training methods. American Journal of Public Health, 96(2), 315.

Chen, S. E. (1995). Quicktime VR: An image-based approach to virtual environment navigation. In Proceedings of the 22nd annual conference on Computer graphics and interactive techniques (pp. 29-38). ACM.

Comu, S., Iorio, J., Taylor, J., Dossick, C. (2013). Quantifying the Impact of Facilitation on Transactive Memory System Formation in Global Virtual Project Networks. Journal of Construction Engineering and Management, 139(3), 294-303.

Frese, M., Zapf, D. (1994). Action as the core of work psychology: A German approach. Handbook of industrial and organizational psychology, 4, 271-340.

Fruchter, R. (1999). Architecture/Engineering/Construction Teamwork: A Collaborative Design and Learning Space. Journal of Computing in Civil Engineering, 13(4), 261-270.

Guo, H., Li, H., Chan, G., Skitmore, M. (2012). Using game technologies to improve the safety of construction plant operations. Accident Analysis & Prevention, 48, 204-213.

Ho, C. L., Dzeng, R. J. (2010). Construction safety training via e-Learning: Learning effectiveness and user satisfaction. Computers & Education, 55(2), 858-867. ISO 690

Hoffman, H., Groen, Rousseau J. S., Hollander A., Winn W., Wells M., and Furness T., (1996). “Tactile Augmentation: Enhancing Presence in Virtual Reality with Tactile Feedback from Real Objects,” Meeting of the American Psycho- logical Society, San Francisco, CA.

Hong Kong Census and Statistics Department. (2016a). “Gross Domestic Product (GDP) by economic activity at current prices”

Hong Kong Census and Statistics Department. (2016b). “Gross Domestic Product (GDP) by economic activity - percentage contribution to GDP at basic prices”

Iorio, J., Taylor, J. (2014). Boundary Object Efficacy: The Mediating Role of Boundary Objects on Task Conflict in Global Virtual Project Networks. International Journal of Project Management, 32(1), 7-17.

Kıral, I. A., Çomu, S., Kavaklıoğlu, C. (2015). Enhancing the construction safety training by using virtual environment: V-SAFE.

Kirkpatrick, D. L. (1979). Techniques for evaluating training programs. Training and Development Journal, 178-192. Training & Development, American Society for Training and Development.

Kolb, D.A. (1984) Experiential Learning: Experience as the Source of Learning and Development. Englewood Cliffs, N.J.: Prentice-Hall.

Li, H., Chan, G., Skitmore, M. (2012). Multiuser virtual safety training system for tower crane dismantlement. Journal of Computing in Civil Engineering, 26(5), 638-647.

Lin, K. Y., Son, J. W., Rojas, E. M. (2011). A pilot study of a 3D game environment for construction safety education. Journal of Information Technology in Construction, 16(5), 69-83.

Shapira, A., Filin, S., Wicnudel, A. (2014). Quantitative analysis of blind tower-crane lifts using laser-scanning information. Construction Innovation, 14(3), 383-403.

Shapira, A., Lucko, G., Schexnayder, C. J. (2007). Cranes for building construction projects. Journal of Construction Engineering and Management, 133(9), 690-700.

Shapira, A., Lyachin, B. (2009). Identification and analysis of factors affecting safety on construction sites with tower cranes. Journal of Construction Engineering and Management, 135(1), 24-33.

Shapira, A., Filin, S., Wicnudel, A. (2014). Quantitative analysis of blind tower-crane lifts using laser-scanning information. Construction Innovation, 14(3), 383-403.

Shepherd, G. W., Kahler, R. J., Cross, J. (2000). Crane fatalities—a taxonomic analysis. Safety science, 36(2), 83-93.

U.S. Bureau of Economic Analysis, [online] “GDP by Industry”.

Available at: < http://www.bea.gov/industry/gdpbyind_data.htm> Accessed 15 July 2016

AUGMENTED REALITY BY DEPTH CAMERA FOR IMAGE-BASED PIPELINE INSPECTION

Takuma Yorimitsu, Hiroshige Dan, Akira Kobayashi and Yoshihiro Yasumuro

Faculty of Environmental and Urban Engineering, Kansai University, Japan

ABSTRACT: *This paper proposes an augmented reality (AR) investigation system that focuses on examinations of underground pipelines in situations where excavations are difficult or unnecessary. Currently, industrial endoscopes combined with video cameras are among the primary tools used in such situations, but when severe damage is found and repair work is required, above and underground conditions around the damaged section of pipe often cannot be easily verified. In our scenario, in addition to live camera images of pipe inner surfaces, we believe it would be effective to overlay various other images onto the inspector's view so that the situation between the ground surface and inner pipe can be clarified. In normal practice, industrial endoscopes are usually inserted from maintenance hatches that are installed in pipelines at set intervals. In our prototype implementation, a visual marker is placed on the maintenance hatch and an observation camera that shows the inspector's viewpoint is prepared to support the AR system. The extended length of an endoscope mounted (or self-propelled) camera, and the direction of the pipe can then be used to capture the relative location of the camera in the pipeline. From that point, mapping the collected image onto a cylindrical three-dimensional (3D) model that shows the nominal pipeline size facilitates visualization of the situation inside the pipe. In our prototype system experiments, as the camera moves forward, the live texture-mapped 3D pipe model is properly overlaid onto a realtime video image of the exterior view of the scenery. The various overlaying viewing information was also examined in a case study.*

KEYWORDS: *Augmented reality, Pipeline inspection, Industrial endoscopy, Depth camera, Posture compensation*

1. INTRODUCTION

Maintenance schemes and strategies aimed at the reinforcement and repair of the civil infrastructure are gathering considerable attention recently as numerous developed countries face problems resulting from the deterioration of decades-old infrastructures. Water pipelines, which have various uses such as potable water supply, sewerage, agricultural irrigation, and so on, are among such typical aging infrastructures. Since most such pipeline networks are buried, it is often hard to ascertain their physical conditions before deterioration-related damages become critical. However, dealing with every deteriorated infrastructure facility in every part of a country is not realistic, especially under the prevailing severe fiscal circumstances common to aging societies.

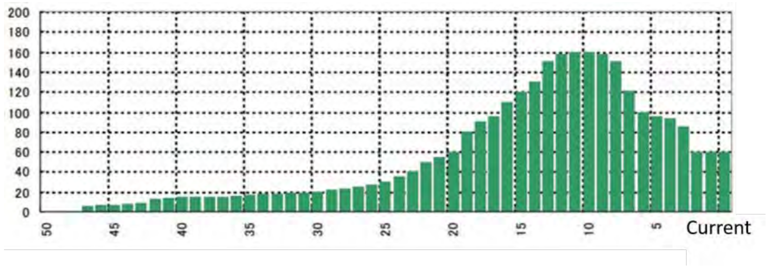


Fig. 1: (left) Newly built total pipeline length (km) vs. elapsed years (Japan Ministry of Construction and Transport, Sep. 2013). (Right) Pipeline repair work (Yoshimizu Kenki Co., Ltd. http://www.yoshimizu.co.jp/)

Therefore, in order to maintain the structure and functionality of existing pipelines, it is important to monitor and comprehend conditions inside and outside of the pipes *in situ*. There are two primary existing methods of inspecting such pipelines: indirect investigation from ground surface and direct investigation of pipe interiors.

Indirect investigation targets water leakage, flow volume, and corrosion by sampling the water volume, electrical potential, and soil at different points. Imaging pipe exteriors via video cameras provides another form of indirect investigation. In the case of interior investigations, the interior wall of the pipeline can be examined and diagnosed by direct measurement with a depth gauge or by visual inspections.

Direct investigations target crack conditions, snaking and/or pipeline sinking, deflection, as well as rust and sediment conditions. Thus, whereas indirect investigations provide macroscopic level information on the characteristics of existing pipelines, direct investigations are capable of ascertaining quantitative metrics of pipe configurations (Liu 2013). However, since direct investigations often require excavations to expose the pipe structures for direct access, their usage must still depend on a discrete sampling approach.

In recent years, high-resolution cameras have been installed on self-propelled, remote-controlled robots to perform examinations. Nevertheless, while color images can provide informative material for experienced operators, quantitative metrics of pipe characteristics are still required for objective investigation and management. Therefore, the purpose of this study is to propose an objective and comprehensive approach for investigating pipeline interiors that minimizes excavations.

Building information modeling (BIM) along with augmented reality (AR) techniques have recently been introduced to outdoor infrastructure maintenance workflow (Kamat, 2007, Woodward, 2010, Chi, 2013, Jiao, 2013, Park, 2013), and a number of specialized systems for underground pipeline structural maintenance have been proposed (Lawson 1998, Behzadan, 2005, Schall, 2009). One such practical service is provided in the form of Visual City by South East Corp. in Melbourne, Australia, where common information modeling (CIM) of underground municipal gas and water pipelines has been prepared, and where onsite AR visualization is achieved on mobile devices such as tablet personal computers (PCs). Use of this service accelerates decision-making processes from inspection to repair.

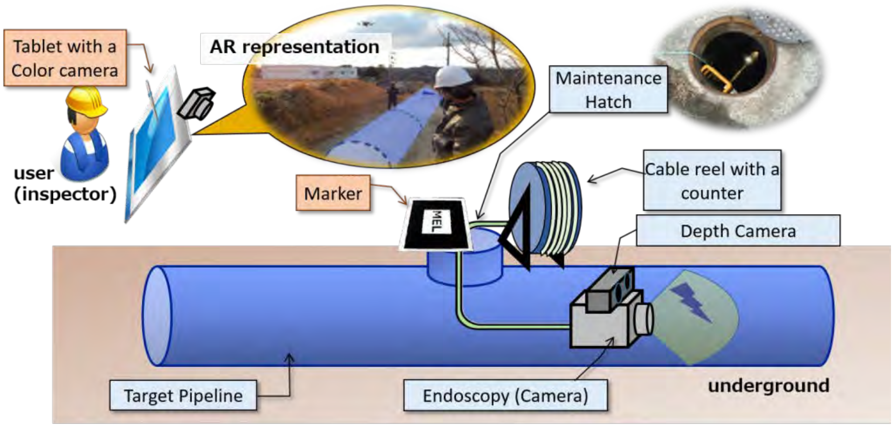


Fig. 2: Marker-based AR for realtime inspection

2. APPROACH

2.1 Marker-based AR

Existing AR applications for visualizing underground infrastructure have focused on overlaying pre-constructed underground pipeline models or computer-aided design (CAD) data onto aboveground live images. These functionalities are designed for use when planning excavations. In contrast, we have been developing an AR visualization utility for use during inspection work in order to provide more dynamic onsite assistance, as shown in Fig. 2 (Yorimitsu et al., 2015).

When using endoscopic systems, the inspector is expected to monitor and check images obtained from the camera system from a first-person perspective, which is most likely to be a distorted wide angle view, as shown in Fig. 3 (left). However, when the first-person perspective is combined with the third-person view, it provides the ability to “see” through the ground in a way that is helpful for taking the surrounding situation into account. Furthermore, a visual understanding of the relative geometry between the inspection point in the pipe structure and aboveground features and/or terrestrial conditions may potentially provide an awareness-raising environment that will assist in identifying the underlying causes of pipeline deterioration.

In our scenario, an inspection camera that can collect wide-angle color images is installed on the tip of an endoscopic cable or a self-propelled wheeled robot that can measure the camera’s travel distance and transmit that information to a host computer in realtime. We also employ another camera to capture the aboveground scenery in order to provide a “see-through” perspective from the operator’s viewpoint. A visual marker is used to provide a landmark and establish a local coordinate system at the maintenance hatch or manhole, from which the camera system is inserted for inspection purposes.

At the start of the inspection, the initial position of the camera and the pipe direction relative to marker coordinates are recorded. Then, image-based inspection is conducted by manipulating the camera system. Based on the camera’s movements, which are basically forward motion along the pipe, the camera position can be monitored by measuring the extended length of the camera cable.

Many reel-type cabled endoscopic camera systems are equipped with rotary encoding sensors that measure the length of the extended camera cable.

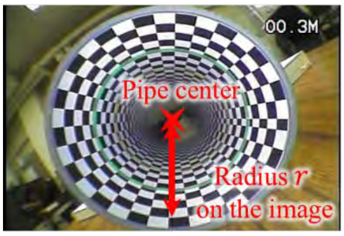
Our system scenario envisions a three-step process: (1) capturing live image frames from both the inspection and aboveground cameras, (2) using the inspection camera to capture raw pipe interior imagery, and (3) applying such imagery onto a texture image plane that is mapped onto the nominal size of the cylindrical model. This information is then overlaid onto the scenery image based on the relative position of the marker coordinates. Assuming that a guide device installed on the camera head basically ensures that the camera is always positioned at the center of the pipe and directed along its length, depth from the camera z and apparent radius r [pixels] on the inspection image can be expressed according to the following perspective projection:

$$z = \frac{fR - rz_0}{r},$$

where R is a physical size of the radius, z_0 is an offset depth from the camera, and f is the focal length of the camera, as shown in Fig. 3.

2.2 Camera Posture Compensation by Depth Information

Since, in practice, the camera direction always moves and often faces away from the center of the pipe during the operation, the resultant mapped texture is often distorted. In this paper, we compensate for this camera direction distortion based on normal vector distributions captured by using a depth camera combined with endoscopic camera (Inoue et al. 2015). The mesh structure of the depth image provides each normal vector n_i on each vertex i. We denote the normal vector n_i on each vertex i as follows:



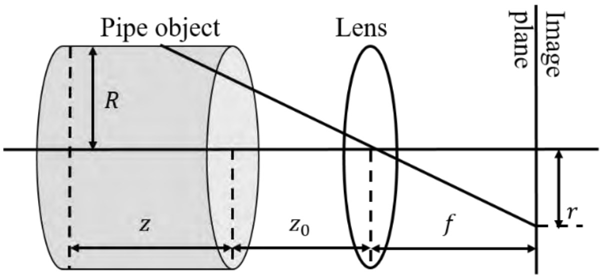


Fig. 3: AR implementation from two views: (left) marker based coordinates mapped onto a 3D model, (right) interior inspection view.

$$n_i = \begin{pmatrix} x_i \\ y_i \\ z_i \end{pmatrix} \quad (i = 1,2,\cdots,k)$$

We also define a matrix N, which is a collection of k normal vectors as

$$N = \begin{pmatrix} n_1^T \\ \vdots \\ n_k^T \end{pmatrix} \quad (k \times 3\; matrix)$$

and denote the axis direction vector *v* along the pipe as

$$v = \begin{pmatrix} \bar{x} \\ \bar{y} \\ \bar{z} \end{pmatrix}.$$

Assuming an ideal case, vector *v* would be orthogonal to every normal vector n_i. In other words, each inner product *Nv* equals zero. Since such *v* does not exist due to the measurement errors and inner surface roughness, in practice, we will choose *v* as a solution that minimizes the squared error as follows:

$$\underset{v}{\operatorname{argmin}} \frac{1}{2} \|Nv\|^2 = \frac{1}{2} v^T N^T N v = \frac{1}{2} v^T M v, \qquad , \tag{1}$$

where $M = N^T N$ (3×3). We simply stipulate that $\bar{z} = 1$ as a constraint in order to avoid a solution of $v = 0$. Then, equation (1) can be written as follows:

$$\underset{\bar{x},\bar{y}}{\operatorname{argmin}} f(\bar{x},\bar{y}) = \frac{1}{2} \begin{pmatrix} \bar{x} \\ \bar{y} \\ 1 \end{pmatrix}^T \begin{pmatrix} m_{11} & m_{12} & m_{13} \\ m_{12} & m_{22} & m_{23} \\ m_{13} & m_{23} & m_{33} \end{pmatrix} \begin{pmatrix} \bar{x} \\ \bar{y} \\ 1 \end{pmatrix} = \frac{1}{2} \begin{pmatrix} \bar{x} \\ \bar{y} \end{pmatrix}^T \begin{pmatrix} m_{11} & m_{12} \\ m_{12} & m_{22} \end{pmatrix} \begin{pmatrix} \bar{x} \\ \bar{y} \end{pmatrix} + \begin{pmatrix} m_{13} \\ m_{23} \end{pmatrix}^T \begin{pmatrix} \bar{x} \\ \bar{y} \end{pmatrix} + \frac{1}{2} m_{33} \tag{2}$$

Next, we will find $(\bar{x},\bar{y})$ so that the differential of the $f(\bar{x},\bar{y})$ equals zero.

$$Df(\bar{x},\bar{y}) = \begin{pmatrix} m_{11} & m_{12} \\ m_{12} & m_{22} \end{pmatrix} \begin{pmatrix} \bar{x} \\ \bar{y} \end{pmatrix} + \begin{pmatrix} m_{13} \\ m_{23} \end{pmatrix} = 0$$

$$\begin{pmatrix} \bar{x} \\ \bar{y} \end{pmatrix} = -\begin{pmatrix} m_{11} & m_{12} \\ m_{12} & m_{22} \end{pmatrix}^{-1} \begin{pmatrix} m_{13} \\ m_{23} \end{pmatrix}$$

Finally, the solution of the directional vector of the pipe is $(\bar{x}, \bar{y}, 1)^T$. This direction can be aligned along the

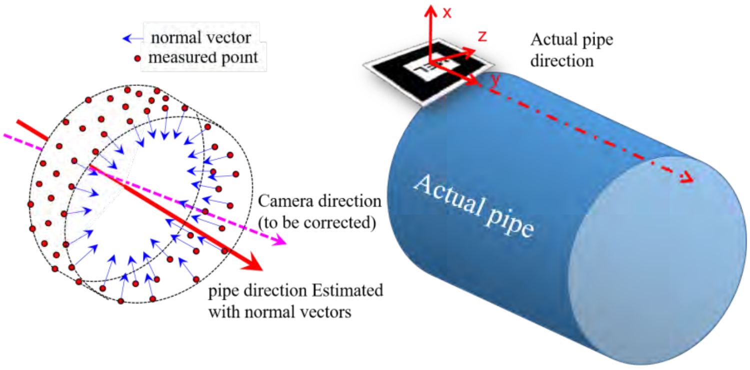


Fig. 4: AR implementation from two views: (left) marker based coordinates mapped onto a 3D model, (right) interior inspection view.

physical target pipe by finding a transformation so that the vector $(\bar{x}, \bar{y}, 1)^T$ faces parallel to one of the marker axes, according to the initial marker setup of the system, as depicted in Fig. 4.

3. EXPERIMENT

We conducted an experiment to demonstrate the proposed method using an actual endoscopic camera and a depth camera. The specifications of the inspection and depth cameras are shown in Tables 1 and 2, respectively. A 1.3 M pixel, 30 frame-per-second (FPS) universal serial bus (USB) camera (Qcam Ultra Vision, Logicool Inc.) was used to record the aboveground scenery.AR toolkit (Kato 1998) was used for implementing AR visualization software. AR toolkit provides useful application programming interfaces (APIs) for image stream capturing from multiple cameras, as well as marker-based AR handling. These include marker registration,

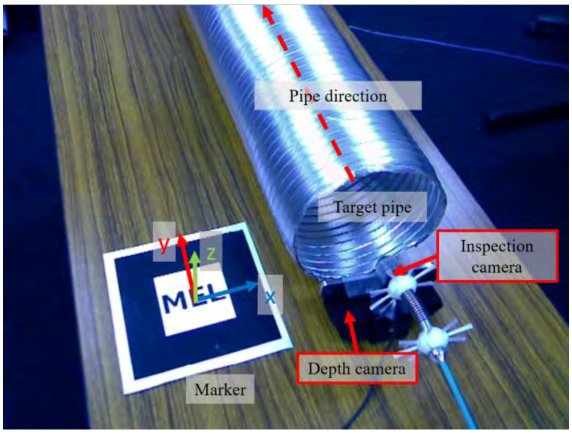


Fig. 5: Experimental setup: A marker is positioned beside the maintenance hatch, where the camera head is inserted. The head consists of jointed an endoscopy and a depth camera.

Table 1: Industrial Endoscopic Camera Specification

Field of view	160° (diagonal)	
Lens	F2.8, f = 2 mm	
Image sensor	2.5 Mpixel, 1/4” charge-coupled device (CCD)	
Frame rate	30 fps	
Distance measure	Encoding on cable drum (10 cm increments)	

Table 2: Depth Camera Specification

Device	Intel® RealSense™ SR300	
Device Size	150 × 30 × 58 mm	
Depth FoV (D × W × H)	80 × 68 × 54	
Depth FPS	30, 60	
Depth Method	Coded light IR	

camera calibration, viewing matrix estimation, and 3D object drawing in conjunction with OpenGL graphics library. We can also adjust the scaling factor that converts textured 3D objects in computer graphics along with the actual size of the pipe and camera movement distance in millimeters. The aboveground scenery camera recognizes the pre-registered visual marker and calculates the position and orientation of the inspection camera relative to the marker coordinates.

As shown in the endoscopic camera specifications, the camera cable reel is equipped with a rotary encoding sensor that is capable of counting the cable extension in 10 cm increments. Figure 5 shows the overview of our experimental setup, in which the marker is settled so that the y-axis is the direction of the target pipe. The endoscopic camera and the depth camera are fixed together and the rotational transformations between the directions of the two cameras are calculated beforehand. The pipe size is ϕ 200 mm.

Figure 6 shows an example of the depth image and the normal vector distribution captured by the depth camera, which contains 35,000 points (67,000 triangle meshes). Figure 7 shows the resultant AR representation example.

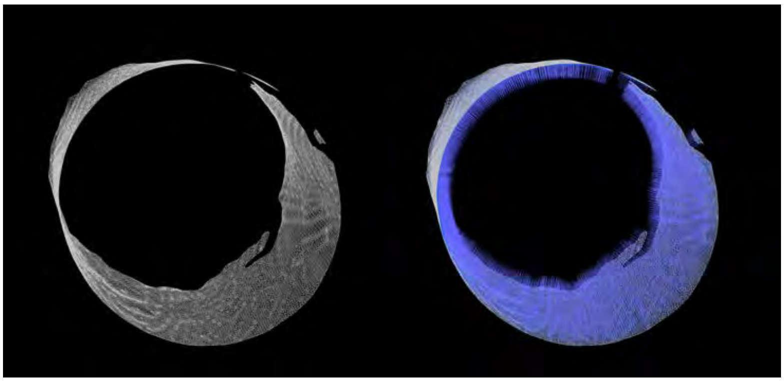


Fig. 6: (left) Captured depth data as a 3D point set, (right) the normal vectors at the points depicted by blue lines

The left-hand side shows the original output and the right-hand side shows the result of the proposed method to compensate for the camera direction, which faces off the center of the physical pipe. Although the difference seems quite slight, the measured inner surface of the pipe is correctly aligned to the physical pipe image and the AR view is consistent with the perspective of the shooting camera. The computational cost was low enough to create an AR view in realtime.

4. CONCLUSIONS

Herein, we proposed an implementation scheme for a pipeline investigation system that combines live texturing AR representation of an actual pipeline inspection endoscopic camera with camera direction compensation functionality. Using a depth camera combined with an endoscopic camera, it was possible to overlay the inner imagery stably and correctly from the third person's perspective.

Our next step will be to validate the precision of the texture-mapped investigation images in terms of distortion and resolution, as well as the presented position on the AR representation. We are also planning actual physical inspection case studies aimed at validating the visual guidance and support functionalities of the proposed method. Our research focus will also delve deeper into the interactive AR representation design with aims toward magnifying the textured model, showing arbitrary intersections, refining imagery, creating 3D inspection histories, and so on.

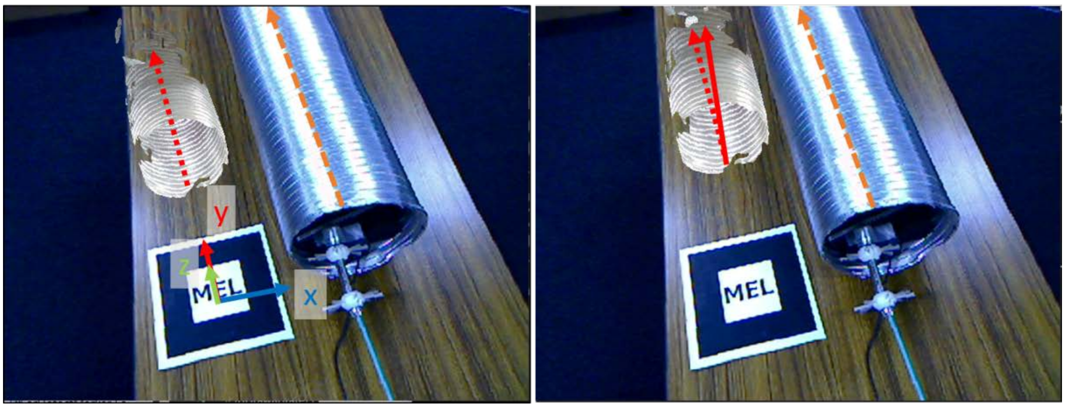


Fig. 7: Proposed method result: (left) original output, (right) output corrected via the proposed method so that the measured inner surface of the pipe model is precisely aligned with the physical target pipe.

ACKNOWLEDGMENTS

This work was partially supported by Japan Society for the Promotion of Science (JSPS) Grants-in-Aid for Scientific Research (15H02983, 16H05000).

REFERENCES

Behzadan, A. H. and Kamat, V. R. (2005). Visualization of construction graphics in outdoor augmented reality, *Proceedings of the Winter Simulation Conference*, pp. 1914-1920.

Chi, H. L., Kang, S. and Wang X. (2013). Research trends and opportunities of augmented reality applications in architecture, engineering, and construction, *Automation in Construction* 33, pp. 116-122.

Hiroki Inoue, Yoshihiro Yasumuro, Hiroshige Dan, Akira Kobayashi, (2015),Deflection Computation of Pipeline Surface Based on 3D Point Cloud, Proc. of 15th International Conference on Construction Applications of Virtual Reality in Construction, Paper ID:42.

Jiao, Y., Zhang, S., Li, Y., Wang, Y. and Yang B. (2013). Towards cloud augmented reality for construction application by BIM and SNS integration, *Automation in Construction* 33, pp. 37-47.

Kamat, V. and El-Tawil, S. (2007). Evaluation of Augmented Reality for Rapid Assessment of Earthquake-Induced Building Damage, *Journal of Computing in Civil Engineering*, 21(5), pp. 303-310.

Kato, H. and Billinghurst, M. (1999). Marker Tracking and HMD Calibration for a video-based Augmented Reality Conferencing System. *International Workshop on Augmented Reality (IWAR 99),* pp. 85-94.

Nextspace: *http://www.nextspace.co.nz/visual-city* (accessed in 2015 Jun)

Park C., Lee D., Kwon O. and Wang X. (2013). A framework for proactive construction defect management using BIM, augmented reality and ontology-based data collection template, *Automation in Construction*, Vol. 33, pp. 61-

71.

Lawson, S. W. and Pretlove, J. R. G. (1998). Augmented reality for underground pipe inspection and maintenance. *Proc. SPIE 3524, Telemanipulator and Telepresence Technologies V*, pp. 98-104.

Schall, G., Mendez, E., Kruijff, E., Veas, E., Junghanns, S., Reitinger, B. and Schmalstieg, D. (2009). Handheld augmented reality for underground infrastructure visualization, *Personal and Ubiquitous Computing, Special Issue on Mobile Spatial Interaction* 13 (4) pp. 281-291.

Woodward, C., Hakkarainen, M., Korkalo, O., Kantonen, T., Aittala, M., Rainio, K. and Kähkönen, K. (2010). Mixed Reality for Mobile Construction Site Visualization and Communication, *Proceedings of 10th International Conference on Construction Applications of Virtual Reality (CONVR)*, pp. 35-44.

Takuma Yorimitsu, Hiroki Inoue, Hiroshige Dan, Yoshihiro Yasumuro, (2015) AR Presentation of Image-Based Pipeline Inspection, Proc. of 15th International Conference on Construction Applications of Virtual Reality in Construction, Paper ID:41.

Zheng L. and Kleiner Y. (2013) State of the art review of inspection technologies for condition assessment of water pipes, *Measurement* 46. 1, pp. 1-15.

A STUDY OF 'SITE BIM' IMPACT ON HEALTH AND SAFETY IN CONSTRUCTION SITES

R. K. Shah and [1]J. Edwards

*Senior Lecturer and [1]PG Student,

School of Built Environment, Liverpool John Moores University, Liverpool, L3 3AF

Corresponding author Email: r.shah@ljmu.ac.uk*

ABSTRACT: *According to the 2014 report of HSE, the construction industry in the UK is the second most dangerous industry in terms of fatal and minor injuries of site workers. The use of the mobile devices such as tablets or smart phones on the construction projects is also on the increase in the UK after the 2016 - Level 2 BIM target, set by the UK Government. Hence, the use of such devices may become a distraction from work activities on the construction sites and will cause a major risk to the end users. The subject of improving safety of BIM use is widely researched, but there is a gap in knowledge about the actual use of mobile devices and perception of 'Site BIM', on the construction site activities. The main gap identified in the 'Site BIM' is the safety aspect of using such mobile devices on the live construction sites. A safer way of working with tablets needs to be identified to avoid any potential site risks and fatalities before the widespread use of those devices is seen on projects. Hence, the paper is aimed to highlight the safety issues that are required to address for the successful implementation of the mobile devices, which are key tools for safer use of 'Site BIM'. Questionnaire survey was used to collect the site information among construction professionals in the UK. The findings suggested that a proactive approach may potentially stop any harm and potential improvements need to be identified before any injuries occur. The paper concluded that training, changing size of mobile devices and ensuring a separate induction for 'Site BIM' tools will improve the safety of the end users at the construction sites.*

KEYWORDS: *Health and Safety risks, Mobile devices, Site BIM, Construction site, BIM Implementation.*

1.0 INTRODUCTION

In recent times digital information is becoming more familiar on construction projects. Construction is an information-intensive industry, and the success of a project depends upon the availability of accurate data (Haas et al. 2002). Site work is generally paper based and due to the adverse weather and conditions it is challenging for site engineers to collect and share site information in real-time (Kim et al. 2013). Sites offices can often be a long walk on projects, forgetting necessary documents or a pen all happens down to human error. But often data information may get lost if distracted. A mobile device may improve the reporting processes due to the information getting inputted and stored immediately. Recent research (Son et al. 2012) stated "the main problems associated with manual and labour-intensive processes are delays in obtaining, processing, and accessing information, as well as the inconsistencies and inaccuracies in the information itself due to the manual entry of data." Therefore an efficient way of inputting data on a construction site is in demand and the possible solution in this direction is effective implementation of new information modelling system such as BIM (Building Information Modelling).

The use of tablets and mobile device on projects is on the increase in the UK, this could be largely due to the 2016 - Level 2 BIM implementation target set by the UK Government (applies to central government funded projects). Contractors will not want to lose competitiveness through the non-implementation of BIM. Research in this area has predominantly been based around the projects benefits in terms of cost, scheduling and system architecture. Davies and Harty (2012) in their research introduced the implementation of an innovative site based BIM tool 'Site BIM', which is going to significantly change how day-to-day construction management occurs. This is possible through the use of mobile computing technology that will automate the construction phase for the through the affordable devices, capable of receiving an internet/intranet signal, which will help to send live site information and also receive design information instantly. This is supported by Chen and Kamara (2011) and they suggested that the advance in affordable mobile devices, increases in wireless networks and the enhancement in mobile applications have given on site construction management the potential to improve the process. However, a factor that seems to lack in research is the health and safety of the end user whilst using a mobile device on a live construction site.

Construction in the UK is the second most dangerous industry, although it only employees 5% of Britain's it accounts for 27% of fatal injuries and 10% of reported major injuries (HSE, 2014). Use of a mobile device may become a distraction, and with heavy vehicular movement on construction sites this could be a major risk to the end user. Being hit by a moving vehicle in 2012/13 accounted to 10 percent of the total fatalities in the construction industry (HSE, 2013). The subject of improving safety through BIM use is widely researched, but there is a niche area of the actual use of BIM on a live construction project through the use of a mobile device or 'Site BIM'. This phrase was coined by Davies and Harty (2012). Moreover, Sacks et al. (2010) suggested that the practicality of tablet PCs is questionable due to the security, and site conditions from the health and safety aspects. Hence, the paper is aimed to address the issues by analysing the safety impact of the site BIM tools on end user's perception during the live construction projects, and identifying the practical barriers to implement the site BIM tools such as tablets and mobile devices. The rest of the paper is structured under literature review, research methodology, survey data analysis, presentation of results and discussions followed by conclusions, future recommendations and references.

2.0 LITERATURE REVIEW

The role of mobile IT in construction has the potential to automate many processes. Bowden et al. (2005) found through case studies that mobile technology through various forms can reduce; construction time and capital cost, operation and maintenance costs, defects, accidents, waste and increase productivity and predictability. Typically devices of the modern day have various functions that can improve on site construction management. Smartphones are now typically equipped with touch screen, GPS receiver, gyroscope, accelerometer, and wireless communication technology (Kim et al. 2013). There is a view that efficient communication systems are important to the improvement of information speed between the site office, headquarters and the supply chain (Chen and Kamara, 2011). Having moved forward in the forms of mobile technology it is know the opportunity to embed mobile device use on construction projects. Although the theory of site based mobile technology has been developed by Son et al. (2012), the key factors that influence a successful application of mobile IT was investigated, they found that user satisfaction was important to the success of implementation.

The whole idea of bringing mobile device to the live construction site is to aid in the provision of key live data so that may be lost using traditional paper based formats. However, site management work is still dominated by paper whether in the form of drawings and other design information or in the use of paper notes and forms for capturing information (Davies and Harty, 2012). It is only know through collaborative IT solutions such as BIM that information flow can be exchanged throughout all stages of a project life-cycle. The need for the use of mobile technology is ever apparent and the benefits of such are widely researched. Although questions remain whether or not the introduction of mobile device for live data capture poses a risk to end user safety? As identified by Suzuki and Nagayusu (1996) various types of devices have been adopted for field use throughout construction sites in Japan. More commonly in the UK construction industry, electronic devices are used to provide and capture information such as digital cameras. But the adoption of using a device that allows the user to interact with vital construction information in a dangerous site environment may pose significant risks.

In addition, past studies highlighted that the mobile devices affected their work and impaired safety (Vanichackhorn, 2013), however, Vanichackhorn (2013) suggested that safety risks are dependent not on frequency, but rather than method of use for the device. The fact remains using traditional paper based methods and other less interactive mobile devices (digital cameras, radio etc.), the additional safety concerns barely exist. In the study, the main work where attention is paid will be inside a site office. Reducing the potential distractions on a mobile device is the key during site instructions. Davies and Harty (2012) suggested for the construction site use the device, which was installed with a brief-cased mode. Such mode would then lockdown a device ensuring applications such as social media and cannot be accessed. This then also shows a clear differentiation to the worker because the tool is solely for task purposes. Therefore, mitigating such risk of distraction is necessary, particularly when using mobile dives on construction sites.

2.1 Introduction of Site BIM

Site BIM is defined as using a means of mobile device to automate site based activities that will record project data and inform the BIM in real time. This reflects the view of Davies and Harty (2012) who in their research implemented BIM related tools and tablet computers for use on site during the construction phase - 'Site BIM'. This is in line with the view of Sacks, et al. (2010) who suggested that most academic research relating to BIM use has been based around design, pre-construction, planning and there has been far less effort to develop BIM based tools to support production management on site. A connection from site to access BIM systems needs to be established in order for the information flow to exist. Davies and Harty (2012) found that tablet computers provided the vehicle for making use of BIM model data but also acted as a functional capability. As mobile technology is advancing it has the potential to take the onus off other work flows enhancing the effectiveness of using a tablet. The use of tablet PCs and the development of site BIM systems are seen as building on the existence of the coordinated 3D models (Davies and Harty, 2012), which is similar views that site BIM is expanding the usual uses of BIM, and using it practically for construction site use. To enable a collaborative work flow to ensure level 2 BIM is achieved an onsite entity needs to exist to provide the information work flow. Without onsite automation true BIM will not exist as design information may become lost in paper form.

BIM adoption in UK construction is lacking behind other countries, and the UK Government has set a 2016 target for Level 2 BIM adoption on centrally funded projects. BIM will change the future of the UK Construction Industry and in achieving the Government's target, site information to inform the model will be required. This supports the view of Davies and Harty (2012) who suggested that mobile devices can be the vehicle to access the BIM model on site with aim of improving site productivity. This stance is supported by Bowden et al. (2005), Chen and Kamara (2011) and Saidi et al. (2002). It is inevitable that an increase of devices will occur, due to lower costs of devices and an increase in BIM adoption.

2.1 Health and Safety impact from Site BIM

From the industry prospect, Costain policy states to ensure accidents and near misses do not occur as a result of inappropriate uses of mobile devices their use is prohibited within the site boundary unless it is carrying out a designated operation where the equipment has been sanctioned by managers and documented in the risk assessment and method statement (Costain, 2008). To use a device it could be suggested that use is mandatory in a 'safe sectioned zone', although this may have an adverse effect due to the open collaborative nature the tool is introducing, this theory will be tested later in the study. The policy is the correct direction companies should be taking to mitigate the risk and also bringing clarity to the potential argument of "He's using iPad, why can't use my phone". Huge steps are not needed to ensure end user safety just awareness and training will be needed with slight alterations to company policies to accommodate for the increasing use of mobile devices.

Davies and Harty (2012) suggested that use of a smaller device such as an iPad mini for example may improve manoeuvrability. A smaller device may be able to be stored within the users PPE whilst walking around site, thus potentially minimising the risk of slip, trips and falls, therefore challenging the view of Sacks, et al. (2010). The study by Kim et al. (2013) proposed to use mobile computing technology for on-site construction management. But this research is focussed to systems and does not assess any end user information within the study. Davies and Harty (2012) use a real world project case study of implementing 'Site BIM', feedback of the end user is within this study which has generally been accepted by the end user. Although the information does not highlight any potential H&S issues with using a device.

Eadie et al. (2013) research is the most prominent piece of research as it measures the BIM use throughout a project lifecycle; this confirms that the perception from users is that BIM is most often used at early stages of a project.

The construction phase is the third most significant stage where BIM use is identified through the study. This research confirmed the need to further research Site BIM implementation and the subsequent measurement of the impact. Moreover, past study reveals that a mobile system is built from the beginning it can offer a real-time database that can monitor site safety activity, thus having a positive impact toward site safety through using a mobile device. But the question remains what if the user who is inputting the safety information becomes harmed as they are unaware of their surroundings. Protective gloves protect from abrasion, cuts and punctures, skin infection and disease or contamination (HSE, 2013).

Protective gloves are mandatory on major construction projects, due to the nature of using a mobile device this area will be included to investigate further in the study. Siegenthaler et al. (2012) highlights in their research that LCD displays received a higher fatigue rating; this may become a hazard to a user's health. This will be contained within the investigation to see if industry professionals feel the same way as the researcher.in this context, this study aimed to investigate the health and safety aspect from industry and user prospective by conducting a structural survey.

3.0 RESEARCH METHODS

In this study, both quantitative and qualitative research approach was selected. The web-based questionnaire survey was used to collect the survey data. A total of ten civil/construction organisations (250+ employees), five client organisations (150+ employees) and five supply chain organisations (25+ employees) from the UK were selected for the sample frame as shown in Figure 1 below. The sample size of the population was derived using an online sample size calculator. Statistical analysis using SPSS (Statistical Package for the Social Sciences) was used to analyse the collect survey data and present the survey findings from the survey. The results are presented in graphs and table to highlight potential cultural trends and existing practice from the answers. In the survey, a simple-random sampling method was utilised. This method selects a sample or population within a total sample frame. Every participant within the sampling frame has an equal probability of being involved within the final sample.

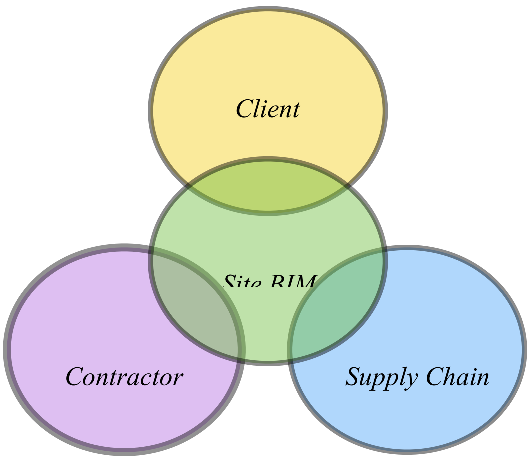


Figure 4: Type of organization involved in the questionnaire survey

To analyse the data collected from the survey questionnaire, a statistical tool was utilised. This allows for trends to be measured through cross-tabulation. This tool is an integrated function within the Bristol Online Survey system. The sample size was calculated using on online sample size calculator to ensure the study is representative of the population. It was found that 80 samples are enough for the study. The actual achieved response rate (93%) of the investigation was slightly lower than expected and actual responses were 74 collected from the target of 80). The reason for this could be partly due to the holiday period. The expected response rate was set at a higher number so if it wasn't achieved the study will still have enough responses to validate the credibility of the study, and provide an accurate sample. Wave analysis was the method utilised to check for response bias. The analysis occurred weekly, to ensure maximum responses were achieved within the seven-day period.

4.0 SURVEY RESULTS AND DISCUSSION

The results found from the survey of safety impact of 'Site BIM' to the end users are presented under graphs and tables. At first couple of charts are presented to show the demographical representation, involved in the survey. The information of participants in terms of years of expertise and age group are shown in Figures 2 and 3 below.

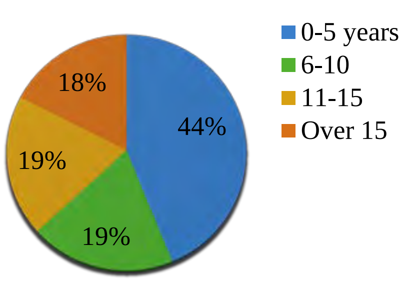


Figure 2: Years of Experience

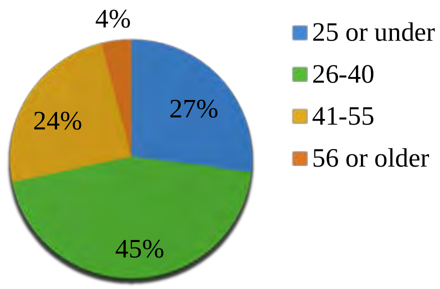


Figure 3: Age group

After presenting the demographical information, the site experiment and BIM knowledge of participants in the survey, is presented in Figures 4 and 5 below.

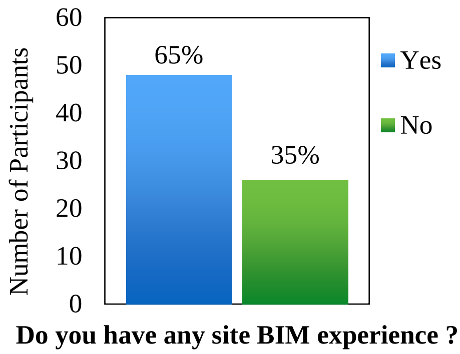


Figure 4: Site BIM Experience

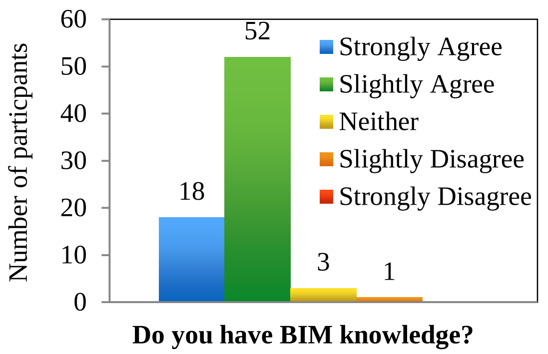


Figure 5: BIM Knowledge

A survey question was utilised to measure whether the "increase in productivity outweighs the potential safety impact of using a mobile device on-site" and the results are shown in Figure 6 below. The responses indicated that there is a health and safety hazard when using the mobile devices on live construction site, but these risks could be mitigated by ensuring end user safety. This kind of response is not unusual due to the construction industry being the second most dangerous in the UK (HSE, 2014).

Q. Do you feel that the increase in productivity from using a mobile device outweighs the potential health and safety impact?

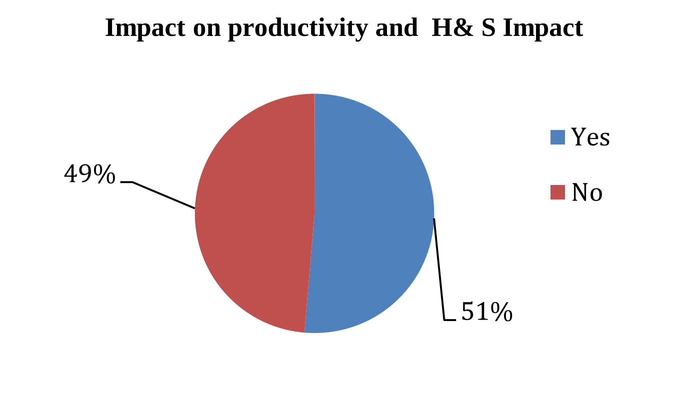


Figure 6: Productivity vs. health and safety impact

Since the paper is aimed to present the findings of the potential safety and health hazards whilst using a mobile device on live construction sites. The survey results (see Figure 7) revealed that 39% of H&S safety hazards occurred due to the slips, trips and falls followed 39 % from vehicular movement during the use of mobile devices in live construction projects. The survey also exposed that eye strain to user also contribute to H&S hazard followed by falling objects, neck strain and back strain. The survey findings provide a holistic view of the health and safety impact and future recommendations to the safe uses of the site-based mobile devices/tools, which play major roles for the safe implementation of 'Site BIM'.

Q: What do you feel the main health and safety hazards whilst using mobile device?

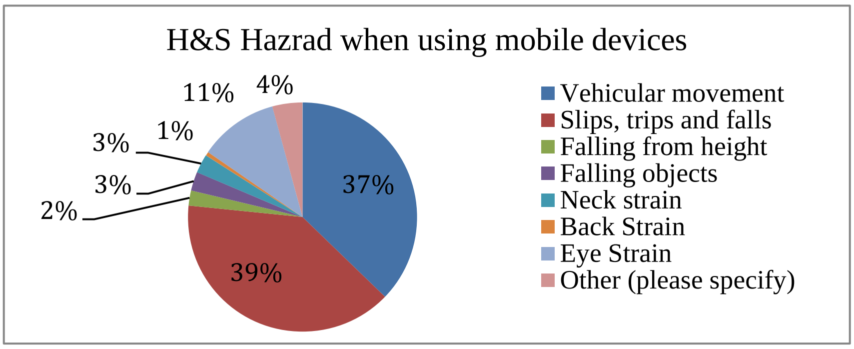


Figure 7: Health and safety hazards

In case of safety question regarding selection of mobile devices such as tables or PCs for the implementation of Site BIM tools, it was found that majority around 73% was agreed to use smaller devices to improve the site movement (see Figure 8). The suggestion made from this was that use of a smaller screen device may improve maneuverability. The findings could be a simple solution to the problems found by the previous researchers.

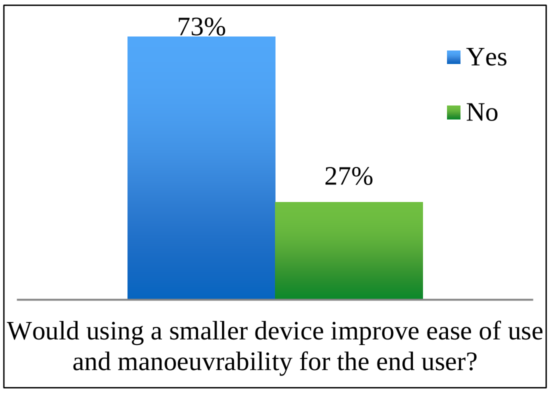


Figure 8: Selection of mobile devices

The case for sectioned areas for device use on a live construction site is ever present. Sites can be dangerous environment without the distraction of an electronic device. Figure 9 illustrates the results made from the further analysis of the primary data. The optional comments left by respondents also held the position that there should not be a sectioned area for mobile device use. One respondent commented, "How can you capture true field data if you don't have full access". This view illustrates the exact point that needs to be addressed in order to ensure level 2 BIM is achieved.

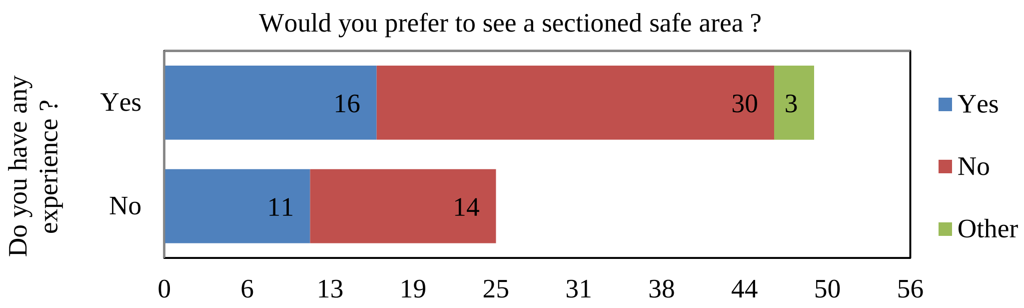


Figure 9: Industry experience vs safe area

Construction sites differ from project to project and can be very hazardous if the correct precautions and training are not taken. This is why site inductions are a compulsory element before beginning site work. The survey results shown in Figure 10 exposed that 54% of respondents agreed that users of a mobile device "should be subject to a separate induction" whereas 46% disagree with the induction. Training operatives at the induction stage and approving them to use a device may be a solution. This would ensure all parties are aware of the risks associated with the use of mobile devices and end users will not hamper the productive time for training throughout the project lifecycle.

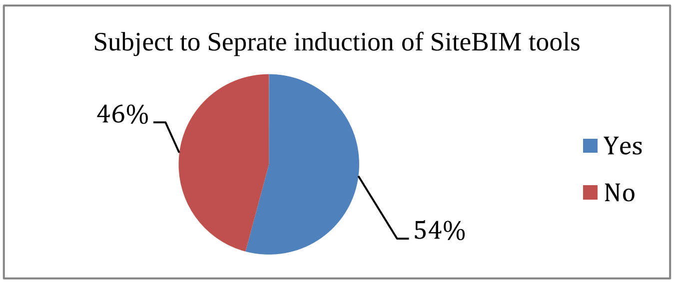


Figure 10: Responses of separate induction amongst site expert

To justify the case of separate induction training and awareness about site BIM tools, different theme as shown in table1 were asked to respond and rank them in order of overall perception and importance of use of mobile devices in live construction site. The results discovered, users are aware that use of mobile devices and agreed that these devices help to improve the productivity, easy in training and awareness but at same time they also highlighted that these devices also create a greater safety hazard and sometimes affects works due to software and systems issues on these devices. These results only reflected the perceptions of mobile devices users from the developed countries like the UK, where more Government is targeted for the BIM implementation by 2016. Hence, the results will be totally different if similar question asked in developing country where mobile devices uses are increasing but BIM implementation is less priority.

Table 1: Main themes of overall perception question

Rank	Theme
1	Acceptance of mobile device use
2	Productivity increase
3	Training and awareness
4	Increased amounts of devices may potentially become a greater hazard
5	Software and systems issues may affect the usefulness of the mobile device uses

The survey also revealed that training and awareness is necessary since it was ranked at third level of perception. The most important fact that survey discovered that the increasing trend of using mobile devices for effective implementation of SIT BIM will causes a serious health and safety hazard and all possible measures need to adopted before fully implementation of BIM by most of the contractors in UK in 2016. Hence separate induction training, awareness about the tools and providing safer space for the use of 'Site BIM' tools at the live construction project might help to reduce the safety hazards and improve user's health and safety impact on the construction projects.

5.0 CONCLUSIONS

It is concluded that the use of mobile devices for site management in the construction projects is emerging a valuable tool but these devices also create the health and safety risk to the end users. The study examined the construction professional perceptions about the health and safety risk/anxiety from these devices to the end users. A questionnaire survey was conducted in the UK from the participant having knowledge about BIM. A total of 74 responses were received and used them for statistical analysis. The survey results highlighted that the health and safety concerns to the users of 'Site BIM' tools such as mobile devices were slips, trips and falls followed by vehicular movement. Eye strain was another safety concern amongst respondents. To reaffirm participant's knowledge of BIM was above average with 99 percent of respondents having a level of awareness. The study also found that using a smaller device may improve ease of use and maneuverability for the end user. Users are aware that the use of mobile devices can help to improve the productivity, easy in training and awareness but at same time, these devices also create a greater health and safety hazard. From the site investigation combined with the comprehensive literature review, suggested that necessary measures need to be taken in advance to mitigate the health and safety risks when using mobile devices for 'Site BIM'. A proactive approach to this may stop any harm and hazard. The conclusion from the study was that hazards and potential improvements need to be identified before any injuries occur. On the construction projects, safety is paramount, therefore further study is necessary from the safety aspect of 'Site BIM' tools before full implementation of BIM by 2016 in the UK.

6.0 RECOMMENDATIONS

Based on the findings from the study, there are several potential areas where further research are necessary to improve the safer use of 'Site BIM' tools such as mobiles devices. These include:

There is potential to implement a system that encompasses a social media aspect to inform device users of hazardous areas;

In-depth case study analysis of the implementation of 'Site BIM' but concentrating on the safety impact;

Further research into training of mobile device to measure correctly if this affects acceptance and;

Fully analyse the cultural shift required for the workforce.

The further research may aid in the safe implementation of devices and ensure no end-users have harmed directly caused by the mobiles devices associated with 'Site BIM'.

REFERENCES

Bowden, S., Dorr, A., Thorpe, A., Anumba, C., and Gooding, P. (2005), "Making the Case for Mobile IT in Construction", *Computing in Civil Engineering* (2005), Pp 1-12.

Chen, Y. and Kamara, J. M. (2011), "A framework for using mobile computing for information management on construction sites", *Automation in Construction*, Vol. 20 pp. 776-788

Costain Group PLC, Policy Statement, (2008), "The safe use of mobile phones and personal electronic equipment" [Accessed 14 March 2014] available at http://www.costain.com/media/504838/18_safe_use_of_mobile_phones_and_personal_electronic_equipment_policy_statement.pdf>

Davies, R. and Harty, C. (2012), "Implementing 'Site BIM': A case study of ICT innovation on a large hospital project", *Automation in Construction*, vol. 30 (2013), pp. 15-24

Eadie, R., Browne, M., Odeyinka, H., McKeown, C., McNiff, S (2013), "BIM implementation throughout the UK construction project lifecycle: An analysis", *Automation in Construction*, vol. 36 (2013), pp. 145-151

gov.uk/sites/default/files/resources/Government - Construction-Strategy.pdf

Haas, C., Tucker, R., Saidi, K. and Balli, N., (2002), "The value of handheld mobile computers in construction" *In Report for the Construction Workforce Thrust Team,* University of Texas at Austin: Austin, TX

HSE (2013), "Health and safety in construction in Great Britain, 2013" [Accessed March 2014] available at http://www.hse.gov.uk/statistics/industry/construction/construction.pdf

HSE (2014), “Construction Industry” [Accessed 02 February 2014] available at http://www.hse.gov.uk/statistics/industry/construction/index.htm>

Kim, C., Park, T., Lim, H., and Kim, H. (2013), “On-site construction management using mobile computing technology”, *Automation in Construction*, vol. 35, pp 415-423

Sacks, R., Radosavljevic, M., Barak, R. (2010), “Requirements for building information modelling based lean production management systems for construction”, *Automation in Construction*, vol. 19, pp. 641-655

Saidi, K.,Haas, C., and Bali, N., (2002), “The value of handheld computers in construction”, *Report for the Construction Workforce Thrust Team,* University of Texas at Austin: Austin, TX

Siegenthaler, E., Bochud, Y., Bergamin, P. and Wurtz, P. (2012), “Reading on LCD vs e-Ink displays: effects on fatigue and visual strain”, *Opthalmic & Physiological Optics,* Vol.32, pp.367-374

Son, H., Park, Y., Kim, C. and Chou, J. C. (2012), “Toward an understanding of construction professionals’ acceptance of mobile computing devices in South Korea: An extension of the technology acceptance model”, *Automation in Construction*, vol. 28, pp. 82-90.

Suzuki, O. and Nagayasu, O. (1996), “Development and future prospect of site Inspection System with portable terminal” *Proceedings of 12th Symposium on Building Construction and Management of Projects*, AIJ, Kyoto, Japan.

Vanickachorn, G. (2013), “Mobile Device Use and Work Safety in a Healthcare System”, *Master of Public Health Thesis, University of Washington:* School of Public Health.

REAL-TIME VISUALIZATION OF CRANE LIFTING OPERATION IN VIRTUAL REALITY

Yihai Fang & Yong K. Cho

Georgia Institute of Technology, GA, USA

ABSTRACT: *In the construction domain, previous efforts in utilizing Virtual Reality (VR) mainly focused on training and education, pre-planning, and simulation. The understanding of their benefits in real-time applications during the construction phase is scarce. This research presents an approach to leverage VR for real-time sensor data visualization for the monitoring of equipment operations. Two critical components in this approach, 1) equipment motion visualization and 2) workspace condition visualization, are explained in detail. The effectiveness of the proposed real-time visualization approach is presented by a case study of crane lifting operations. The pipeline for developing real-time crane operation visualization is presented by the steps of sensor data visualization, point cloud processing and visualization, and the design of a graphical user interface. Results of a field test show that with the proposed approach, crane motion and workspace condition can be effectively visualized in real-time during the lifting operation, which has a positive impact on supporting timely decision-making of crane operators.*

KEYWORDS: *Virtual Reality; Crane Lifting Operation; Real-time; Point Cloud; Graphical User Interface*

1. INTRODUCTION

Construction equipment plays a critical role in the efficient and safe execution of a construction project. The location, motion, and status of a piece of equipment are essential information for tasks such as safety management, asset inventory and maintenance, and progress monitoring. Visualizing equipment activity provides the stakeholders intuitive understanding of equipment operations on a construction site which will assist them in decision-making. Despite much research in utilizing Virtual Reality (VR) for construction applications, they mainly focus on training and education, pre-planning, and simulation. Very few explore the benefits of VR in real-time applications during the construction phase, such as equipment motion visualization, workspace condition modeling, and real-time operation assistance.

This research presents an approach to leverage VR technology for real-time sensor data visualization for the monitoring of equipment operations. The methodology contains two critical components, 1) equipment motion visualization and 2) workspace condition visualization. The effectiveness of the proposed real-time visualization approach is presented by a case study of crane lifting operations. Test results are presented by comparing the virtually reconstructed crane motion and workspace condition to the actual ones. With the proposed approach, crane motion and constraints in the workspace can be visualized in real-time during the lifting operation, which has a positive impact on supporting the decision making of crane operators.

2. RELATED WORK

2.1 Virtual Reality and Game Engine

Virtual reality (VR) is a multi-disciplinary field of computing technology that emerged from research on three-dimensional (3D) interactive graphics and pilot simulations in the 1960s. Rather than a single technology, virtual reality is a combination of a set of technology that keeps evolving over time. These technologies are essentially computer graphics/displays, human-computer interfaces, and simulation. They are used to create a 3D computer-generated simulation in which the user can navigate around, interact with, and be immersed in a virtual environment (VE).

A game engine is software to create and develop VR content, such as video games or serious games for professional training. The core functionality of a game engine typically includes a rendering engine, a physics engine, and other critical components including sound, scripting, animation, artificial intelligence, networking, and streaming. Due to the close-to-reality simulation and flexibility in customizing the script, game engines are replacing traditional VR platforms and have been extensively used in the development of VR content for various construction applications.

2.2 Virtual Reality for Construction Applications

In the field of construction, VR has been extensively utilized for design verification (Yan et al. 2011), education and training (Albert et al. 2014), equipment simulation (Kamat and Martinez 2005), and occupant/worker behavior analysis (Zou et al. 2016). Inspired by the application of VR in pilot and surgery training, the construction industry has been exploring how VR can enhance the education and training of construction operations. Several risk-free virtual training systems are developed to expose users to a virtual construction site with potential hazards (Lin et al. 2011; Li et al. 2012). Virtually walking on the site, users will learn how to identify the hazardous situations and how to mitigate them properly. To improve the collaboration among crane lifting crew members (e.g., crane operator, riggers, signal person), Fang and Teizer (2014) presented a virtual training environment where the entire lift crew can participate in virtual lift tasks cooperatively.

Compared to visualizing static objects, simulating the dynamic operation of construction equipment is more challenging as the kinematics of each kind of equipment are different. Cho et al. (2002) proposed a framework for rapid local area sensing and 3D modeling for the planning and visualization of equipment operation. Using the principles of forward and inverse kinematics, Kamat & Martinez (2005) developed an approach for dynamic 3D visualization and simulation of articulated construction equipment. With a specific focus on cranes, Kang & Miranda (2006) developed a computer system that provides detailed simulation and visualization of crane operations. Al-Hussein et al. (2006) integrated 3D visualization and simulation for modeling the lifting operation of tower cranes.

Emerging remote sensing technology has greatly expended the sources of field information and the way they are collected on construction sites. The potential of visualizing real-time field data in a virtual environment is investigated by Xie et al. (2011). They implemented Radio Frequency Identification (RFID) and real-time VR simulation in construction processes to improve the control and monitoring of construction projects. Fang et al. (2014) proposed a framework for visualizing real-time location data in an as-built virtual environment. They visualized the worker's location in a BIM-enabled virtual construction site based on the location data collected by Ultra-Wide Band (UWB) technology. However, the real location data of construction workers were only used for crane operator training, instead of real-time applications.

In addition to visualizing the location of construction equipment and workers, visualizing the workspace around the equipment is critical for a more comprehensive awareness of the equipment operation. Cho and Haas (2003) reported a 3D visualization method for modeling unstructured construction workspace. This method uses simple sensors combined with human perception and highly descriptive CAD models to rapidly model and visualize geometric information of entities such as equipment and materials in the construction workspace. To help the heavy equipment operators rapidly perceive the surrounding environment, Cho and Gai (2014) introduced a dynamic object recognition and registration methods using computer vision and laser scanning technologies. Wang and Cho (2015) proposed a smart scanning technique for tracking the location of construction equipment and modeling the dynamic workspace. Although their approach significantly accelerates the 3D modeling process of dynamic equipment, the model update rate is not fast enough for an operator to make a timely decision due to the slow laser scanning rate.

3. METHODOLOGY

3.1 Framework

This research proposes a framework for real-time visualization of crane motion and site condition. As shown in Figure 1, this framework is comprised of three parts: 1) crane motion capturing, 2) site condition modeling, and 3) user interface and interaction. First, crane motion is captured by multiple sensors and transmitted to a processing unit in real-time. Then, site conditions (e.g., existing buildings, trees, powerlines) are represented by laser-scanned point clouds and the bounding boxes constructed based on the point clouds. The following sections will explain the two key components of the framework that are enabled by game engine technology: 1) sensor data visualization and 2) point cloud visualization. Details of other components in this framework can be found in (Fang et al. 2016).

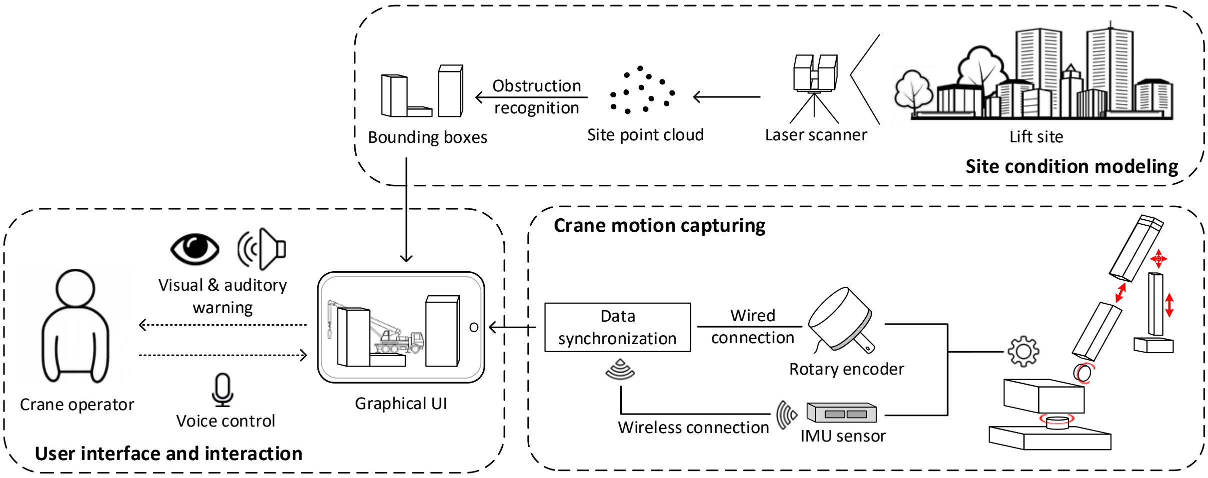


Figure 1: A framework for real-time visualization of crane motion and site condition

3.2 Sensor Data Visualization for Real-time Crane Motion Reconstruction

To capture the crane motion in real-time, multiple sensors are deployed on a crane to measure critical crane motions, including boom swing, lift, and extension, and load sway based on a kinematics analysis (Figure 2).

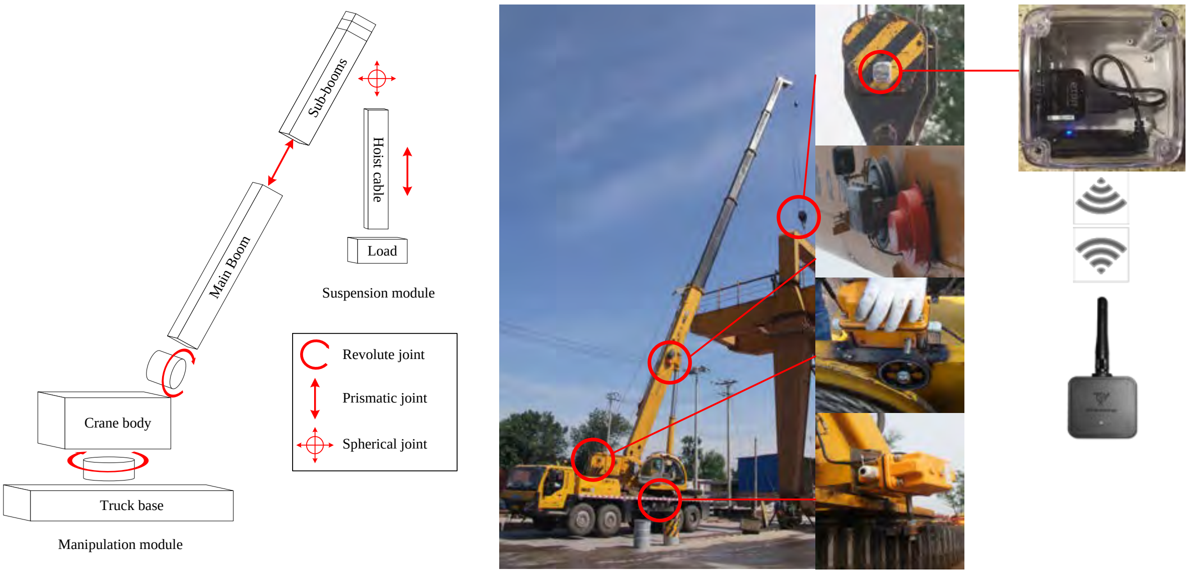


Figure 2: Sensor deployment for critical motion capturing

These sensor data are synchronized and transmitted to a computer through a serial port. In the game engine, the crane motion data are read from the serial port and linked to different parts of a virtual crane model (e.g., cabin, boom, load) represented by multiple rigid bodies (see Figure 3).

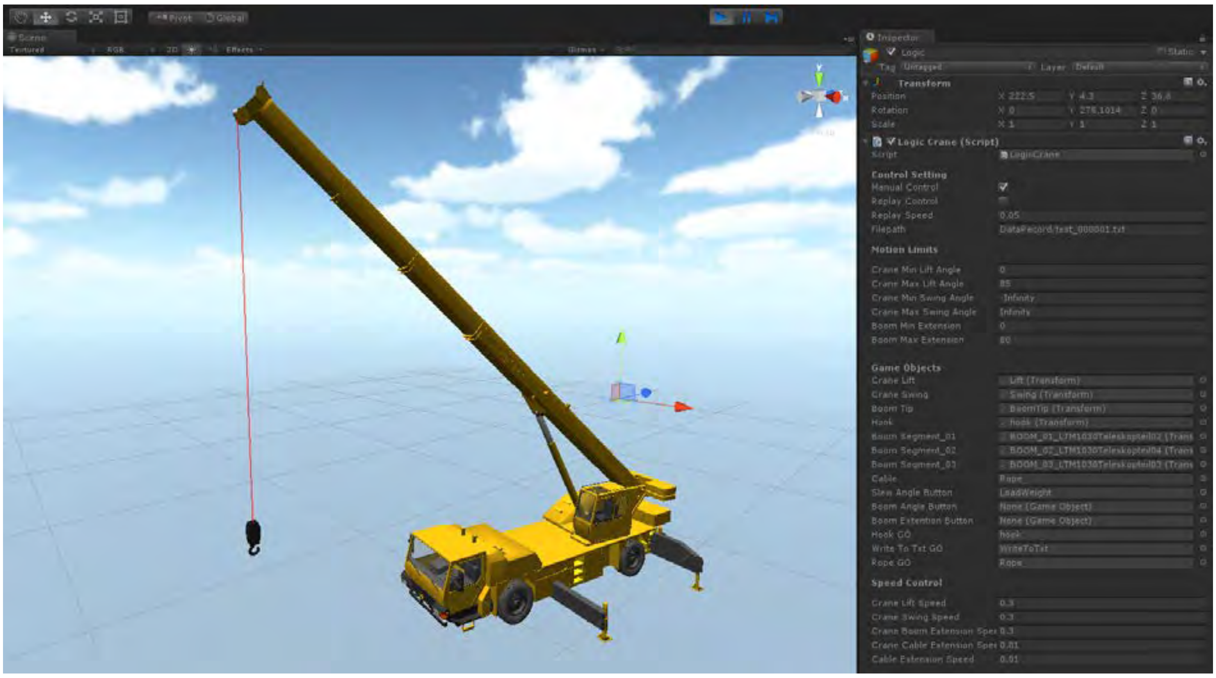


Figure 3: Sensor data visualization in a game engine for real-time crane motion reconstruction

3.3 Point Cloud Visualization for Site Condition Modeling

The goal of site condition modeling is to model a lift site with as-is conditions, especially the presence of obstructions such as vehicles, trees, and powerlines. 3D point clouds acquired by a laser scanner can correctly reflect the as-is condition of a lift site with comprehensive 3D geometric information. However, continuously computing the distance between each point and the crane parts is too computationally heavy. Therefore, the site point cloud needs to be converted into bounding box objects to represent the location and dimension of all the obstructions in presence. As illustrated in Figure 4, the pipeline to obtain an oriented bounding box from a point cloud involves the steps of segmentation, clustering, and orientation estimation. The input point cloud is first down-sampled from its original number of points to around 10,000 points by performing voxel grid filtering. Next, ground plane segmentation is performed using Random Sample Consensus (RANSAC) (Schnabel et al. 2007). Finally, an oriented bounding box is computed for each point cluster by considering the physical spread of points in the z-axis (vertical axis) and the x-y-plane. Once the bounding boxes for obstructions are automatically created, they are prepared for visualization with the adjustment of surface transparency level and being labeled as obstructions in the game engine. Furthermore, the crane model is placed at the planned position and specific pick and place locations can be manually positioned in the virtual lift site.

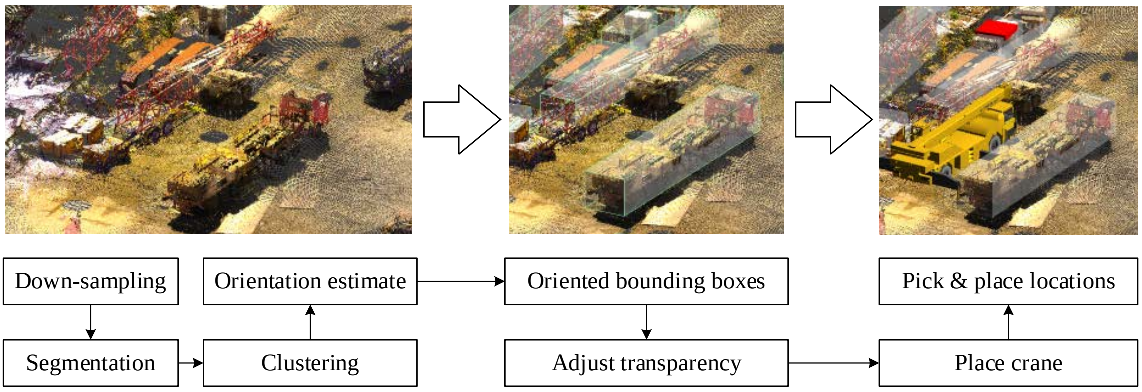


Figure 4: Pipeline for point cloud visualization

3.4 Graphical User Interface

A user interface (UI) is the main channel of the communication between the operator and the system. The information presented by the UI must be concise and easily understandable so that the operator can perceive the information with minimal cognitive workload. The UI of the developed system consists of three main views of the virtually reconstructed lift scene: a voice control free view, an elevation view and a top view. All views simultaneously show the virtually reconstruction lift scene in real-time that consists of the crane movement and the environment conditions (see Figure 5). The main free view is controlled by the voice commands from the operator (e.g., zoom in/out, left/right, up/down, reset) so that the operator can easily focus on the objects of interest from an occlusion-free angle. The elevation view and the top view are useful to understand the elevation and position of crane load and parts. In addition to the three views, the UI is augmented by information including 1) visual warnings for collision hazard and excess load sway, 2) highlighted obstructions in proximity to the load or crane parts, 3) previous lift path, and 4) a voice control panel.

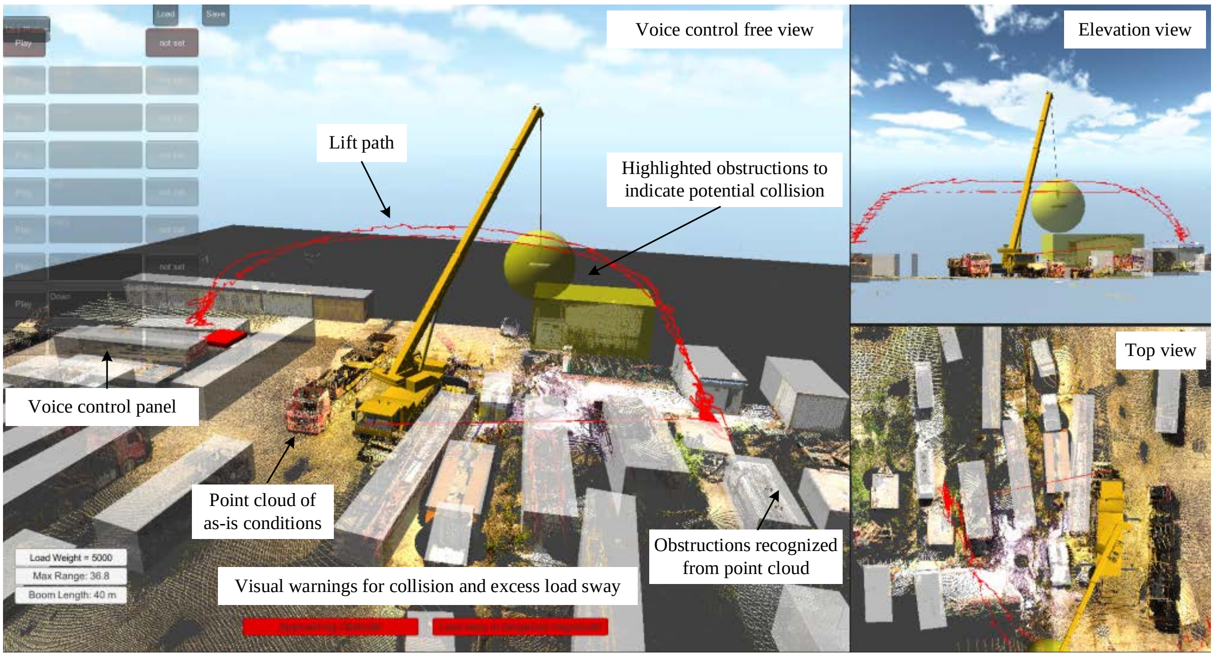


Figure 5: User interface (UI) shows virtually reconstructed lift scene and critical information in real-time

4. FIELD TEST RESULTS

The proposed method was implemented in an actual crane lifting operation. The site point cloud was processed prior to the operation and the sensor data was processed and visualized in a game engine by a tablet computer installed in the crane cabin. The results of real-time visualization were validated by comparing the virtually visualized crane operation to site camera recordings from two view angles: site overview and top view from the crane boom tip. The site overview comparison demonstrates the visualization results in reconstructing crane boom motions (see Figure 6) and the top view from boom head comparison demonstrates the accuracy in visualizing crane load position (see Figure 7). From the comparison, it can be seen that visually, the virtually reconstructed crane motion and the site condition match with the actual scenarios closely. In addition, the delay between actual and reconstruction crane motion is almost unnoticeable.

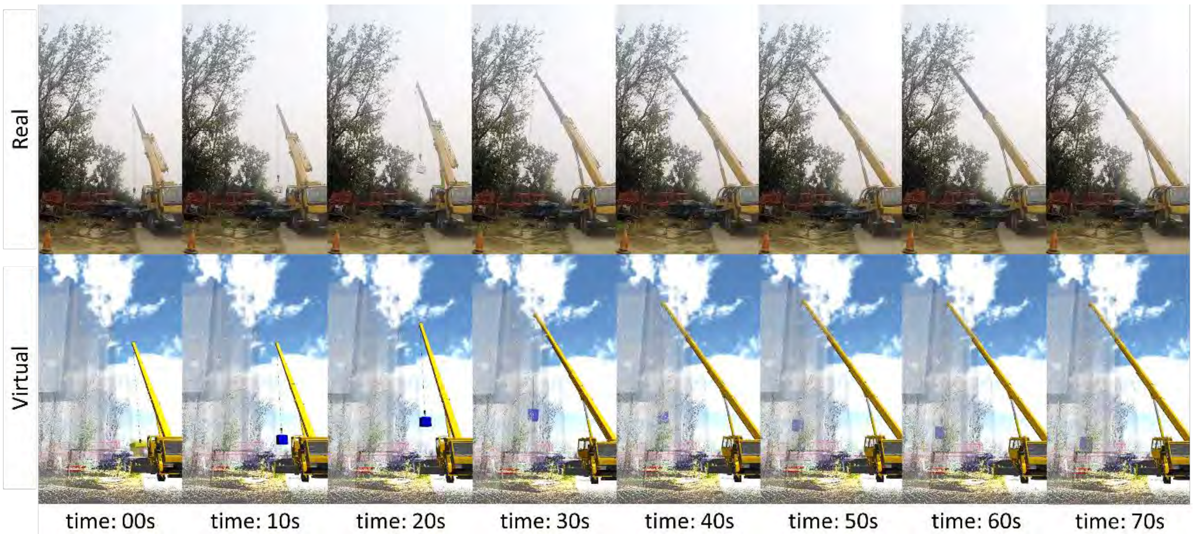


Figure 6: Comparison between actual load sway motion (upper) and reconstructed load sway motion (lower) from the boom's top view.

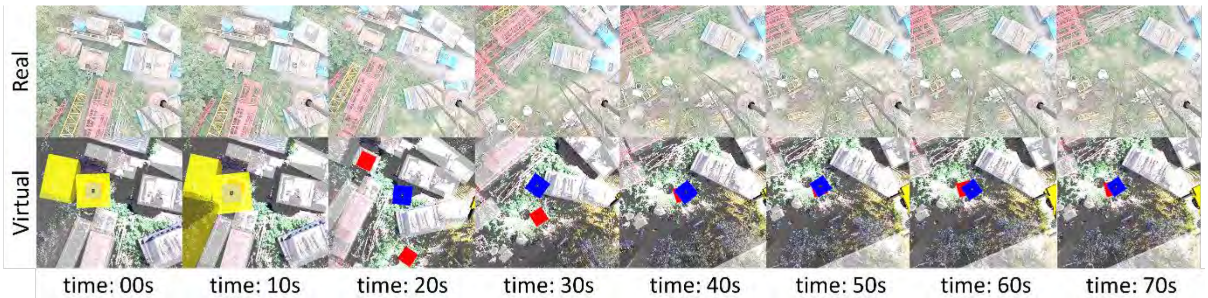


Figure 7: Comparison between actual lifting (upper) and reconstructed lifting process (lower) in site overview

5. DISCUSSION

This research demonstrates the feasibility of using VR technology for real-time visualization of crane operation.

However, several limitations have to be overcome before this method can be applied in daily equipment operations. First, certain steps in the proposed approach remain as semi-automated processes, including setting up crane rigid bodies in the game engine for motion visualization and importing site point cloud to game engine. These steps will be automated in future work by creating a standard format in the game engine for model setup and import. Another limitation of the presented work is that site point cloud is currently collected using a laser scanner. The scanning process must be completed prior to the operation, which can be laborious and time-consuming. This is out of the scope of this research but automated point cloud collection methods, for example using drones, will be explored in the future to minimize the efforts in data collection.

6. CONCLUSION

This research proposes a method for real-time visualization of crane operation using VR technology. It specifically addresses the challenges in real-time equipment motion visualization and site condition modeling. This approach is demonstrated by a case study of crane lifting operation visualization. The proposed method was implemented in an actual crane lifting operation and the results show that the crane motion and lift site condition can be closely visualized in real-time with minimal delay. User feedback indicated that visualizing the crane operation in real-time have positive impacts on improving the efficient and safety performance of crane operators, and supporting the decision making of the lift supervisor.

7. ACKNOWLEDGEMENT

This material is based upon work supported by the National Science Foundation (Award #: CMMI- 1358176). Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the NSF.

8. REFERENCES

Albert, A., Hallowell, M. R., and Kleiner, B. M. (2014). “Enhancing Construction Hazard Recognition and Communication with Energy-Based Cognitive Mnemonics and Safety Meeting Maturity Model: Multiple Baseline Study.” *Journal of Construction Engineering and Management*, 140(2), 04013042.

Al-Hussein, M., Athar Niaz, M., Yu, H., and Kim, H. (2006). “Integrating 3D visualization and simulation for tower crane operations on construction sites.” *Automation in Construction*, 15(5), 554–562.

Cho, Y. K., and Gai, M. (2014). “Projection-Recognition-Projection Method for Automatic Object Recognition and Registration for Dynamic Heavy Equipment Operations.” *Journal of Computing in Civil Engineering*, American Society of Civil Engineers, 28(5), A4014002.

Cho, Y. K., and Haas, C. T. (2003). “Rapid geometric modeling for unstructured construction workspaces.” *Computer-Aided Civil and Infrastructure Engineering*, 18(4), 242–253.

Cho, Y. K., Haas, C. T., Liapi, K., and Sreenivasan, S. V. (2002). “A framework for rapid local area modeling for construction automation.” *Automation in Construction*, 11(6), 629–641.

Fang, Y., Cho, Y. K., and Chen, J. (2016). “A Framework for Real-time Pro-active Safety Assistance for Mobile Crane Lifting Operations.” *Automation in Construction*.

Fang, Y., and Teizer, J. (2014). “A Multi-user Virtual 3D Training Environment to Advance Collaboration Among Crane Operator and Ground Personnel in Blind Lifts.” *Computing in civil and building engineering*, 1179–1184.

Fang, Y., Teizer, J., and Marks, E. (2014). “A Framework for Developing an As-built Virtual Environment to Advance Training of Crane Operators.” *Construction Research Congress 2014*, (1), 31–40.

Kamat, V. R., and Martinez, J. C. (2005). “Dynamic 3D Visualization of Articulated Construction Equipment.” *Journal of Computing in Civil Engineering*, 19(4), 356–368.

Kang, S., and Miranda, E. (2006). “Planning and visualization for automated robotic crane erection processes in construction.” *Automation in Construction*, 15(4), 398–414.

Li, H., Chan, G., and Skitmore, M. (2012). “Visualizing safety assessment by integrating the use of game technology.” *Automation in Construction*, Elsevier B.V., 22, 498–505.

Lin, K., Son, J., and Rojas, E. M. (2011). “A Pilot Study of a 3D Game Construction Safety Education Environment.” *Journal of Information Technology in Construction*, 16, 69–84.

Schnabel, R., Wahl, R., and Klein, R. (2007). “Efficient RANSAC for point-cloud shape detection.” *Computer Graphics Forum*, 26(2), 214–226.

Wang, C., and Cho, Y. K. (2015). “Smart scanning and near real-time 3D surface modeling of dynamic construction equipment from a point cloud.” *Automation in Construction*, Elsevier B.V., 49, 239–249.

Xie, H., Shi, W., and Issa, R. R. . (2011). “Using RFID and Real-Time Virtual Reality Simulation for Optimization in Steel Construction.” *Journal of Information Technology*, 16(Feb 2011), 291–308.

Yan, W., Culp, C., and Graf, R. (2011). “Integrating BIM and gaming for real-time interactive architectural visualization.” *Automation in Construction*, Elsevier B.V., 20(4), 446–458.

Zou, H., Li, N., and Cao, L. (2016). “Immersive Virtual Environments for Investigating Building Emergency Evacuation Behaviors : A Feasibility Study.” *33rd International Symposium on Automation and Robotics in Construction (ISARC 2016)*.

CUT/FILL OPTIMISATION UNDERPINNED BY BIM IN LANDSCAPE SITE REALISATION PROCESS: A CASE STUDY

Dr Huda Dawood & Prof Nashwan Dawood

Teesside University, UK

Prof Shang-Hsien Hsieh & Dr YI-Wen Chen

National Taiwan University, Taiwan

ABSTRACT: *Landscape Architecture deals with the creation of thoughtful and inspiring places that enrich society and environments. Through exceptional and expert approach, benefits society and ecology for which landform is an important part of the design and realisation. Landscape architects are posed for more involvements in the realisation processes, which can include, as well as ascetics and selection of materials design, scheduling, estimation, phasing, and optimisation of landscape architect projects.However, Current Landscape site processes are affected by numerous inefficiencies from the early specification of site surveys through the development of design to site operations. These are due to poorly integrated processes among clients, Landscape Architects, Engineers and site and the lack of processes and technologies for optimising information flow and cut/fill site operations. The prime objective of the paper is to develop and adopt optimisation technologies to identify optimal relationship between project variables (cut/fill quantities, cost, aesthetics and schedules) underpinned by BIM technologies and processes. The paper outlines BIM functions in landscape development and details the development of a prototype to optimise cut/fill quantities in 3D CAD environment. The paper also discusses the results of case studies and tests the user-friendliness, accuracy/reliability/repeatability of results obtained with different prototype functionalities.*

1. INTRODUCTION

In landscaping architecture, grading is one of the primary design consideration, since every site design project requires some essential change in grade. These changes influence the design project functionally, visually and experimentally. These changes in grading play an important role in terms of aesthetic, perceptual, spatial, and environmental consideration of design. Landscape Architects and Civil Engineers professionals are required to ensure that health and safety and the appropriate Construction and Design Management regulations are adhered to and the resulting landscape is one that is structurally sound, and meets all of the needs that people and wildlife have for the site. Furthermore, with the imposition of land-fill tax and the cost of shifting soil from and to site is very high, Landscape architects are required to seek balance between cut (soil removed) and fill (soil added) within their topographic design to reduce the need for transporting materials from or to site. This has the added advantage of not only reducing costs but also reducing the impact on the environment hence minimising construction carbon footprint.

The mainstream research on earthwork cut and fill application is based on road constructions. This usually involves the planning of earthwork allocation to determine the economic distribution of earthwork from cut sections to fill sections and disposing excess to disposal sites. Most research on earthwork planning is predominantly focused on minimising the haul distance in order to reduce costs. Amongst popular techniques used for earthwork allocations, are centred on using the mass haul diagram, mathematical modelling. The mass hall diagram is simply a graphical representation of the cumulative amount of earthwork moved over the centreline and distances over which the earth and other materials are to be transported (Hickerson 1967, Oglesby and Russell 1982, stark and Mayer 1983, Anderson and Mikhail 1985 and Son et al 2005). However, this method proved inadequate as if the cut and fill are not balanced and it does not take into account the different types of soil and different degrees of compactions. Consequently, Stark and Nicholls firstly suggested mathematical modelling of earthwork allocation using linear programming in 1972. This was developed later, by Nandgaonkar (1981); Easa (1987, 1988); and Jayawardane and Harris (1990), to integrate not only the bulking factors to allow for swell and shrinkage but also includes the allocation of borrow/disposable sites, their set up cost and project duration. Later researchers concentrated not just on the cut/ fill and haulage distances but included other associated planning activities such as space allocation, equipment planning, and site working conditions (Alkass, 1991; Castro, 2009; and Shah and Dawood, 2011).

This paper specifically presents a method of optimising the cut/fill earthwork within the worksite, as well as visually augmenting landscape site data and integrating this into Building Information Model (BIM). Autodesk's Revit software is specifically built for BIM (Autodesk REVIT) and is predominately deployed in many architectural, civil engineering and construction projects. However, most landscape architects do not use it, as the software is incompatible with the workflow of landscape architects and there are two drawback, which are interoperability between programs and lack of predefined site parametric objects (Flohr, 2011). Furthermore, Weygant (2011) stated that the main challenges of BIM are poor data exchange in using ots use is limited in landscaping architecture due to the lack of specific BIM compatible software for landscape design (Ahmad and Aliyu, 2012). Moreover, it is claimed in this paper that Autodesk's Revit that has been effectively used by architects to design buildings, is incompatible with the workflow of landscape architects. The most prominent is the lack of site grading and hence Autodesk Civil 3D has been used to calculate the grading and is then exported to Revit (Flohr, 2011). Furthermore, several researchers in the field of Landscape Information Modelling (LIM) have stated that existing BIM packages do not model landscape processes (Pietsch et al., 2009; Sipes, 2008). Nevertheless, Nessel argue the fact that "this is not wholly true" and that Autocad Civil 3D model many landscape processes including drainage and grading volumes and interoperability with Revit should pose no problem as it is within a larger BIM suite from Autodesk. However, Flohr described "the process as very time consuming and pushes a

Windows x64 system to the limit of its processing power." Though Ahmad and Aliyu listed several BIM tools ready for use in Landscape architecture including Vectorworks Landmark, Siteworks, Graphisoft ArchiCAD, they then concluded that interoperability was the ultimate challenge of BIM. In addition, landscape architects also use Vectorwork Landmark as a site information model for grading and plant specification and the file can then be imported into Revit in IFC format or a 3D drawing, however, end users reported unsatisfactory file conversion and they usually end up remodeling in Revit.

In this paper, we tackle the aforementioned issues by the development of an Application Program Interface (API) prototype to optimise cut/fill quantities in 3D CAD environment and incorporate landscaping workflow processes. The developed API is embedded into Revit. The remaining of the paper outlines the technical development of the work, prototyping of the requirements and case studies testing.

2. RESEARCH METHOD

Research methodology selected is modelling and prototyping the proposed solutions. The Revit .NET API has been used as prototyping environment and it allows the programing with .NET compliant language including visual Basic.NET, C#, and C++. C++ is used for our developed API.

The accuracy of the API has been verified by performing cut and fills volume calculations of regular polygon shapes and results were backed up by hand calculation. Results were analysed in terms of average Percentage error and standard deviation. The cut/fill optimisation functionality of the API is tested further by using a simple test project design. Finally, the robustness of the API design function is performed on a real case study.

3. TECHNICAL DEVELOPMENT OF CUT/FILL OPERATION

Grading to Site planners and Landscape architects must exhibit the aesthetic and design principles as well as the ecological understanding and technical capability. However, these factors are greatly influenced by costs and lower carbon footprint hence optimization of the cut and fill is vital.

There are two main ways to perform grading, firstly, is to balance the cut and fill required within site. Secondly, import or export soil to satisfy cut and fill requirements. This method is costly and is only used when the cut and fill do not balance. Therefore, balancing the cut and fill within site is the method considered in this project.

3.1 Computation of Cut/Fill volumes

Estimates must be made of cut and fill volumes to establish landscaping costs and to optimise the cut and fill operation in order to minimise costs and lower the carbon footprint. Therefore, a more accurate calculation of the cut and fill volumes is an essential component to any site development project. There are three methods, namely, Cross-section, Grid, and Prisims methods are considered for this project.

•The cross-section method, also known as “The average end area method” and is most suitable for lineal construction such as roads, paths, and utility trenching (Strom 2013). The volume of the cut (or fill) is calculated by averaging two adjacent cross sections multiplied by the distance between them. For estimates that are, more accurate shorter intervals between sections are used.

•The grid method, also known as “The borrow pit method”, and is most appropriate for complex grading and urban conditions. It involves drawing a uniform grid onto a plan of the landscape project, and taking off the existing levels at each node of the grid. The average depth of cut/fill required is calculated for each cell, hence, the volume for each cell is calculated by multiplying the average depth by the cell area. The total cut and fill volumes can be estimated by summing up all the volumes for all cells.

•The Prisms method, also known as “Volume by triangulation” and is a volume computation method that compares two triangulation networks, one being the base surface and the other is the design surface. This method uses TIN

–to-TIN (Triangular irregular network) prismoidal volumes. Furthermore, a bulking factor can be introduced into the volume calculation to allow for the quality of soil that is either a cut "swell" factor and or a fill "shrink" factor. The site map is split up into triangles, which are parameters, the projection points of the design landscape onto existing landscape are determined to form another triangle and a triangular prism is formed by setting up a depth. The total volume between the base surface and the design surface is calculated by summing the volume of all the prisms.

The Prism method is used for the cut/fill optimisation calculations as it the most accurate (Andrew Y.T Kudowor and George Taylor).

The developed API tool has been tested on the Cut and Fill volume calculations and the results are compared to the actual volume by performing the calculation manually. The tests are performed on different geometrical polygons such as triangle, rhombus, square, and a pentagon. The percentage error between the computerised and manual volumetric calculation is also calculated to determine the accuracy of the calculation. Additionally, the average percentage error and the standard deviations are calculated for each shape to determine any discrepancy between each shape (Dawood et al, 2015). Table 1 shows the average percentage errors in calculating volumes for the different geometrical shapes.

Table 1: Average percentage error and standard deviation for different shaped Prismoidal volumes.

Shape	Average percentage error	Standard Deviation
Equilateral triangle	0.000546173	5.81188E-06
Rhombus	0.000405589	0.000270413
Square	0.0004705	0.000233022
Pentagon	0.000542694	6.99822E-07

3.2 Computation of the cut and fill volumes using the API

For most projects, it is desirable that all grading be self-contained on site so that no soil can be imported or exported from it to keep both costs and carbon footprint down. However, in reality this could be almost impossible to achieve especially when landscape architects are challenged with existing structures and or building. Hence, the API is developed to efficiently and quickly calculate cut/fill volumes for site grading using Revit, thus optimising the cut/fill volumes according to a desired specification set by the landscape designer. That is the landscape architect can manipulates different designs in order to optimise grading process thus increase efficiency and minimise carbon foot print.

The landscape designer starts by importing the existing landscape map into Revit. The map is firstly split into section and then each section is split into triangles (ground triangulation), see figure 1and the volume between the base surface and the design surface is calculated for each triangular column. In order to calculate each triangular column accurately and since both the base surface and the design surface is not parallel to the projection surface, the column is subdivided into three different parts: the top parallel prism, two triangular based pyramids and a general prism. The total volume is then calculated by summing up all triangular columns. Figure 2 shows the setting up of triangular column and figure 3 shows a triangular column with its coordinates.

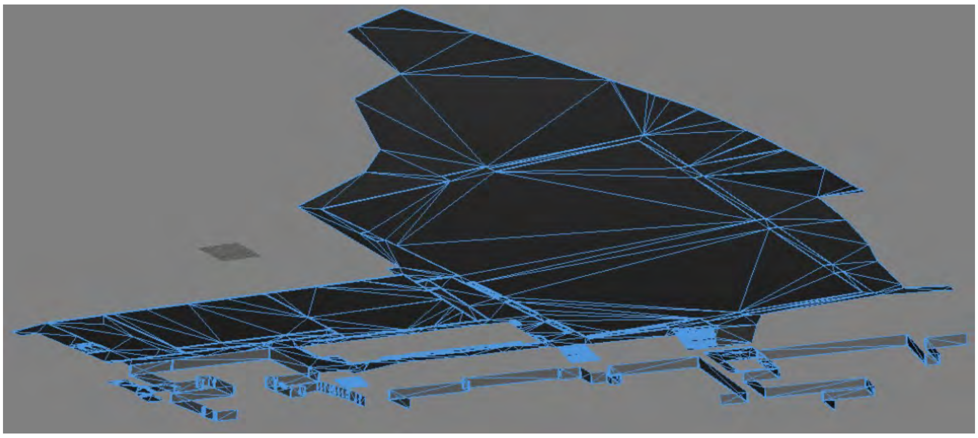


Figure 1: Ground Triangulation

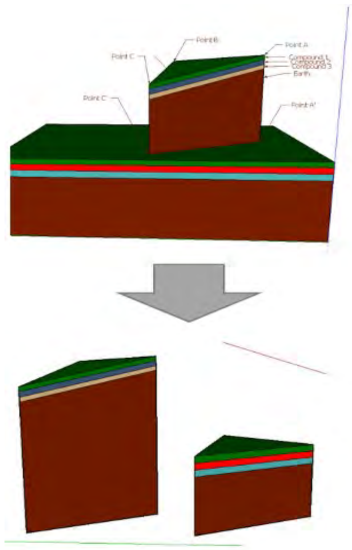


Figure 2: Setting up Triangular column

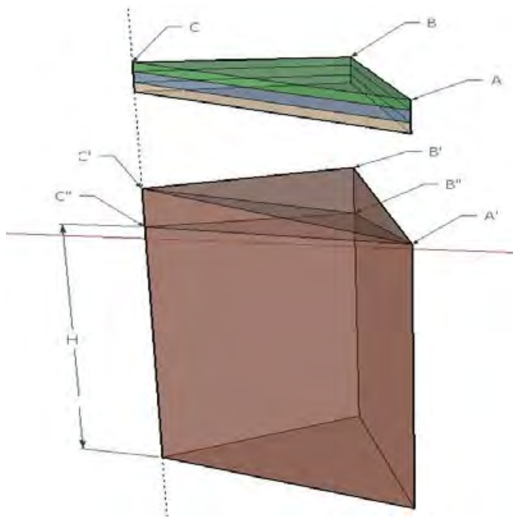


Figure 3: Triangular column coordinates

The volume calculation for the triangular column depicted in figure 2, is expressed in equation 1. The balance volume of cut and fill operation equals the total difference volume of each prisms pairs of base surface and design surface. The projection prisms from design surface on to base surface could be determine vertically from points of design surface, shown as figure 3.

$$V = \sum \quad (\text{Area of } \Delta ABC \times \text{Compound depth}_i \times \text{Bulking factor}_i) \tag{1}$$

$$+(area\ of \Delta A'B''C'' \times H$$

$$+ volume\ of\ tetrahedron\ A'B''C'C''$$

$$+ volume\ of\ tetrahedron\ A'B'B''C') \times Bulking\_factor_{Earth}$$

4. Cut and Fill Optimisation: Case Study

4.1 Design Consideration

Previously, testing of the functionality of the API is achieved by using a simple test design project that focuses on the optimisation of the cut and fill balances at the design phase (Dawood et al, 2015). However, the authors concluded that the API functionality needed to be tested on an existing landscape design to test the API's efficiency and robustness in performing the cut/fill calculations. Thus in collaboration with Colour Urban Design (CUD) landscape architects, the API is tested on an existing design project, Jack Hunt School, Peterborough, UK.

During the landscape masterplan development, a number of potential configurations needed to be considered such as all-weather pitch (AWP) and new dining/teaching block position. However, the assessment criteria was on how to best position the AWP as it created several limitation such as existing services, existing sporting provisions and proximity to residences. Three designs options are considered A, B, C. However, Option A is designated design as it represented the optimum design for balancing all the aforementioned considered issues. Figure 4 shows the school's site plan and Figure 5 illustrate the proposed landscape design options.

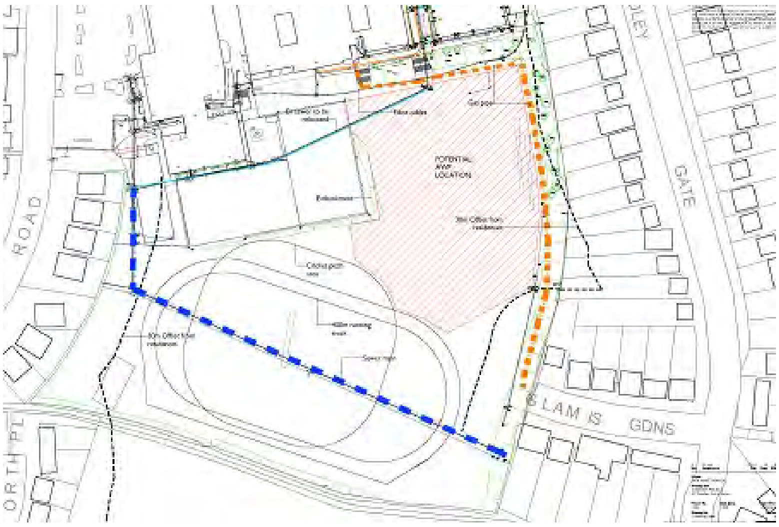


Figure 4: Jack Hunt School Site Plan

Option A

Option B

Option C

Fig. 5: Landscape Layout Design Options

4.2 Cut/Fil Design Procedure and Calculation

The earthwork design workflow begins with an up to date and coherent ground survey that effectively describes the site topography. Site Surveyors generate a 3D contours using GPS equipment. The GPS equipment generate x, y, z coordinate in CVS (comma separated value) file. The generated coordinates from the site survey include spot elevation, contour elevations, and building outline. Revit imports these points from the CSV file and generate an accurate 3D site model. Figure 6 depicts the existing construction site and figure 7 shows the proposed option A project design. Finally, figure 8 illustrates the superimpositions of the project design on to the existing landscape site.

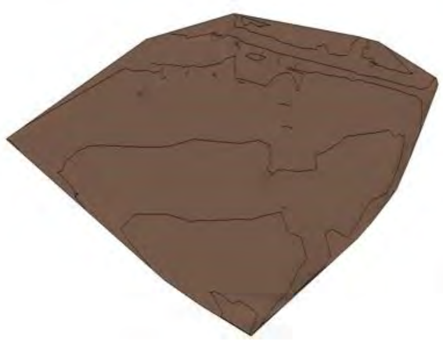


Figure. 6: Existing Construction Design

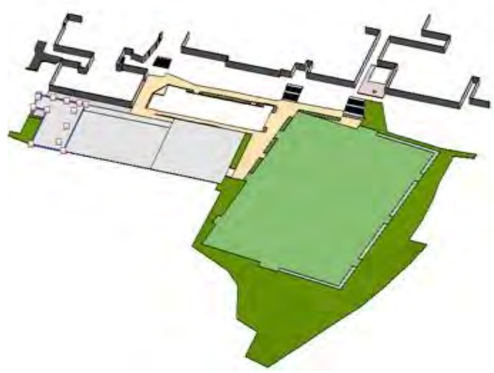


Figure. 7: Option A project Design

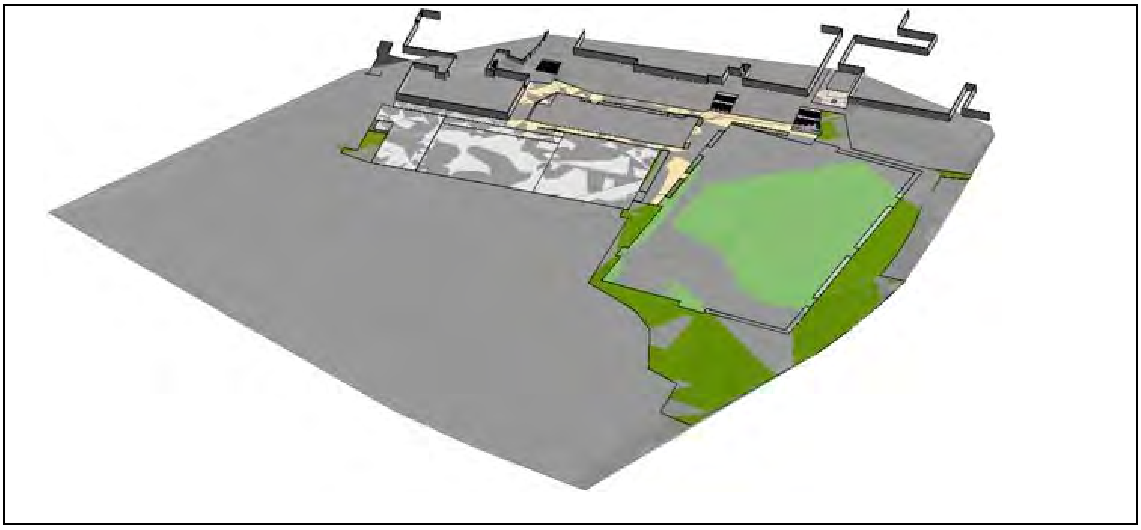


Figure. 8: Superimposition of the Design on the Existing landscape site.

Before using the API functions, Revit functions are used first to generate existing landscape site creating phases. This is followed by landscape initialization where the landscape is separated into separate phases so that the user can move from one phase to another. The API allows the user to select a floor and then move from one phase to the next calculating the cut or fill and modify floor shape and elevation according to requirement or specification. To ensure accurate calculation of the cut and fill, bulking factors of the different soil compounds are included to rectify swells and shrinkage. The API cut and fill optimisation start by comparing the floors of the existing phase and the current design phase extracting triangles then finding projection points from the current phase to the existing phase forming triangular columns and calculating the volume difference between the current phase and the projected triangle columns. Figure 9 illustrate the operation process map of the API cut/fill calculation.

Option A design cut/fill calculation performed within the building and landscape phases. Table 2 shows the overall cut/fill calculations. However, the API capability extend for the ability to divide the design into sections hence the cut/fill volume can be calculated accordingly. This procedure supports the optimisation of cut/fill work and workload scheduling.

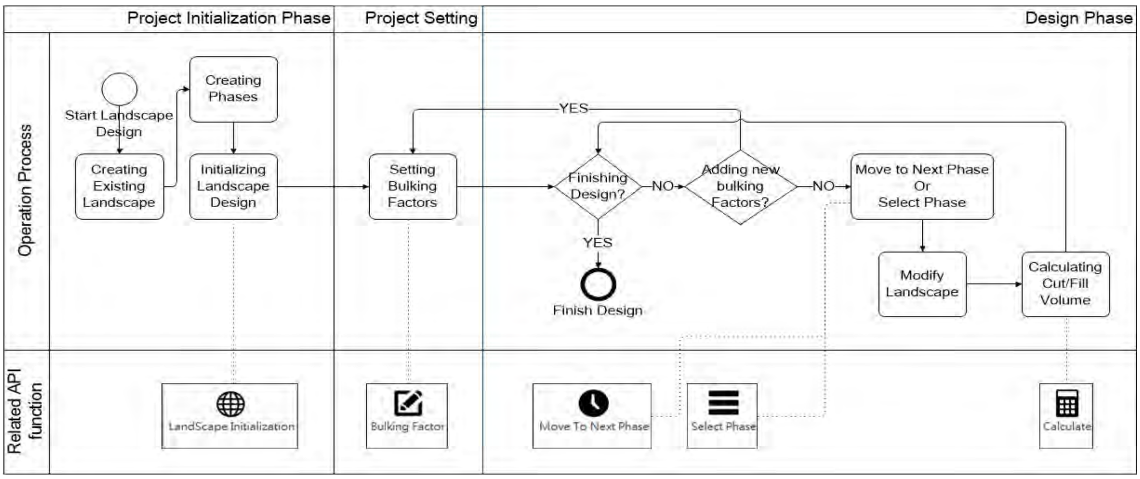


Figure 9: Operation Process Map of the API Cut/Fill Calculation

Table 2: Cut/Fill Calculation

Design Phase	Cut Volume (m^3)	Fill Volume (m^3)	Balance Volume (m^3)
Building Section	18.683	15.119	-3.564
Landscape Section	50.632	1295.258	1244.626
Overall	69.315	1310.377	1241.062

5. Conclusion

In this research, a methodology and an API have been developed for process optimisation of cut/fill for construction projects in Landscape Architecture underpinned by 3D data-rich BIM environment. The issues associated with interoperability among the different software currently being deployed by Landscape architects is resolved as the landscape design can be implemented within one software thus, keeping all data in one software environment. Furthermore, the integration of the API within Revit enabled the development of BIM-specific functions for Landscape Architecture practices and augmenting Landscape site realisation processes with visualisation and cut/fill optimisation.

The API cut/fill volume calculation capability has been verified using a test and an actual landscape design. Test results of cut/fill volume calculations, performed on different geometrical shapes, proved to be very reliable as the average percentage error was very similar for all shapes, and ranged between approximately 0.00041% and 0.00055% and the standard deviations are minimal, ranging between 0.0000007 and 0.0003. Moreover, the implementation of the API and testing its functionality to perform cut and fill optimisation, using a real case study project, proved to be successful as optimisation is performed efficiently thus saving time and cost effective.

It is envisaged that the integration of the API within Revit will not only provide a 3D data-rich visualisation of construction site operations; planning and scheduling of cut/fill operations in construction projects, and BIM protocols and processes applied to landscape design projects but also be developed further, to include time and cost. Hence, supporting 5D processes (that is integration of 3D, time, and cost) as well.

6. References

Alkass, S., & Harris, F. (1991). Development of an integrated system for planning earthwork operations in road construction. *Journal of Construction Engineering and Management, 9* (3), 263-89.

Kudowor, A.Y.T., & Taylor, G. (1998). Triangulation based volume calculation. *GIM International, 12*, 2-9.

Ahmad, A. M., & Aliyu, A. A. (2012). *The Need for Landscape Information Modelling (LIM) in Landscape Architecture*. In 13th Digital Landscape Architecture Conference, Germany.

Castro, S. & Dawood, N. (2009). Automating road construction planning with a specific-domain simulation system. *ITCon, 14*, 556–73.

Eastman, C. M., Eastman, C., Teicholz, P., Sacks, R. & Liston, K. (2011), *BIM Handbook: A Guide to Building Information Modelling for Owners, Managers, Designers, Engineers and Contractors*. Canada: John Wiley and Sons.

Dawood, H., Dawood, N. N., Fenby-Taylor, H., Chen, Y. (2015). *Development of a Prototype for Optimising Cut/Fill Underpinned by BIM in Landscape Site Realisation Process.* 15th Annual International Conference on Construction Applications of Virtual reality, Canada.

Essa, S.M. (1987). Earthwork allocations with non-constant unit costs. *Journal of Construction Engineering and Management, 113* (1), 34–50.

Essa, S.M. (1988). Earthwork allocations with linear unit costs. *Journal of Construction Engineering and Management, 114* (4), 641–55.

Flohr, T. (2011). A Landscape Architect's Review of Building Information Modelling Technology. *Landscape Journal, 30* (1), 169-170.

Jayawardane, A.K.W. & Harris, F.C. (1990). Further development of integer programming in earthwork optimisation. *Journal of Construction Engineering and Management, 116* (1), 18–34.

Mayer, R. & Stark, R. (1981). Earthmoving logistic. ASCE *Journal of the Construction Division, 107*(2), 297–312.

Nandgaonkar, S. M. (1981). Earthwork transportation allocations: Operation research. *Journal Construction Divdivision, 107*(2), 373–392.

Nessel, A. (2013). The Place for Information Models in Landscape Architecture, or a Place for Landscape Architects in Information Models. In: Buhmann, E., Ervin, S. M. & Pietsch, M. (Eds.), *Peer Reviewed Proceedings of Digital Landscape Architecture 2013 at Anhalt University of Applied Science*. Wichmann, Berlin/Offenbach, 65-72.

Shah, R. K. & Dawood, N. (2011). An innovative approach for generation of a time location plan in road construction projects*. Journal of Construction Management and Economics, 29*, 435-448

Son, J., Mattila, K.G. & Myers, D.S. (2005). Determination of haul distance and direction in mass excavation. *Journal of Construction Engineering and Management, 131*(3), 302–9.

Stark, R.M., & Nicholls, R.L. (1972). *Mathematical foundations for design: Civil engineering systems*. New York: McGraw-Hill.

Strom, S., Nathan, K., & Woland, J. (2013). *Site Engineering for Landscape Architects* (6th Edition). John Wiley and Sons EBook ISBN 9781118419090.

7. Acknowledgement

The authors gratefully acknowledge the support of Mr Stephen Blacklock, Technical Director of Colour Urban Design Limited (Newcastle, UK), for providing case study landscape design data and his expertise in Landscape Architecture practices.

INVESTIGATING THE USE OF BIM MODELS FOR BIM WORK STREAMS IN TRADITIONAL CONSTRUCTION CONTRACTING IN QATAR

Ahmad Mohammad Ahmad, Atif Hafeez Mian & Khalid Naji

(Qatar University, Qatar)

Nashwan Dawood., Sergio Rodriguez-Trejo & Vladmir Vuckovic

(Teesside University, UK)

ABSTRACT: *Design Authoring in Architecture Engineering and Construction (AEC) industry is a process where clients' requirements are converted into digital models using 3D parametric and analytical modelling tools. BIM Models are the outputs created by different stakeholders using different BIM Work Streams at project stages. BIM Work Streams require different modelling requirements and would benefit from early stakeholders' involvement (including contractors and sub-contractors) which traditional contracting procedures hinders.*

This paper is part of Qatar Foundation project which aims to develop a Whole Life Cycle information flow enabled by BIM protocols and technologies for Qatar construction. This paper investigates how BIM Models produced at design stages are utilized by contractors in projects using traditional contracting in Qatar. Within those, it also explores the extent and purposes of the use of BIM Models produced in Design Authoring process by contractors. The paper infers from focused expert interviews, the obstacles towards the use of BIM models for different BIM Work Streams in projects using traditional contracting. The selected experts are contractors with a tracked record in the Qatar construction industry. The paper aims to increase awareness of the problem, highlighting obstacles and opportunities of the use of BIM models in current practice. There is a need for early collaboration, coordination, communication and common use of information classification standards to exploit the use of BIM models for different BIM Work Streams. Among many, some of the factors inhibiting effective utilization of BIM Models for BIM Work Streams in current practice include: lack of early contractor input, trust, and sufficient construction information in building elements used during the design stage.

KEYWORDS: *BIM; BIM Work Streams; BIM Model use;*

1. INTRODUCTION

BIM Work Streams (BIMWS) are processes which are conducted at different project stages (i.e. design, construction and operation) underpinned by BIM technologies. Though BIM technologies are progressively being adopted by Qatar Construction Industry, this adoption is uneven and usually extents to the technologies and software rather than to the methodologies, processes and contracts. (Vukovic et al., 2015). Eastman et al., (2011) stated that BIM is valuable in creating, sharing, utilising data within a building lifecycle. In BIM enabled construction projects, models developed at Design Authoring process are used to facilitate BIMWS by different stakeholders at different stages. The use of BIM has some limitations such as incomplete interoperability between software, and inaccurate communication between stakeholders, leading to process inefficiency. This humpers the untapped potential benefits of BIM which have been shown in several real life examples (Eastman, 2004, Gallaher et al. 2004, Becerik-Gerber et al., 2009).

A building life-cycle approach is crucial to seize the potential value of BIM for the construction industry (Kassem et al., 2015, Sanchez and Thompson, 2016). The Whole Life Cycle Information Flow enabled by BIM protocols is an approach that requires the participation of the relevant stakeholders to define the technologies, processes and policies framework and produce the BIM paradigm shift. Project 'DNA approach as described in Dawood, (2016) can facilitate lifecycle information flow in BIM enabled projects. It involves the integration of process, people, policy and technology with a focus on adoption of classification standards and application of compatible software at the early stages.

In practice, there are a number of barriers that impede a satisfactory Model based collaboration in a Common Data Environment (CDE), so called BIM level 2 (PAS 1192-2:2013). BIM Models may need to be adjusted or rebuilt by the contractor during construction, leading to information redundancy and time loss (Cao et al., 2015). In addition, early contractor input is most of the times hindered by existing Governmental Contracting Rules (Engelmann et al., 2008), or existing procurement practise, based on Design Bid Build (DBB) procedures (Hafeez et al., 2015). To contribute to time and cost optimization, there is a need to limit redundant information. The latter can be achieved by adding consistency to the models originated in the Design Authoring process, hence improving information exchange between different stakeholders and BIMWS.

This paper aims to investigate the current practice in BIM Models use by contractors within different BIMWS working in Qatar. The paper examines the existing literature regarding BIMWS and BIM model authoring. The paper makes use of semi-structured interviews with relevant stakeholders in the Qatar Contracting sector, and inferred from them, highlights the main obstacles and opportunities. As conclusion, this paper offers a structured and expert-based diagnosis of the current strenghts and weaknesses regarding the use of BIM Models originated in the Design Authoring BIMWS in the context of Qatar. The value of this paper includes informing contractors of possible challenges when using different BIMWS in traditional construction contracts to make informed decisions and reduce the possibility of recreating information at construction stages.

3. METHODOLOGY

Literature review was conducted to explore the different BIMWS relationships and BIM Model utilisation. As well the paper bases on previous interviews and analysis (Vukovic et al., 2015). Primary data was collected to explore challenges and compatibility of BIM Models used for different BIMWS during construction. As from previous experiences, gathering expert knowledge has been carried out making use of context aware methodology to avoid cognitive and motivational biases prevalent in informal expert judgments. The latter accounted for preparation of the problem, elicitation and analysis (McBride and Burgman, 2012). A qualitative evaluation was undertaken through the use of semi- structured interviews. Six Interviewees were identified with Qatar construction experience as described in Table 1. Interview findings were backed up with case studies. Project names are left anonymous to avoid liabilities. Prior to the interview, the interviewees were provided with interview questions and introductory information with: description; importance; duration of interview; and targeted responsess to the study. Interviewees were asked about five questions. These include: Opportunities; and Obstacles to utilisation of BIM Model for different BIMWS in traditional construction projects; Extent of BIM Model use in traditional construction projects; issues arising from utilising BIM models for BIMWS at construction stage, and factors to consider for effective utilisation of BIM Models for BIMWS in traditional construction projects. A methodical and thorough analysis was conducted for the interview results. Braun and Clarke, (2004) identified six steps. *Familiarisation with data*: this was achieved through reading the transcribed data many times. Impressions were written as the data was read. *Focus the analysis*: key questions, the analysis should answer were identified. *Initial codes* were generated as the basic meaningful way of assessing the data (Boyatzia, 1998) as coding is part of the analysis process (Miles and Huberman, 1994). The codes in this study were data driven and used to *develop theme which relate to the questions stated.* Themes were presented under the five study questions above.

Table 1: Interview Participants

Interview Participants	**Consultant / Contractor**	**Year of BIM experience**
Participant 1	Contractor	5 years
Participant 2	Contractor	4 years
Participant 3	Contractor	5 years
Participant 4	Contractor	5 Years
Participant 5	Contractor	8 years
Participant 6	Contractor	10 years

4. LITERATURE REVIEW

Interoperability, lack of compliance to standards and Early Contractor Involvement (ECI*)* have been identified to hinder BIM Model utilization (Eastman et al., 2011). The current procurement used in traditional contract practice (*Design-Bid-Build)* is related to diminishing the opportunity for ECI *(*Song et al., 2009). Eastman et al., (2011) stated that a constructible building project requires *design information* to cover knowledge of construction *processes and products.* The lack of input through ECI with (Design Authorities) affects the utilisation capability of the BIM Model developed during the design stage for different BIMWS at the construction stages. Integration of relevant stakeholder knowledge in BIMWS appears to be needed. However, other authors like Potts and Ankrah, (2014) go beyond and state that adopting BIM effectively requires moving away from traditional contracting, to avoid working in silos across different project stages. Table 2 summarizes the literature review findings regarding how BIM models use and requirements as seen in real use cases and BIMWS.

Table 2: Requirements to consider for linking BIM Models with different BIM Work Streams

BIM WORK STREAMS	**CONTRACTOR INPUT**	**SOURCE**	**BIM MODEL REQUIREMENTS FOR DIFFERENT BIMWS**
1.	Shared	Berlo and	There should be only one IfcProject object per file (no more, no less);

COORDINATION	Responsibility	Papadonikolaki, (2016)	There should be only one IfcSite object per file; All objects should be linked to an IfcBuildingStorey object; There should be at least one IfcBuilding object in the dataset; There should be at least one IfcBuildingStorey in the dataset; The naming of the building storeys should be consistent and in order, i.e. floor-numbers; and so on
2 COST ESTIMATION	Input	BuildingSmart, (2010)	Space Boundary Levels (SBL) are required to be defined (there are different SBL for different BIM Use case
			Require room spaces in areas (area checking capability)
		Statsbygg, (2013)	During early QTO some objects are not yet modelled, SB are used to estimate finishes such as carpet, paint etc
		Monteiro and Martins, (2012)	Boundaries of building elements should be separated. For example, glass and frames such as doors, windows or curtain walls should be differentiated. Separate concrete from plasters in columns. Layers/ materials separately.
3. 4D PLANNING	Responsibility	Staub-French and Khanzode, (2007)	Reorganizing 3D Models. This is necessary because the 3D models represent the design perspective (e.g., pipes are organized by system) and in a 4D model, they are in the construction perspective (e.g., pipes are organized in construction zone “designers” and pipe size “contractor”) (e.g., move objects from the “Chilled Water Piping” layer to a new layer “Large Piping Zone 1”)
3a. FIRE MODELLING	Input	Statsbygg, (2013)	There is a need for spaces to be modelled by using zones (IfcZone). Indoor spaces are in one zone and only one zone for fire compartmentation.
3b. HEALTH AND SAFETY	Shared Responsibility	Zhang, et al., (2015)	Workspace tolerance have to be clearly defined to identify space clashes. Workspace conflicts are detected based on geometric conditions of different settings in the workspace.
		Zhang, et al (2013)	Rule based checking system requires each building object to have object name, type, attributes and relationships. The metadata include date, author and object ID

3. INTERVIEW FINDINGS

4.1 EXTENT OF BIM MODEL USE FOR BIMWS DURING TRADITIONAL CONSTRUCTION

According to responses to the first question, the following general aspects have been highlighted. The contractor receives the BIM Models at LOD 300. These models are used to facilitate different BIM Uses that supports the construction process. In most of the cases contractors receives completed set of 2D drawing (printed and digital) during the construction stage. In some projects design and engineering teams are required to provide 3D models to contractors, but that is not always the case, mostly due to “*incomplete models and unresolved geometry that are* *different from the flattened 2D drawings*". There are two common used approaches for BIM Model identified:

***1. Improve BIM Model*: ** Starting from the received BIM Model, the contractor is able to further develop the model from LOD 300 to 400 or as described in the construction contract. The extent of possible changes to the BIM Model during construction have been presented in a range of 15-35% depending on the specific project. It is also reported that "*the federated models stops getting used because the supply chain is not yet ready to contribute to updating the models*". Figure 1 show an improved consultant model with construction information attached.

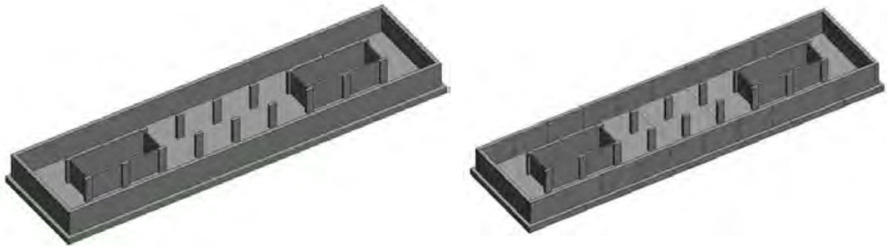


Figure 1: BIM Model updated with construction information provided by one interviewee

***2. Rebuild and improve BIM Models*: ** In this approach, no reuse of the handled BIM Model is done. Interviewees stated "*Once we receive the BIM Models we rebuild it ourselves, we only use the consultant`s BIM Model for axis and elevations information extraction*". The contractor uses the Universal Reference Source (URS) which has grids, levels and coordinates, for geometrical reference. Different disciplines use the URS file, to include their BIM objects on the grid using Copy Monitor Tool in Revit. If there are changes in the URS file, they are updated and kept tracked. One of the participants stated that "*90% of the BIM Model is remodelled, we only used it for material procurement purposes*". In some cases, the BIM Model is only used as an outline and for specifications given to sub-contractors. They produce highly detailed models that replace parts of the model. It is here were the greater definition of the BIM Model is made. Figure 2 shows MEP services remodelled (in red) and laid over/ into the BIM Model (in grey) with improved routing and greater detail. One of the challenges of rebuilding the model identified by the one interviewee refers to contract clauses (addendum), stating Design prevalence in case on inconsistencies between the 2D drawings provided (consultant) and 3D models developed (contractor).

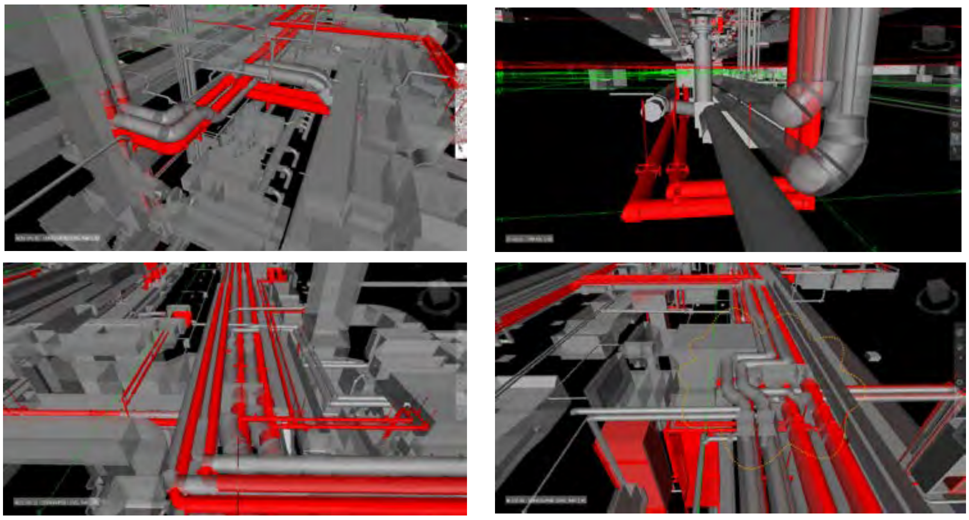


Figure 2: BIM Model (consultant) vs BIM Model (contractor)

For (MEP services) provided by one interviewee

4.2 ISSUES RELATED TO UTILISING BIM MODELS FOR BIMWS AT CONSTRUCTION STAGE.

The interviewees were asked about what the contractor finds preventing the theoretical use of BIM Models from Design Authoring, the interviewees comments were categorised into the following themes as relevant:

Communication: The BIM Model is used as a reference. However, it is considered as to provide design intent only. Also one of the participants stated that "*We do not trust the models, as limited constructors knowledge is communicated during the design stages*". This may lead to inaccuries due to lack of intra disciplinary coordination.

Technology-software: Software or version compatibility is a major issue in BIMWS. One of the interview participants stated that "The ideal method is to work continuously on the same models for better organisation of information, but due to interoperability challenges, it is not possible". There are BIM platform challenges. For example, "Digital Project was used to model the façade of a complex project for Offsite Fabrication. For fabrication and installation purposes the façade had over a thousand unique parts. The façade from the BIM Model was not modelled into the required parts, it had to be remodelled in a different software".

Discipline requirements: Each BIMWS should have some modelling requirements. One of the interviewees stated that "Each discipline build their models to meet their specific requirements. In many cases the requirement of other disciplines are not considered". As a result "Remodelling may seem unnecessary rework, but it is away to guarantee that elements are modelled to our specifications". These specification are specific to each contractor for specific BIMWS.

Inaccuracy in models: BIM Models are *sometimes* inconsistent with shop drawings provided at a later stage by consultants. Another challenge identified was consultants dealing with inaccurate quantities or construction errors in the models provided by consultants.

4.3 FACTORS TO CONSIDER FOR EFFECTIVE UTILISATION OF BIM MODELS FOR BIMWS IN

TRADITIONAL CONSTRUCTION.

According to all the Interviewees, BIM Models can be effectively utilised in the context of traditional contracting through improvements and changes. These were categorised into the following themes:

Strategic planning**:** Can be achieved through adequate Employer Information Requirements (EIR), BIM Implementation Plans (BIP) and BIM Execution plans (BEP). Continuous model use requires describing modelling roles, requirements and all scheduled model exchanges within a project at the early stages. One of the interview participant stated "*The use of a proper Employer Information Requirements (EIR) with BIM implementation and strategy plans enables the systematic flow of information from client requirements to high level information and detailed planning strategies*". Also stated that "*Projects should discuss proposed project BIM Uses against client requirements*".

Collaboration**:** Is required between all relevant stakeholders to enable lifecycle information flow. The BIM Models should incorporate knowledge of construction and fabrication to enable utilisation of models. Traditional contracts limit the ability of ECI in the design stages, but contractors can find clients that support ECI and disseminated benefits to the industry. Maximum inter-stakeholder coordination is required before Issuing For Construction (IFC). The contractor can use the URS data from consultant BIM Model to follow a one model theory. It is also noteworthy to understand that there is no use of one model in totality, but the use of a single or network of models.

Modelling requirements: Are required to use BIM Models for different BIMWS, the models in many cases have to be adjusted to meet desired BIMWS requirements. But this should be conducted early, an interview participant stated that "*A single or network of models can be utilised from design to construction. But it is important to get it right at the early stages to reduce rework at the later stages*". Table 2 describes some BIMWS requirements (non-exhaustive list) to consider during BIM Model exchange. Some organisations do not have BIMWS requirements. Another interview participants stated that "*we do not have our own organisational modelling requirements However, if models are poorly done, we Request for Information (RFI)*". The use of RFIs causes' time wasting for parties involved. Frequent RFI`s used over time can be used to extract BIMWS *generic requirement*s, while BIMWS *recommended requirements* will vary from project to project. Figure 3 describes early information (requirement) exchange between Design Authoring team and defined BIMWS team to enable informed decision making that could inform both teams of modelling requirements early on, reducing the possibility of recreating information. Communication with relevant stakeholders identified in Figure 3 would be easier to adapt during the design stage compared to construction stage due to consultant/ contractor legal limitations. An interviewee stated "*flexible contracts should be introduce to allow ECI to assist during the design stage*"

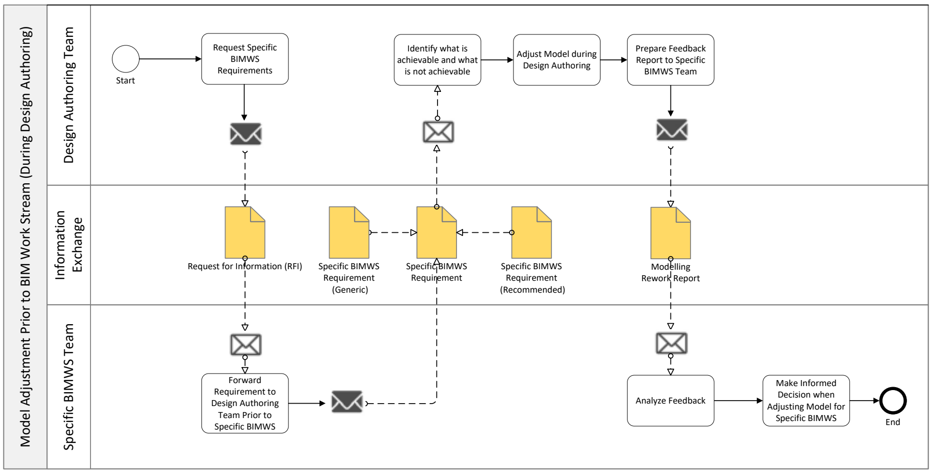


Figure 3: Early collaboration prior to BIMWS

Training supply chain (model update): Model update capability should be attainable by sub-contractors through training. There is a need to update the model when changes take place. A participant noted that "*Changes to BIM Model have to be updated into the Contractors Model. For example when building elements such as doors, windows or mouldings are changed by the contractor*". Also it is important to adapt the use of free viewer exchange format. It enables "*open access to mobile platforms to view models on site*". Furthermore, enhanced training is required to enable model use and interrogation by more stakeholders involved.

4.4 OBSTACLES AND OPPORTUNITIES OF USING BIMWS DURING TRADITIONAL CONSTRUCTION

Based on the interviews with experts, the following analysis has been undertaken. The obstacles and opportunities identified are shown in Table 4. They appear categorised using the 4 pillars of the Project DNA. This Whole Lifecycle Information Flow approach identifies Technology, Policy, People and Processes as crucial enablers to effective adoption of BIM methodologies in the Qatar construction industry. Main stakeholders (owner, contractor and fabricator) at the construction stage benefitting from the different elements in the table are identified.

Table 4: Summary of opportunities and obstacles of BIM Model Utilisation for BIMWS

BIM MODEL UTILISATION FOR BIM USES DURING CONSTRUCTION (ABSTRACTION FROM INTERVIEWS)

OPPORTUNITIES	(TO WHOM) STAKEHOLDERS		OBSTACLES
	Opportunities	Obstacles	
Option analysis through virtual (3D modelling)	C, F and O	C, F and O	Lack of contractor input in models
Facilitates (visualisation) to enable better client engagement	C and O	C, F and O	Lack of adequate coordination
Facilitates visualisation of construction (schedule planning pattern) to enable better communication professional/non-professionals	C, F and O	C, F and O	Lack of adequate communication

Reducing construction time through (schedule planning)	C and O	C, F and O	Lack of adequate collaboration
Facilitating accurate information through model based (Quantity Take-Off) leading to reduced construction waste	C, F and O	C, F and O	Lack of trust in shared model
Reduce suprises and construction conflicts through (4D planning)	C, F and O	C, F and O	Increased information management processes are required
Reduce construction cost by conducting (clash detection)	C and O	C, F and O	Lack of compliance to standards
Reduce abortive work through (coordination)	C, F and O	C and F	Lack of BIMWS modelling requirement
Reduce construction risks and accidents through (site planning),	C and F	C, F and O	Contract limitations of early multi-stakeholder engagement (legal issues)
Planning and monitoring construction progress through (4D planning)	C and F	C, F and O	Lack of awareness when information is lost
Progress report and monitoring through laser scanning against BIM Model (record modelling)	C, F and O	C, F and O	Lack of sufficient information in equipment (model)
Accelerates (Quantity Take-Off) extraction and reduce risks during pricing through the use of models	C and O	C, F and O	Lack of sufficient information in building elements (model)
Improved quality of information through combined manual and automate (clash detection)	C, F and O	C and F	Lack of supply chain software capability to update model
Support claims through (record modelling)	C, F and O	C, F and O	Software interoperability
Less paper work through (model exchange)	C, F and O		
Identifying building element location for assisting contractor/ sub contractors through effective (modelling)	C and F		
Parametric workspace representation during construction through (health and safety modelling)	C and F		
Tracking of changes for accurate information (record modelling)	C, F and O		
Ensuring BIM model update on site and conformance to client requirement during	C, F and O		

	construction through (field management tracking)

LEGEND: **Relevant stakeholders: C**: Contractor; **O**: Owner; **F**: Fabricator

Process ***Policy***

Technology

According to the interviewees, Legal issues are part of the barriers impeding model utilisation. "Some in-flexible contracts allow contractors to assist during the design stage. But clearly state what can and what cannot be offered as advice due to liability". The contractor does not want extra liability for the design intent. The contractor usually takes responsibility for ensuring accuracy at the construction stage. This humpers ECI and collaboration.

Coordination is another major issue, as well as accuracy and compatibility with other discipline models. A Coordination tolerance framework between different sub-contractors models is required. For example, one interviewee said "*the tolerance standard used by a steel sub-contractor may vary from that of curtain wall or window installer*".

Rework and drawbacks. Due to lack of input from ECI an interviewee said "sometime we go back to designers saying can you break the columns into floors or into segments (say from ground to level 10, from level 10 to level 20 etc) because we will have higher rates for higher columns of the same building". Increased information management is required.

Interoperability appears as well as limiting the scope of BIM benefits. There are multiple BIM Models and software programs used to complete construction on site. *Challenges of updating the BIM Model*. An interviewee said "*HVAC units could be installed differently than as shown in the BIM Model, some installers may find the design intent difficult to complete. The model would need to be updated with changes and the installers might not have the capability to adjust the BIM Model*".

Another obstacle is the sub-contractor *modelling challenge*. BIM Model parts are removed and replaced by sub-contractors. The BIM Model elements (e.g cladding systems) removed and replaced by the cladding specialist sub-contractor models may come with some proposed design changes that would require consultant approval causing delays. Relevant sub-contractors need to be capable of modelling their parts of the model to be integrated into the model developed by the contractor, which still is not common practice. Hence, the contractor will have to improvise. One of the interviewer stated that "*In cases where the sub-contractor cannot model their parts to be integrated into our models, we might detail in 2D or simplify in 3D*".

There are yet opportunities for using BIM Models for different BIMWS. "BIM models reduce number of information request for clarifications". Another interviewee said "Contractor can overlay temporary works on the permanent design. The integration leads to identifying possible difficulties". With regards to health and safety and space tagging, an interviewee said "A GPS can be attached to workers` helmet to identify when a worker leaves his workspace and goes into another workspace/ designated space. These spaces are tagged in the BIM Model. Space conflict can lead to hazards".

6. LIMITATIONS

There is a limited number of interview participants for this study. However, practical concerns of industry professionals have been raised. This paper has identified opportunities and obstacles for utilising BIM Models for different BIMWS during traditional construction projects currently delivered in Qatar, though it limits to a qualitative assessment.

7. CONCLUSION

Literature review was used to show samples and the need for modelling requirements to be considered when developing BIM Models within a project. It is noteworthy to understand that different BIMWS face different problems to be solved. BIM Models are not always provided to the contractor, and when provided, they need to be either rebuilt or updated with construction information. Interview findings show a large part of the BIM Models are not updated during construction stage, but replaced by specialist sub-contractors` model instead. The BIM Models are used by the contractors for different purposes such as an outline for sub-contractor modelling, to define scope of design changes, for assessing construction progress and for conducting different BIMWS. The interview findings also showed several obstacles towards the utilisation of BIM Models for BIMWS at the construction stage. They can be categorised according to a Whole lifecycle Information Flow approach. This approach identifies four main areas of knowledge or pillars to achieve effective implementation of BIM protocols in Qatar. The latter, as part of the outputs of the referenced research project, outlines diagnoses and solutions to the identified obstacles.

ACKNOWLEDGEMENT: This paper was made possible by NPRP grant [NPRP No.: 6 - 604 - 2 - 253.] from the Qatar National Research Fund (a member of Qatar Foundation). The statements made herein are solely the responsibility of the author[s].

8. REFERENCES

Becerik-Gerber, H., Thomas, S.R., Hass, C.T., Caldas, C.H. (2009). Measuring the Impact of Rework on Construction Cost Performance. *Journal of Construction Engineering and Management,* Vol. 3, No.135, 187-198.

Boyatzis, R.E (1998). *Transforming Qualitative Information: Thematic Analysis and Code Development*. Thousand Oaks, CA: Sage.

Braun, V. and Clarke, V. (2006). Using Thematic Analysis in Psychology. *Qualitative Research in Psychology*, Vol. 2, No.3, 77-101.

Berlo, L.V and Papadonikolaki, E. (2016). Facilitating the BIM Coordinator and Empowering the Suppliers with Automated Data Compliance Checking. *ECPPM*.

BuildingSmart, (2010) *IFC Implementation Agreement Space Boundary*. Available from:

file:///D:/Users/aa16530/Downloads/IFC%20Space%20Boundary%20Implementation%20Agreement%20Addendum%202010-03-22.pdf. Accessed on: 5th July, 2016.

Cao, D., Wang, G., Li, H., Skitmore, M., Huang, T. and Zhang, W. (2015). Practices and Effectiveness of Building Information Modelling in Construction Projects in China. *Automation in Construction*, Vol. 49, pp. 113-122.

Dawood, N., Akinsola, A. and Hobbs, B. (2002). Development of Automated Communication of System for Managing Site Information Using Internet Technology. *Automation in Construction*, Vol.11, No. 5. pp. 557-572.

Dawood, N. (2016). Project DNA, Whole Life Cycle Approach to Qatari Construction Industry, *ICCCBE*, July, Osaka, Japan.

Eastman, C., Teicholz, P., Sacks, R. and Liston, K. (2008*). BIM Handbook: A Guide to Building Information Modelling for Owners, Managers, Designers, Engineers, and Contractors*. Hoboken, New Jersey: John Wiley and Sons

Eastman, C., Teicholz, P., Sacks, R. and Liston, K. (2011). BIM Handbook: *A Guide to Building Information Modelling for Owners, Managers, Designers, Engineers, and Contractors*. 2nd (ed). Hoboken, New Jersey: John Wiley and Sons

Engelmann, H., Gehbauer, F., Steffek, P. (2008). Software Agents to Support Decision Making in Design and Execution Planning.*16th Annual Conference of the International Group for Lean Construction*. Manchester, UK. 783-794

Gallaher, M. P., O'connor, A. C., Dettbarn, J. L., Jr. and Gilday, L. T. (2004). *Cost Analysis of Inadequate Interoperability in the U.S. Capital Facilities Industry*. Advanced Technology Program, National Institute of Standards and Technology. (NIST GCR 04-867)

Hafeez M.A, Chahrour R., Vukovic V., Dawood N., Kassem M. (2016). Investigating the Potential of Delivering Employer Information Requirements in BIM Enabled Construction Projects in Qatar'. 12th International Conference of Product Lifecycle Management, Qatar.

Kassem, M., Kelly, G., Dawood, N. Serginson, M. and Lockley, S. (2015). BIM in Facilities Management Applications: A Case Study of a Large University Complex*. Built Environment Project and Asset Management*, Vol. 5 No 3, 261 – 277.

Kerosuo, H., Miettinen, R., Paavola, S., Mäki, T. & Korpela, J. 2015. Challenges of the expansive use of Building Information Modeling in Construction Projects. *Production*, Vol 2, No. 25, 289-297.

Smith, D.K. and Tardiff, M. (2009*). Building Information Modelling: A Strategic Implementation Guide for Architects, Engineers, Constructors, and Real Estate Managers*. New Jersey: John Wiley and Sons.

Mc Bride, M.F. and Burgman, M.A. (2012). What is Expert Knowledge, How is Such Knowledge Gathered, and How Do We Use It to Address Questions. In: A.H. Perera, Drew, C.A. and Johnson, C.J. (eds.). *Expert Knowledge and Its Application in Landscape Ecology*. New York: Springer Science + Business Media. 11-38.

Monteiro, A. and Martins, J.P. (2012). BIM Modelling for Contractors: Improving Model Takeoffs. *Proceeding of the CIB W78, 29th International Conference Beirut, Lebanon*.

Miles and Huberman, (1994). *Qualitative Data Analysis: An Expanded Source book*, 2nd (ed). Thousand Oaks, CA: Sage.

Potts, K. and Ankrah, N. (2014). *Construction Cost Management: Learning from Case Studies*. 2nd (ed). New York, USA: Routledge.

Staub-French, S. and Khanzode, A. (2007). 3D And 4D Modeling for Design and Construction Coordination: Issues and Lessons Learned, *ITCon*, Vol 12.

Statsbygg, (2013). *Statsbygg Building Information Modelling Manual*, Version 1.2.1.

Sanchez, A.X. and Hampson, K.D. (2016). BIM Asset Management and Metrics. In: Sanchez, A.X., Hampson, K.D. and Vaux, S. (eds*). Delivering Value with BIM: A Whole-of-life Approach*. New York: Routledge. 3-22.

Song, L., Mohamed, Y. and AbouRizk, S.M. (2009). Early Contractor Involvement in Design and Its Impact on Construction Schedule. *Performance Journal of Management in Engineering*, Vol 25 No.1, 12-20.

Vuckovic, V., Kaseem, M., Dawood, N., Atif Hafeez, M. and Chahrour, R. (2015). BIM Adoption in Qatar: Capturing High Level Requirement for Lifecycle Information Flow. *CONVR*, October 5-7, Banff, Alberta, Canada.

Zhang, S., Teizer, J., Pradhananga, N. and Eastman, C.M. (2015). Workforce Location Tracking to Model, Visualize and Analyze Workspace Requirements in Building Information Models for Construction Safety Planning. *Automation in Construction,* Vol. 60, 74-86.

Zhang, S., Teizer, J., Lee, J. and Eastman, C.M. and Venugopal, M. (2013). Building Information Modelling (BIM) and Safety: Automatic Safety Checking of Construction Models and Schedules. *Automation in Construction*, Vol. 29, 183-195.

A WEB-BASED CONSTRUCTION SITE RISK EVALUATION AND IFC-BASED PRESENTATION SYSTEM

Yo-Ming Hsieh[1], Shih-Hui Chang[2], and Mao-Sheng Tsai[3]

1) Graduate Student, Department of Civil and Construction Engineering, National Taiwan University of Science and Technology, Taipei, Taiwan, R.O.C. Email: youngood0801@gmail.com

2) Ph.D., Department of Civil and Construction Engineering, National Taiwan University of Science and Technology, Taipei, Taiwan, R.O.C. Email: ymhsieh@mail.ntust.edu.tw

3) CEO, Construction Occupation Health and Safety Center, Taipei, Taiwan. Email: cohsc@mail.ntust.edu.tw

Abstract: Construction site is worldwide known as the most dangerous work environment. Occupational hazard rate in the construction industry is significantly above the average in many countries. It has been suggested construction site safety can be greatly improved by conducting risk evaluation during planning and design phase of construction projects. Thus, a web-based information system is developed to help the risk evaluation process. The system further integrates BIMsurfer, a WebGL based IFC/BIM viewer, to aid inexperienced users during the risk identification process and to visualize construction risk over time. An improved task decomposition procedure is incorporated in the developed system to bridge the gap between the work breakdown structure (WBS) for risk identification and the WBS for construction tasks. It is believed the developed system contributes to improving construction site safety.

Keywords: construction site, safety, information system, BIM, IFC

1. INTRODUCTION

The working environment in civil and construction engineering industry is different from others. It is often in the open air and easily influenced by weather, landscape, geology and other human factors. Most of constructions have subcontracts. Managing human resource, machines, devices and other resources with many subcontracts is challenging. Between subcontracts, there are many interfaces need to be resolved by constant communication. All the above factors make the construction jobsite one of the most dangerous working place. Table 1 is the labor insurance claim rate in Taiwan in year 2014. It is seen in Table 1 the occupational injury rate in construction industry is three times higher than all industry average. The fatality rate is even five times higher than all industry average. This shows that the construction site safety needs to be improved.

Table 1. The labor insurance claim rate in Taiwan in year 2014

(Ministry of Labor Bureau of Labor Insurance, 2014)

industry	labor insurance claim rate (1/1000)			
	total	injury	disability	fatality
all industry	3.467	3.211	0.229	0.027

construction industry	12.015	11.315	0.565	0.136

One major effort to improve construction site safety in Taiwan is the "Labor Safety and Health Risk Assessment Guidelines" published by the council of labor affairs. This guideline suggested: 1) a process to identify and evaluate jobsite risks during project planning and design phase and 2) a set of forms to facilitate such process (Construction Occupation Health & Safety Center, COHSC, 2010). This guideline, if followed and executed accordingly, should help identify all risks on the jobsite. The identified risks, if managed properly, could be resolved and thus improve the jobsite safety. The guideline suggested process and forms, without proper management and tracking, could easily become paperwork without materialized benefit. Therefore, there is a need for an information system to help 1) carry out the guideline suggested process, 2) produce forms and documents needed for risk assessment, and 3) manage identified risks.

In order to manage the identified risks, they need effective presentations to communicate with stakeholders such as construction workers. Basic information about risks include 4W1H – what, who, when, where, how: What is the risk? Who is responsible to resolve the risk? How should the risk be resolved? When and where will it occur or affect? To effectively communicate the when and where, building information model (BIM)-based visualization is often preferred over textual description. By seeing risks, planners and engineers may be able to devise better solution to these risks, and workers may pay more attention on the jobsite to avoid these dangers.

This paper reports our development of construction risk assessment information-system (CRAIS). The system guides its users to carry out the risk assessment process suggested by COHSC. During risk assessment, users can view the associated BIM model to help them better understand the jobsite. At the end of assessment, documents and forms required by government officials can be generated automatically. Furthermore, the system helps users manage identified risks, including the responsible personnel and measures applied. The system can also conducted 4D (3D + time) visualization for construction simulations, and 5D (3D + time + risk) visualization. The 5D capability allows users understand how risk is distributed on the construction site and how risk varies with time.

2. METHODOLOGY

CRAIS guides its users through the risk assessment process suggested by COHSC. The process is illustrated in Figure 1. The process was carried out using forms in the current practice. Thus, the web-based CRAIS system uses a user-interface mimicking the form-filling operation so that users can quickly understand how to use the system. The steps in Figure 1 are the following:

1. First, users input basic information for the construction project. The most important data in this step are unfavorable site conditions such as high-power electrical wires and dip slope. The more adverse conditions are recorded, the more accurate risks can be assessed. Users can also upload the BIM model at this step. The model can be reviewed at later steps to better identify risks.
2. Then, users need to devise work breakdown structure (WBS) for the entire project. The construction project

is first divided into several subprojects (e.g. sub-structure and super-structure). Each subproject will then be broken down into many tasks, and each task will be further decomposed to many activities. It should be noted this initial WBS is for risk assessment purposes or contractual purposes, and it is not suitable for construction scheduling. For example, formwork is one activity in this WBS. This activity is suitable for subcontracts or for risk assessment. However, the construction scheduling for formwork would further break it down to foundation formwork, first-floor outer-wall formwork, etc.

3. Then, in order to prepare for construction scheduling, users need to create work units. For each task under a subproject, there will be several work units involved to complete one task. One work unit may be repeated several times, and it may be associated with many activities. For example, slurry wall construction starts with guide wall construction. Then, the slurry wall is constructed by several work units of panels. Each panel's work-unit involves trench grabbing, steel cage installation, stop-end placement, concrete pouring using tremie pipe and stop-end-removing. This panel work-unit is associated with many construction activities such as tower crane operation, concrete pouring, and excavation.
4. Once work-units are created, each work-unit needs to be scheduled. This is required to conduct 4D simulation.
5. For each activity, the user needs to identify its unfavorable factors that may cause risks. The identified factors also need to be categorized into 1) site conditions, 2) activity itself, 3) equipment, or 4) human conditions. For example, in crane operation activities, one unfavorable factor would be a near-by high-voltage electrical wire, and this is categorized as site condition. Or, in the blasting activity for tunneling, blasting itself is an unfavorable factor that may cause injuries. In this case, this unfavorable factor (blasting) is categorized into the activity itself.
6. For each activity, the user needs to input the identified potential risk. For example, the crane operator may be electrocuted if the crane accidentally run into electrical wires. Step 5 and 6 require inputs from experienced engineer to accurately identified unfavorable factors and potential risks.
7. Once all activities are analyzed in step 5 and 6 on their unfavorable factors and risks. Every potential risk needs to evaluate its severity and likelihood. Their product becomes the risk level. If there were activities with unacceptable risk levels, then one should change how the activity is performed or provide some measure to help lower the likelihood.
8. To prepare for 5D simulation, user needs to setup correspondence between work-units and BIM model entities.
9. Output reports on risk assessment results, sorted either by risk levels or by schedule.
10. Output risk management forms. The form documents identified risks, reasons why they may occur, their likelihood, severity, risk level, countermeasures, and responsible personnel executing the countermeasures.
11. Conduct 5D simulation to understand how risks evolve over time and space.

Once user goes through the entire process shown in Figure 1, he/she will have a clear idea on how the construction proceeds, each activity involved in the construction, risks associated with each activity, and when and where these potential hazards may occur.

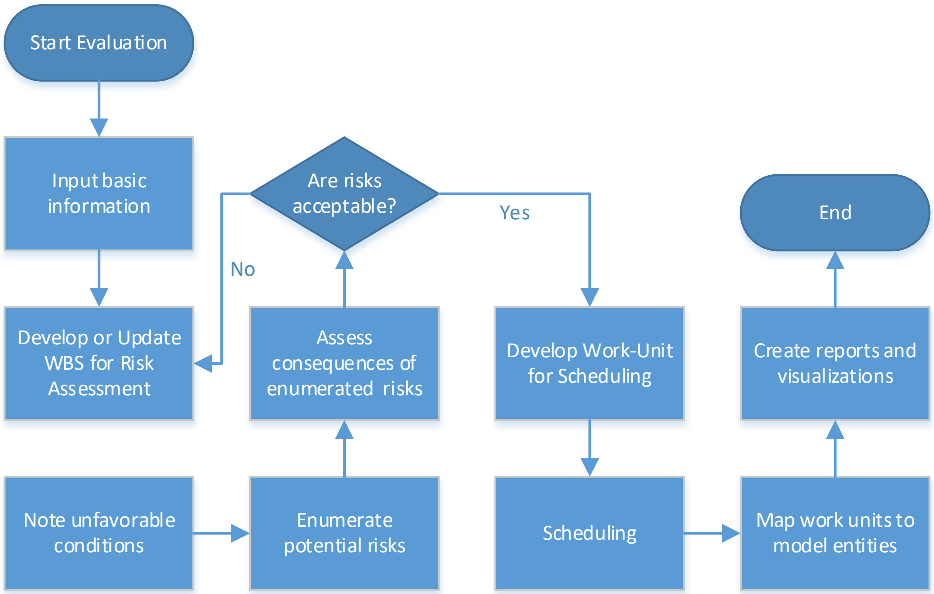


Figure 1. Process of construction risk assessment in this work

3. IMPLEMENTATION AND DEMONSTRATION

CRAIS is created to help its users perform risk assessment on construction sites in order to create a safer jobsite. When the system was conceived, it was designed to host multiple projects and multiple users from multiple companies. It was thus determined to use web-based technology to implement CRAIS. There are three reasons adopting web-based technology. 1) Convenience. Users do not need install any additional software other than standard web browsers such as Chrome, Internet Explorer, Firefox, or Safari. They can use it in the office or on the jobsite as long as they have Internet connectivity. They can also use any computing platform they are most familiar. 2) Data reuse. Users can refer or even reuse others similar projects on the system when they develop WBS for new projects. They can thus save time on setting up projects to be assessed. 3. Experience accumulation. When many projects' assessments are stored in the system, it becomes possible to use data mining or artificial intelligence techniques to identify risks automatically according to WBS user developed. There are three modules within CRAIS: 1) risk assessment module, 2) schedule planning module, and 3) visualization module using web-based BIM system.

In the remaining of this section, we first briefly describe software environment (the languages and libraries used for implanting CRAIS). Then, the three modules above-mentioned will be described and demonstrated.

3.1 Software architecture and its environment

Architecture wise, CRAIS is a typically three-tier web-application as illustrated in Figure 2. The front-tier is web-browser showing webpages. The middle-tier is the web-server hosting CRAIS. The back-tier is the database hosting data. This architecture is flexible. One may choose to install the middle-tier and back-tier on the same machine if security was not of concern (e.g., the machine is only connected to the intranet). One may even run all three tiers on the same machine, so that no network connectivity is required.

CRAIS was developed under LAMP (Linux operating system, Apache web-server, MySQL database management system and PHP server-side scripting language) software stack. The system, however, can also run under WAMP (Windows, Apache, MySQL, and PHP). No operating-system specific component is used in CRAIS. Several software libraries are additionally used to ease the development effort. On the front-tier, jQuery is used to simplify the effort on creating client-side JavaScript programs that can correctly run on all major browsers. CakePHP is used on the middle-tier. CakePHP is a software framework for PHP to develop rapidly web applications, and it follows model-view-controller (MVC) design pattern. Models are in charge of database connectivity, views are responsible for interacting with users, and controllers deal with business logics.

To conduct 5D simulations and display BIM models in web browsers, CRAIS interfaces with BIMserver (BimServer, 2008) and integrates BIMsurfer (BIMsurfer, 2011). BIMserver is an open-source server hosting industrial foundation class (IFC) based BIM models. It provides standardized networking interfaces known as BIM service interface exchange (BIMsie) to access model information. CRAIS uses these interfaces to upload BIM models to BIMserver. The uploaded BIM models are then visualized by BIMsurfer. BIM Surfer is a web based BIM model viewer using WebGL. It can thus visualize BIM models in nearly all mainstream web browsers without any additional software installation. Furthermore, even though the BIMsurfer documentation is scarce, we can still integrate it with CRAIS due to the open-source nature of BIMsurfer. This integration will be demonstrated later.

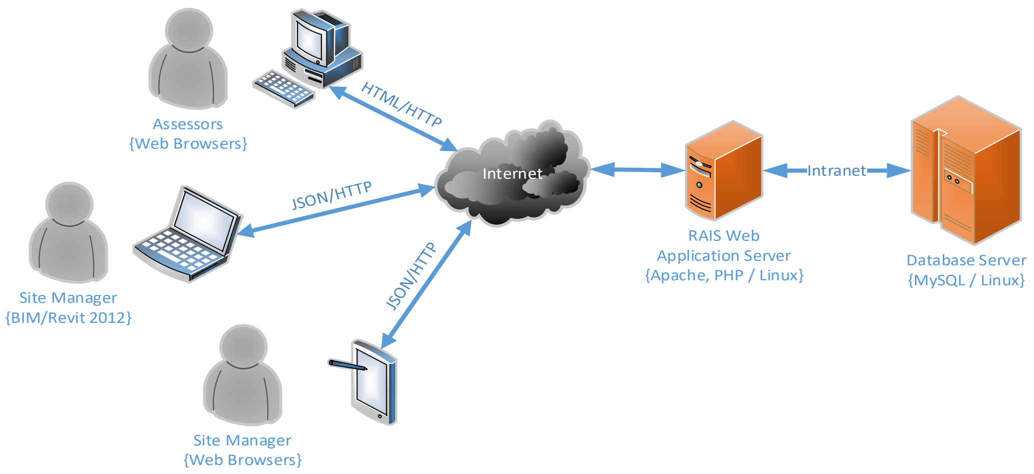


Figure 2. Three-tier web application

3.2 Risk assessment module

Once users logged into CRAIS, they are welcomed by a list of projects that they are involved. This is shown in Figure 3, and it can be seen the system's interface contains five parts: (1) system message bar, (2) main menu bar,

(3) progress indicator, (4) project information panel, and (5) working area.

(1) The system message bar displays system's status or response after users performed some operation. For example, after user tried to log into the system, the system message bar may display login successfully or login failure.

(2) The main menu bar gives users their access to allowable operations on the selected project after they logged in. As mentioned earlier, CRAIS can host multiple projects and multiple users. Each user may play different roles in different projects.

(3) The progress indicator uses colored text to indicate status of steps listed in Figure 1. Red, yellow, and green texts mean their corresponding steps has not been started, has been evaluated, or has been completed, respectively.

(4) The project information panel shows the active project. The active project is the projected selected to work on after a user logged into the system.

(5) The working area is where users perform his/her work under selected function in the menu bar. Thus the content of the working area varies with the selected function.

Figure 4 shows the interface used by users to develop WBS for a selected project. It is composed of four parts: (1) project information, (2) subprojects, (3) tasks, and (4) activities. A project contains many subprojects, a subproject contains many tasks, and a task needs to perform many activities. This information is formatted into a big table, and developing WBS becomes filling forms, which is familiar to most engineers.

Once WBS is developed, users need to document unfavorable conditions for each activity. Figure 5 shows the form for documenting unfavorable conditions. These conditions are categorized by 1) site condition, 2) operations of the activity, 3) equipment, and 4) personnel. There are also subcategories under each of the mentioned category. These categories are defined by the institute of labor, occupational safety and health (ILOSH), ministry of labor, Taiwan.

Finally, users identify and evaluate risks for each activity. This is demonstrated in Figure 6. The system first presents collected unfavorable conditions for each activity as in Figure 6(a). Users then identify risks by simultaneously considering the activity itself and the listed unfavorable conditions, Figure 6(b). For each identify risk, users then evaluate likelihood and severity. Their product becomes the risk level for the evaluated activity. This is shown in Figure 6(c). Thus, each activity in the developed WBS has an associated risk level.

Figure 3. Main interface after a user logged into the system

Figure 4. Project separating interface

(a) unfavorable condition form (b) editing unfavorable conditions

Figure 5. Documenting unfavorable conditions

3.3 Schedule planning module

We have pointed out earlier the WBS developed for the risk assessment purpose is not suitable for 4D simulation purposes. CRAIS thus integrates a schedule-planning module to help develop 4D and 5D simulations. Figure 7 shows the user interface for this module. The interface contains three parts:

(1) Work-unit addition/creation: In the schedule-planning module, users create new work units or schedule existing work units. When new work units are created, user need to input: 1) duration, 2) associated activities. Then created work units must then be added to the schedule to be effective.

(2) Work-unit operations: once work units are added to the schedule, they can be deleted or copied. More importantly, user needs to setup correspondence between work units and BIM model entities.

(3) Schedule: the schedule planned is presented in Gantt chart format that engineers are familiar with. It should be noted work-units can be easily "copied" in CRAIS to facilitate scheduling repeated tasks.

(a) Summary of unfavorable conditions and risks

(b) Editing details of the risk identified

編輯評估

災害類型	感電		
潛在危害	施工緊鄰高壓電線，有感電之慮。		
現有措施	措施類型	措施描述	
災害要因	不安全環境		
風險評估 ☐使用例外評估指標	可能性	嚴重度	風險值
	2	2	4
風險等級	中度危害		
評估衡量指標	3		
風險編號	TC001-TCA001-TCAA001- 1		

(c) Risk evaluation

Figure 6. Risk identification and evaluation

3.4 Visualization module

The visualization module presents BIM models with customizations in web browsers. This module is used in setting up correspondence between work units and entities, and in 4D and 5D simulations.

Figure 8 shows the visualization module used in setting up correspondence between model entities and work-unit. One work-unit may associate with many model entities, and one model entity may be related to many work-units. After user chooses one work-unit to setup its correspondence, the system displays the BIM model so that users can choose associated entities. Currently selected entities are semi-transparent, while other entities are presented with their default color scheme. Furthermore, entities (e.g. slurry walls) can be made hidden temporarily so that users can selected entities blocked by these entities.

After finishing risk assessment, schedule planning, and setting correspondence between work-units and model-entities, users can commence 5D simulations. This is demonstrated in Figure 9. Top of the screen contains controls for model display and timing information. Users can go forward or backward in time using the buttons in this area. Users can let the model present itself, including time marching and orbiting. The entities are made transparent before they are built (according to the schedule planned). When entities are being built, their colors are determined by its risk level. The color of entities being built can be red, yellow, or green, and these colors respectively correspond to high, medium, and low risk levels. After entities are built, their colors are determined by its material definition. This 5D simulation allows users to know which area has high risks that may need more attention on their safety-related issues and how risk varies with time, shown in Figure 10.

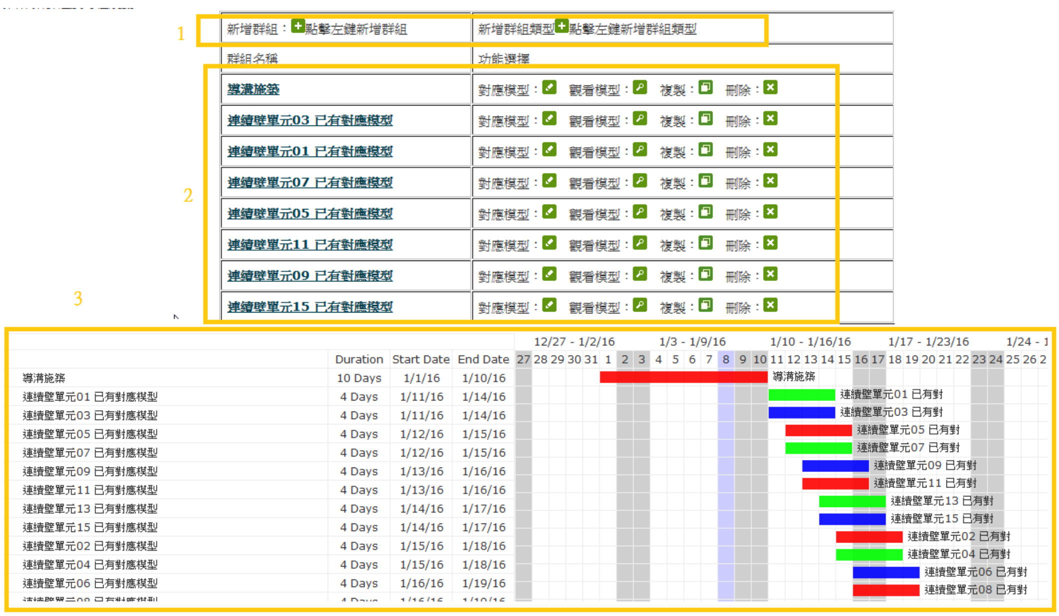


Figure 7. The user interface for schedule planning module

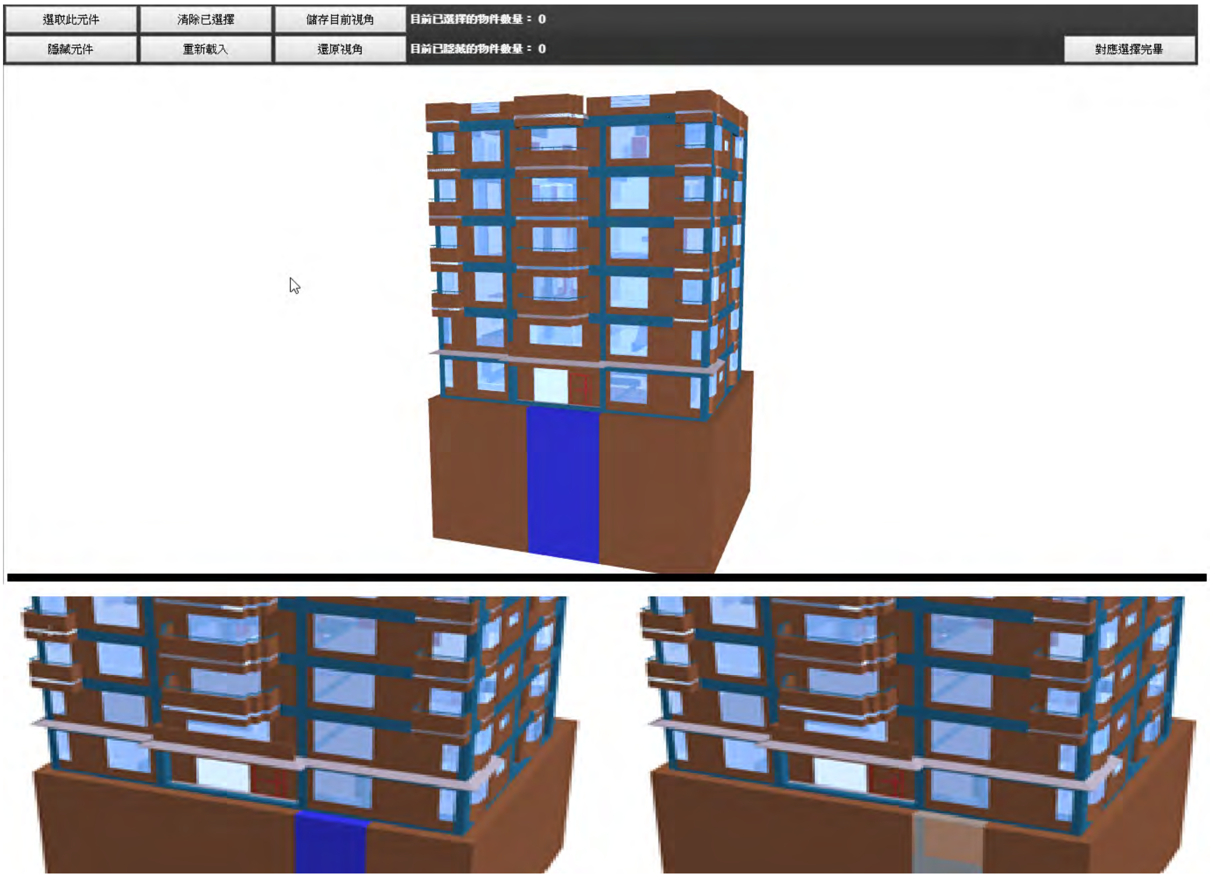


Figure 8. Setting up correspondence between model and work units

Figure 9. 5D simulation with control panels on top

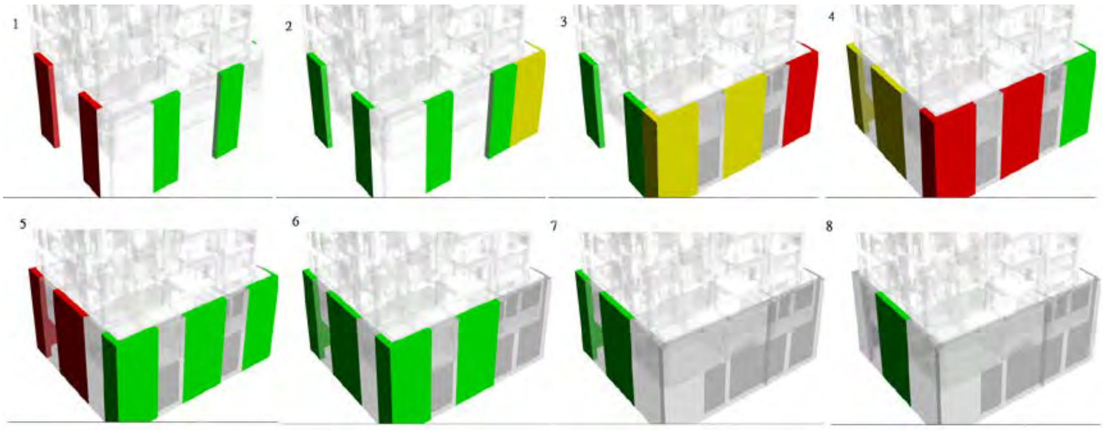


Figure 50. 5D simulations showing varying risk levels in slurry wall construction

4. CONCLUDING REMARKS

Our team built a web-based information system for 1) evaluating risks in construction sites, 2) showing evaluated risks using tables and charts, and 3) visualizing how risk varies with time and space using BIM. The system not only helps its users evaluate construction site risks. Furthermore, it helps site managers communicate effectively with construction workers to help them understand the evaluated risks. By using BIM based visualization, the spatial and temporal variations of risks can be better understood.

5. REFERENCE

BiMserver (2008), http://bimserver.org, last accessed on Jan. 9, 2016.

BIMsurfer (2011), http://bimsurfer.org, last accessed on Jan. 9, 2016.

Yi-Sheng Kang. (2012). Computer-Aided Construction Risk Assessment and Evaluation System with Visualization in BIM, *Master's thesis in the department of civil and construction engineering*, National Taiwan University of Science and Technology.

Shih-Hui Chang (2015), ","Master's thesis in the department of civil and construction engineering, National Taiwan University of Science and Technology.

The System Development and Application Scenarios of an On-site BIM Viewer based on Augmented Reality and Indoor Positioning

Hung-Ming Chen & Hong-Dao Lin

Department of Civil and Construction Engineering, National Taiwan University of Science and Technology

ABSTRACT: *This study applied integrated indoor positioning and Augmented Reality (AR) technologies to develop a model for viewing Building Information Model (BIM) on-site. In the proposed model, BIM information is displayed and superimposed on real building elements in the form of 3D component models or surrounding texts using AR technology. The building must contain a wireless network environment, as the system uses wireless access points (WAP) for indoor positioning to identify the user's location in the room. Each room uses the same set of markers to mark up and identify the building elements in the room. Once a building element is identified, the system retrieves the 3D model or property information from a Cloud-based BIM database, which it superimposes on a view of real building elements. We developed a prototype system based on the proposed model. The proposed system achieved the integrated display of virtual BIM and real on-site scenes on a head-mounted display without manual navigation for model viewing. Furthermore, we propose four application scenarios to support operations in the construction, acceptance, maintenance, and decoration phases of a project. These scenarios indicate that such an on-site viewing model of BIM is functional and feasible.*

KEYWORDS: *IT Applications, Augmented Reality, Indoor positioning, BIM*

1. INTRODUCTION

Building Information Modeling (BIM) is used to integrate a three-dimensional visual model of construction projects and digital data of various fields with properties into a file or a database with a specific format, allowing project designers, project managers, construction units, owners, and clients to view the design through a three-dimensional visual model and obtain relevant digital data of the project in a three-dimensional visual model. Commercial BIM software products can integrate 3D models with architectural, structural, electromechanical, air-conditioning, firefighting, and other various field data and store them in a single common BIM project. A feature of these commercial BIM software products is that they primarily support the CAD system of BIM design for a studio work environment. Currently, BIM has been applied successfully during the planning and design phases of projects. However, when one wants to use BIM to support tasks during the construction and maintenance phases, one must bring the BIM to the site to use it. If a user needs to view and query while on-site, the existing approach is still to export the model as 2D floor plans and bring them to the site to use with conventional methods, or use a tablet, notebook, or other mobile device on the site to run the BIM Viewer software. When a user wants to query the property data of a certain actual building element through BIM Viewer, he/she must first manually search for the 3D scenes in the BIM, find them, and then select the corresponding BIM component to see its relevant components and parameters. Such an approach requires the manual operation of model viewing to return the necessary BIM information to the user. The model is unable to perform automatic interception or provide immediate feedback regarding the information, and the BIM presented through the computer screen and the actual on-site scenes are also provided in two separate views. In this viewing method, the information between the two views is less likely to be synchronized and combined. Therefore, BIM applications in engineering are currently mostly used for the planning and design phases. Its application in the construction or maintenance phase is relatively rare.

Augmented Reality (AR) is a technology which utilizes computer visualization to superimpose virtual objects on real world images for user interaction (Shin & Dunston, 2008). Its mode of operation is to calculate the position and angle of a video device through real-time positioning or image processing and then superimpose a virtual model and information on the image of the real world. Users can instantly and automatically obtain the necessary information based on their location. Its objective is to present virtual objects in the scene of the real world via a video device and allow users to interact with it. Some studies (Behzadan & Kamat, 2011; Bae, *et al.*, 2012; Park, *et al.*, 2013) have attempted to apply AR technology in the field of construction engineering; however, most of these studies applied the AR technology to an outdoor on-site construction environment; relatively few studies have applied the AR technology in an indoor environment to support construction and maintenance operations. Therefore, based on the application concept of an outdoor environment AR system, this study aims to integrate AR and indoor positioning technologies to superimpose virtual reality images of BIM components and properties inside an indoor work environment so that users do not need a complicated operation manual for model viewing. The virtual reality images can be superimposed on a single screen, provide an immediate view of BIM, and apply it to support construction and maintenance operations.

2. OBJECTIVE

The purpose of this study is to propose an on-site view mode of BIM information by integrating AR and indoor positioning technologies. This mode was applied to superimpose the BIM information directly upon a real-time video of the building interior. By overlaying on the architectural elements via an AR device, it displays the 3D model, established using BIM components, and the property parameters of the elements. This is directly presented on-site, providing immediate feedback to the user.

A building contains many architectural elements. To use AR markers to render the BIM components, many markers are required. Taking a ten-story apartment building as an example, if each floor has ten rooms and each room has ten architectural elements, 1000 different markers will be needed, resulting in less efficient implementation. Therefore, the proposed model integrates AR with indoor positioning to keep the number of markers to a minimum. The same group of markers presents different BIM components in different rooms by using indoor positioning to locate the current position of the user. This system should then be able to determine the BIM components for display. For this purpose, the indoor positioning technology is first applied to the room in which the user is located. The location of the user is then coordinated with an AR marker to superimpose the created BIM component, including the building elements and the property parameters. With a 3D model to render the exterior of this component and present the properties in text, this information is superimposed onto an actual building element of the on-site room, affixed with a corresponding marker.

Using Wi-Fi positioning as the indoor positioning technology, viewing of the component through a display requires a corresponding marker. Hence, before using the system, on-site construction and maintenance staff need to set up wireless access points (WAP) for Wi-Fi and configure markers on the building elements, such as walls, doors, windows, and floors. WAP carries out indoor positioning through the signals emitted by the notebook of this system. Based on the positioning space, the system downloads all BIM components of this space and superimposes virtual reality onto the building elements using the marker. Users can view the BIM components through wearable video devices and carry out shifting, rotation, scaling, and transparency changes of BIM components. Before using the on-site viewing mode of BIM information with the integrated AR and indoor positioning technologies, the proposed system must first be pre-set on-site, as described in Fig.1.

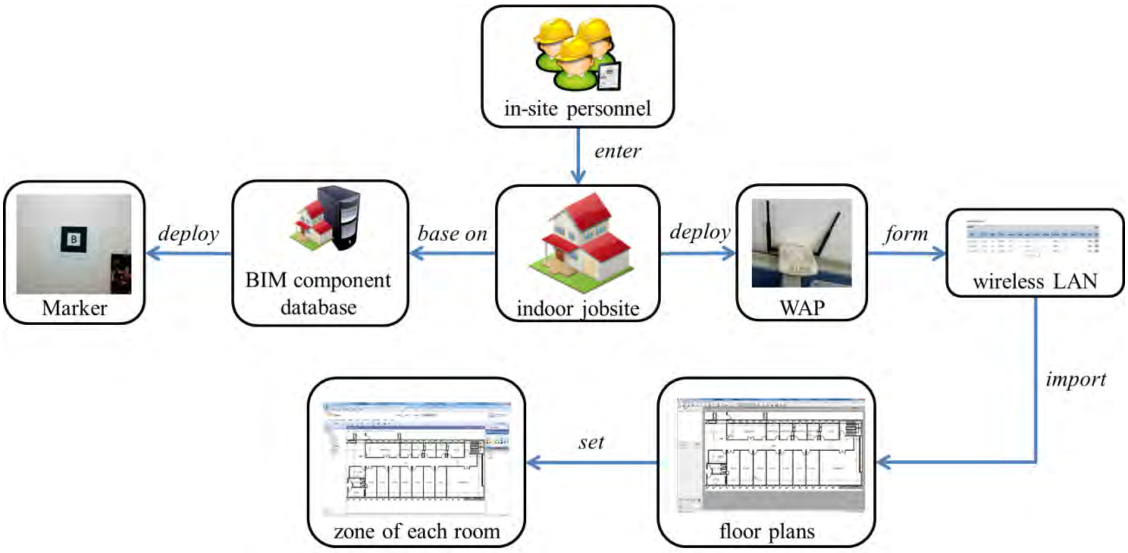


Fig. 1: Pre-setting process of the proposed system.

Fig. 2 illustrates the proposed system's mode of operation. The building interior requires the establishment of a wireless network environment. All rooms use a group of identical markers, according to the database of its BIM components, affixed onto each building element inside the space. When a user enters the room on-site, the system starts downloading a reference table from the BIM database, which contains the rooms of the indoor site and the corresponding BIM component codes. To carry out indoor positioning via WAP and to identify the location of the user, the system automatically downloads all the BIM components of this space, and coordinates them with the marker on the building elements for identification. The system can also access the 3D models and related property parameters of the elements from the BIM database based on the identified building elements. Users can instantly view the BIM model and parameters of the target component via a wearable display device and by using a keyboard or a mouse to rotate, move, and scale the BIM components. They can even change the transparency to facilitate viewing of the BIM components and the hidden components. This integrated model can be conducive to the work of the on-site construction and maintenance staff. They no longer need to view the BIM through notebooks and tablets. By using the model proposed in this study, users will be able to view the BIM in a way that is more convenient, faster, and more efficient.

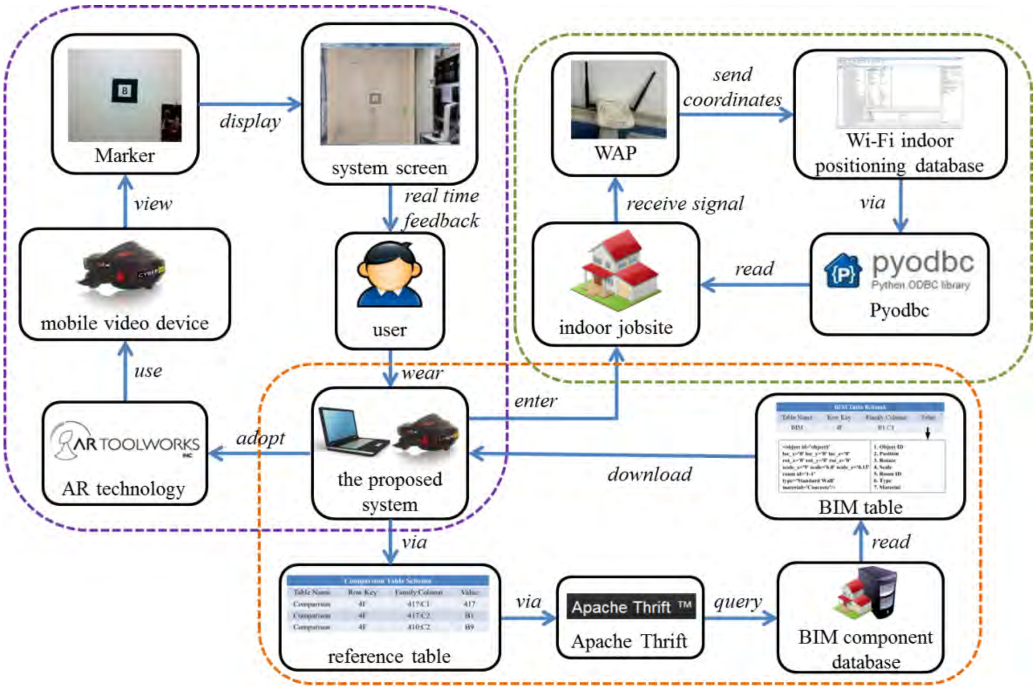


Fig. 2: Operating process of the proposed system.

3. SYSTEM REQUIREMENTS AND MECHANISMS

To achieve the objective of this study, we investigated the system requirements for each function and proposed the mechanism plan for system operations. These functions include types and properties of BIM components, database schema for BIM storage, a BIM component lookup mechanism, workflow of Wi-Fi positioning technology, a connection with the BIM database, BIM component information retrieval, a marker design, a deployment rule, a BIM component display mechanism, and BIM component model manipulation. The following subsections focus on the analysis and planning description of these nine directions.

3.1 Types and properties of BIM components

In a BIM project for construction work, the basic components constructing the main body of the building include the beam, column, wall, and slab, the four types of "structural components" that are mutually linked in assembly and construction. The surfaces of these structural components may be attached to relevant "architectural components," such as the door and window components embedded in the wall. The interior of the structural components may contain "hidden components," such as pipelines or rebar. These components do not exist independently and thus need to be attached to the interior or surface of the structural components. Their locations are proportionally fixed to the structural components to which they are attached. The BIM of a building is not only assembled using the abovementioned structural, architectural, and hidden components, but also the hardware equipment associated with the use and operation of the building, such as air-conditioners and drinking fountains, or mandatory equipment such as that used for fire-fighting stipulated by the statute, e.g., fire extinguishers, fire hydrants, escape lights, or smoke detectors. In this study, these types of components are classified as "equipment components." Although the positions of equipment components do not usually need to be attached above a certain structural component, as this study was based on the principle of consistency, it was essential that the equipment components were attached below a certain structural component based on the model group configuration rules of this system.

According to the abovementioned configuration rules of constructing components for the BIM model in this study, the structural components are classified as "primary members," and the components being attached to the inner and outer parts of these structural components, including architectural, hidden, and equipment components, are classified as "affiliated members." In the design of the system in this study, the primary member is assigned as Parent, and the affiliated member is assigned as its Child. Parent and Child have a relationship of dependency, so that the relative position in between is fixed. When the Parents, such as the beam, column, wall, and slab in the system, are subjected to view operations, such as zooming in and out and shifting or rotating, the Child depending on the Parent will have a corresponding action, so that the relative position in between remains unchanged. Accordingly, Table 1 shows the framework for the types and properties of BIM components of this system.

Table 1. Types and properties of BIM components

Level	Component type	Component instances	Component properties
primary member(Parent)	structural element	wall, column, Beam, slab	object ID, object type, position, length, width, height, volume, steel specification, the amount of steel, concrete strength, concrete volume, material suppliers, etc.
affiliated member(Child)	architectural element	door, window, lighting device, etc.	object ID, object type, length, width, area, material, supplier, etc.
	hidden element	pipe, reinforced steel	
	equipment	air conditioner, drinking fountain, fire equipment	object ID, object type, maintenance personnel, last maintenance date, maintenance company, manufacturer, maintenance record, etc.

3.2 Database schema for BIM storage

In this study, the BIM data sources were obtained from an established database of Apache Hbase. Apache HBase is a NoSQL database system. The storage method provided can be regarded as an infinite table, which consists of the rows, column families, and columns in a hierarchy, in that the information can be stored in a logical and organized way. Based on the storage framework of Hbase, this study stores the BIM component data in a table, named "BIMs." The name indicates that the table can store multiple BIM projects, whereby different BIM projects are distinguished by different rows. On implementation, this study established a BIM project named "E2-4F." The column family under E2-4F is formed by a set of Parents and Children possessing interdependent relationships. The first column of each column family stores the primary members, including the structural components of the beam, column, wall, and slab. The column positioned after the primary member stores the affiliated members that are attached under the primary members, including the architectural, hidden, and equipment components, as shown in Fig. 3, where each column family is composed of a Parent and zero to many Children. Under this framework, the property information of each BIM component is in a string format that is set to the value of the column, as shown in Fig. 4.

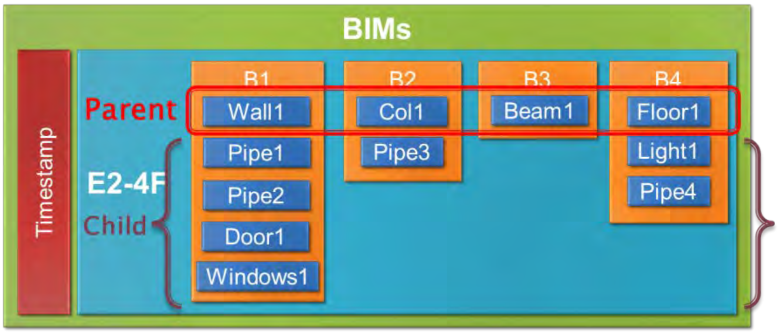


Fig. 3: Conceptual schema of the table of BIM components.

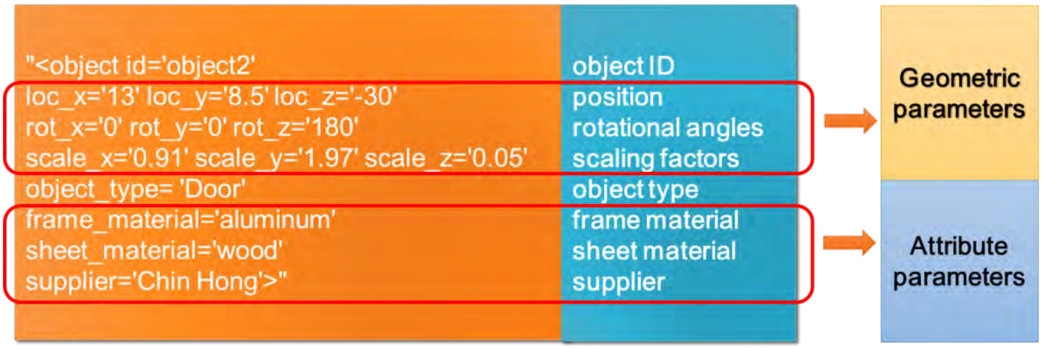


Fig. 4: String format for storing properties of BIM components.

3.3 BIM component lookup mechanism

This system contains two tables in the storage of the BIM database. One table, which stores the properties of BIM components, is called BIM Table, and the other, which stores BIM components and the corresponding room and marker, is called the Reference table. Row in the Reference table adopts the project name of the BIM for classification (e.g., E2-4F). The interior of row is composed of each room within the BIM as the column family (e.g., 417, 415); the column family is composed of a number of AR Marker codes, as stored in column (e.g., A, B). column internally records a set of BIM components that have interdependent relationships in the BIMs data table and correspond to the room and Marker (e.g., B1, B2).

When the system is first initiated, it downloads the Reference table and locates the current position using the indoor positioning system by looking up the Reference table for all the corresponding BIM components in this position and downloading them into the system. Finally, the marker identification is captured by a video device via AR technology to present the corresponding BIM component. This mechanism is shown in Fig. 5. Within the Family Column of the Reference table, we look at 417 with column A, which has a Value of B1. This represents that the marker encoded as A in room 417 corresponds to the BIM component encoded as B1. B1 corresponds to a Column Family in the BIMs table, which stores the co-related BIM components as the columns of the B1 family. Loading the values of the columns of B1 lets us obtain the properties of these co-related components. Throughout this lookup mechanism, data replication of BIM components can be avoided by having Family in the BIM database as the primary key for query. One BIM component is only stored once, which is in line with the principles of BIM.

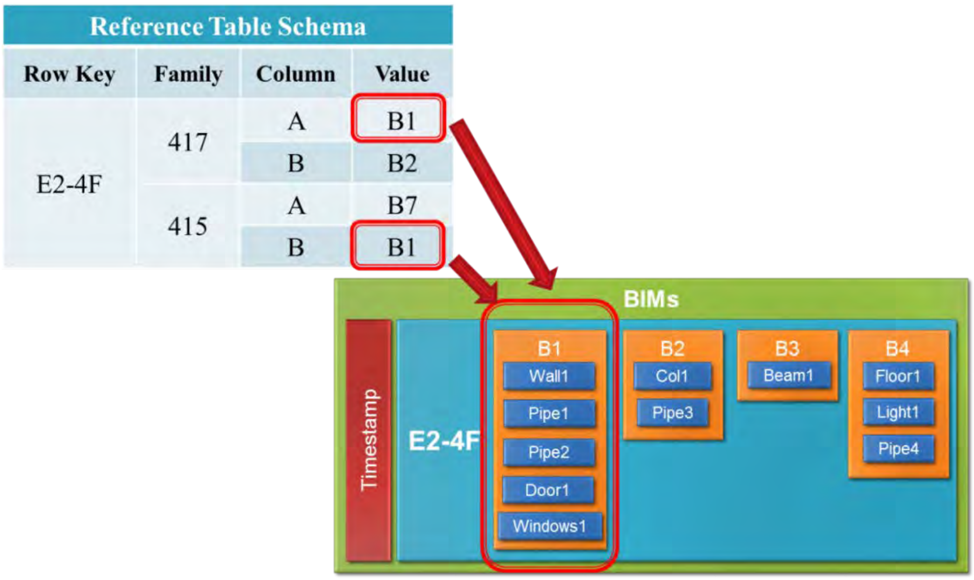


Fig. 5: BIM component lookup mechanism.

3.4 Wi-Fi-based indoor positioning

The indoor positioning technology of this integrated system is a Wi-Fi positioning technology, which adopts the triangulation method. Hence, prior to operation, the indoor construction and maintenance staff on-site need to configure all available WAPs to carry out Wi-Fi positioning for the system. Each separation distance should be within 6~9 meters. The system integrates two sets of Wi-Fi positioning software, AeroScout MobileView and AeroScout System Manager.

3.5 BIM component information retrieval

When the system detects the changes in the room where the user is based using indoor positioning, it will establish a connection with Hbase through the function of Thrift, and implement the abovementioned BIM component lookup mechanism based on the property strings of all BIM components for this room inside the BIMs table. After obtaining the property strings of all BIM components within the room, the system further conducts segmentation and analysis for the strings, and the analyzed property data is stored into a property array. Then, based on the property data inside this property array, the setting of the model's geometric appearance is conducted and stored into the array of the model component.

Fig. 6 shows the parsing process of the property string. First, the system cuts the data content of each BIM component property string according to different parameters, the value of each parameter is listed as a long array, and the conversion of data type is conducted in accordance with the type of each parameter. Since the parameter values after the completion of cutting are all in a pattern of strings, the system needs to convert the parameter values that are real values into floating-point numbers to carry out the subsequent setting of the model's geometric appearance. For the property data that are converted completely, the system stores the data in a corresponding AttributeList, which is a 3D array, the first index is the ID of different Marker, the second index is the ID of a set of components having an interdependent relationship (0 is the primary component; 1~n is the affiliated component), and the third index is the ID of each type of property parameter after storage and analysis are complete. After the setup of the BIM components is complete, the system conducts the setting of the model's geometric appearance based on the stored BIM data and stores the model into the ElementList, whose indices are the same as the first two indices of AttributeList.

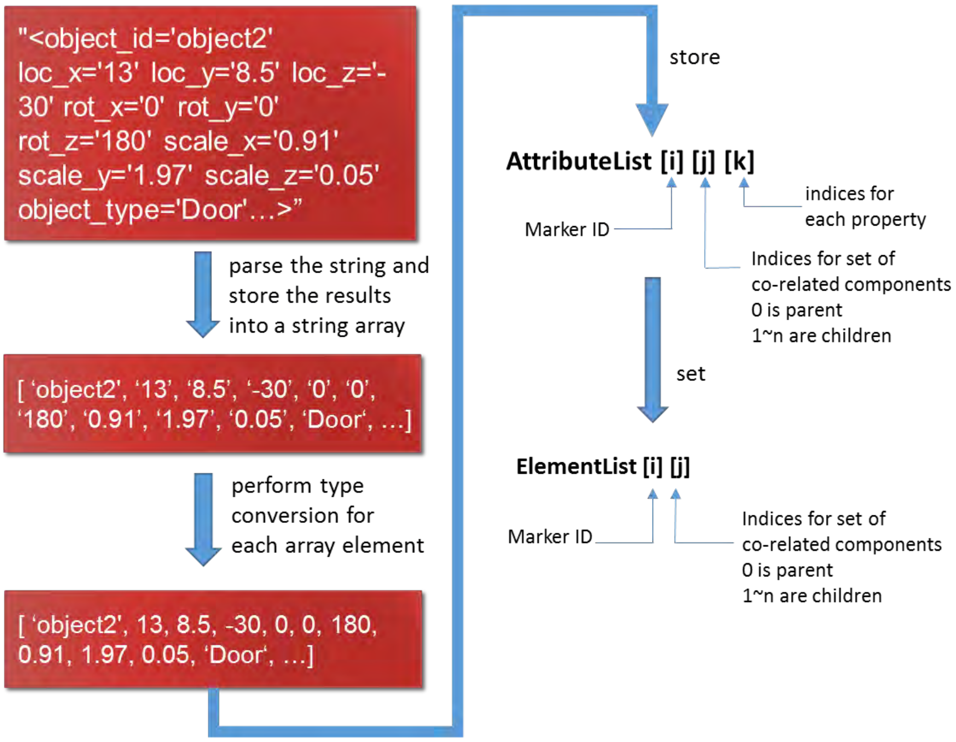


Fig. 6: Information retrieval for a set of BIM components in the same room.

3.6 BIM component display mechanism

In this study, ARToolKit was the AR system used for integration. BIM components and properties need to be presented on the marker. Every 0.1 seconds, the system updates the display image based on the image captured by the lens. First, the system identifies whether this image contains a Marker. If a Marker is identified in the image, it will access the property value of a set of BIM components corresponding to this Marker in the AttributeList with the Marker ID and grab the corresponding affiliated files in accordance with the requirement of the different components (e.g., maintenance manuals, maintenance records, inspection certificate). If a Marker is not identified in the image, it will shut down the contents of the virtual display. Users can operate the virtual display contents in the image using the buttons on the keyboard, mouse, or screen. When the user triggers these events, the system updates the image based on the user's operation. When the system identifies the Marker arranged inside the room in the photographic frame, by default, the image brings out a set of Parent and Children with interdependent relationships. The lower right corner displays the room position currently located. Subsequently, based on the user's switching and operation in the image, the 3D model, property text, or affiliated files of the selected components are presented through virtual reality superimposition.

3.7 BIM component model manipulation

Virtual BIM information presented in this system includes 3D models, property texts, and affiliated files. To present these three types of BIM information, the system provides five kinds of operations for information view, including switching on and off of each type of data, component switching, model independent display, 3D model view operation, and model transparency adjustment.

4. APPLICATION SCENARIOS

Based on the developed prototype system, this study proposes four types of application modes of virtual reality integration presentations to meet the practical needs of the system: (1) the presentation mode for the 3D model of a to-be-built object; (2) the matching mode for the position and quantity of components; (3) the presentation mode for information related to components; and (4) the presentation mode for the hidden objects. These four modes are respectively suitable for use in the four stages of the project life cycle: construction, acceptance check, operational maintenance, and interior decoration. Nevertheless, each mode can also be adjusted according to the operation requirement and applied in different stages, rather than having only one mode support each stage of operation. Moreover, these four modes have different emphases; for example, the second and fourth modes emphasize that the model needs to be aligned with the on-site primary member. As these two modes match and search the component position, the relationship between the relative position and size of the component is more important. However, the first mode emphasizes the functions of model view operations, such as zooming in/out, and shifting and rotating. As its purpose is to give the user the operation item in the current project being assembled, such as assembling a structural rebar, a virtual 3D model can be provided as reference and all the details of the model can be observed by operating the functions of model, such as showing the hooked form of the rebar. The third mode emphasizes the presentation of information and mainly focuses on the feedback of the property parameters and related affiliated file information, thus allowing the on-site maintenance officer to make instant judgments and decisions.

4.1 Presentation mode for 3D model of to-be-built object

The first mode presents the 3D model of the object that does not exist or is to be built in the environment. The list below describes the scenario in which the system is applied to the construction stage. In the scene, a virtual 3D model is presented as a reference for rebar assembly work.

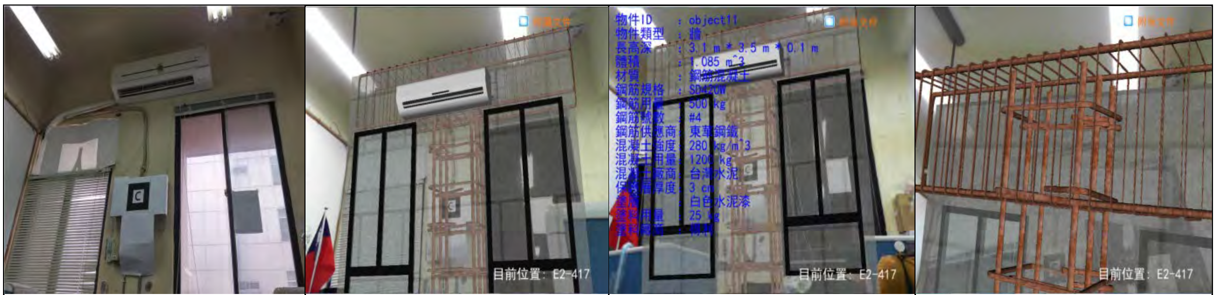
1. First, the user assembles the equipment for the system of this study into the project scenes that are under construction. As the on-site project is still in the construction phase, parts of the structural components may not yet be assembled into the group, or the assembly is in progress.

2. At the site of the project, as the corresponding primary member has not yet been completely assembled, it is possible to arrange the Marker using a signboard at the worksite in a position that is convenient to view, as shown in Fig. 7(a). Since this mode does not emphasize that the component position needs to be superimposed onto the on-site component, but stresses on the operations for the component model view function, the Marker is not necessarily attached to an actual member.

3. After finding the Marker that is laid out, the worker aligns his/her sightline with the Marker, and by default, the system presents a set of 3D models that have a relationship of dependency that has been well-established during the design phase, as shown in Fig. 7(b).

4. Before working on the project item, the worker can open the property text of a component to confirm whether the property parameters fit with the on-site status to understand the possible arising problems in advance, as shown in Fig. 7(c). For example, if the amount of rebar used in the project design is 500kg, but only 200kg is allocated at the site, rebar shortage problems could occur if work is started immediately.

5. This case study is designated as a reference to demonstrate the rebar assembly; therefore, during the work process, the worker can make adjustments to the 3D model image by using the zooming, shifting, and rotating functions of the model's views to understand the details of assembly between each part member. As shown in Fig. 7(d), the model is focused on the part of beam-column joints of the rebar, and it is placed next to the real work item to use as a reference during the work.



(a)	(b)	(c)	(d)

Fig. 7: Application process of the presentation mode for the 3D model of to-be-built objects.

4.2 Matching mode for the position and quantity of components

The second mode views whether the design that has been finalized during the planning and design phase is correctly constructed and completed on-site based on the method of superimposing the presentation of a virtual object on the actual object. The list below describes a scenario in which the system is applied at the acceptance check stage. Using the method of virtual reality superimposition to assist and confirm the operations for the position and quantity of a component, the procedure of its application is as follows:

1. When the project enters the acceptance check stage, it means that the parts of the work item operations have been completed. When the inspection personnel enter the building, it is possible that the construction of not only the structural components, but also the architectural components, such as the existing doors and windows, have been completed.

2. As this mode is designated to conduct the matching of position and quantity, all AR Markers are put up on the primary member, and the inspector can directly enter the scene to find the objects attached to the primary member for checking, as illustrated by the wall in Fig.8(a) and the ceiling in Fig. 8(b).

3. After the sightline is aligned to the Marker on the primary member, the system automatically brings up the 3D model of the primary member. At this point, it is necessary to operate the 3D model through the model view function to superimpose the primary member on the on-site scene, since the Marker may not be completely affixed at the center due to posting factors or errors generated by the depth relationship. After the virtual and physical primary members are completely superimposed, due to the relationship of component succession, the relative position of the affiliated members attached to it will not be offset when the model is being adjusted, as shown in Fig. 8(c) and 8(d).

4. After the model of the primary member is completely superimposed, the inspector can confirm whether the components installed at the on-site project are offset; for example, any errors on the opening size of doors and windows or errors on the installation position can be identified with the BIM model of design.

5. In addition to the matching of position and size, the inspector can check whether there are shortages in the quantity of components, such as fire extinguishers, lamps, and smoke detectors, based on the affiliated members presented by the model.

(a)	(b)	(c)	(d)

Fig. 8: Application process for the matching mode on the position and quantity of components.

4.3 Presentation mode for information related to the components

The third mode presents the information related to adjacent physical objects using the method of virtual reality superimposition. The content of the main presentation is not only the property parameters of components but also the various affiliated files according to the type or usage requirements of the components. The following list describes a scenario in which the system is applied to the operational maintenance stage. Based on the identification of Marker, the system can automatically provide users maintaining the component with the information needed to assist with the job.

1. When a project enters the facility maintenance stage, all the primary and affiliated members of the building construction have been completed, and the equipment maintenance team enter the room where the components are to be serviced by the maintenance operations.

2. When the user has found the primary member to which the to-be-maintained component is attached, the user will move his/her sightline to the Marker of this primary member, as shown in Fig. 9(a).

3. After the system presents the model of the primary member with the method of virtual reality superimposition, the user can use the function of component switching to change to the component to be serviced. Assuming that the maintenance staff wants to conduct routine maintenance operations, he/she can open the property text to view the property information related to its maintenance. Additionally, he/she can bring up the maintenance operation manual for equipment by viewing the affiliated files in this system to aid the maintenance operations, as shown in Fig. 9(b) and Fig. 9(c).

4. While maintaining the component, if it has been confirmed that the approximate location and quantity of models are correct, the user can turn off the models or open only the model of the component that is being serviced to reduce visual interference. Part of the property text can also be turned off as needed, as shown in Fig. 9(d).

5. For the types of affiliated files, not only are equipment maintenance operation manuals presented during the routine maintenance, but the user can also access different files as needed, such as historical maintenance records, quality inspection reports, or other reports.

(a) (b) (c) (d)

Fig. 9: Application process for the presentation mode of information related to the component.

4.4 Presentation mode for hidden components

The fourth mode presents the hidden components internally concealed by the main structural component with the method of virtual reality superimposition, such as pipelines and rebar. The list below describes a scenario in which the system is applied to the use stage to perform operations such as interior decoration or repairs. When it is necessary to find out the location of these hidden components, either to drill holes in the installation object or conduct repairs, the system can directly present the internal hidden components on the physical member to assist such operations:

1. The user enters the indoor environment and finds the primary member to be renovated, such as a wall (Fig. 10(a)).

2. Assuming that the user wants to install an air-conditioner on the beam above the wall, but it is impossible to know in advance whether the position of the fixed machine-drilled holes will interfere with hidden component (such as pipelines or rebar), the user can first make a mark on the position to be drilled.

3. After the user aligns the sightline on the Marker of the primary member, the system automatically brings up the 3D model of this primary member. After the 3D model is superimposed with the real primary member on-site by operating the 3D model through the model view function, the positions of the hidden components are presented in the 3D model inside the real primary member, as shown in Fig. 10(b).

4. The user can then compare whether the marker of the drilled-hole position conflicts with the hidden components. Alternatively, if a hidden component, such as a leaking pipe, needs to be repaired, the user can identify its location and mark the site accordingly.

(a) (b)

Fig. 10: Application process for presenting hidden objects.

5. CONCLUSIONS

This study proposed an on-site BIM viewer by integrating AR and indoor positioning technologies. The purpose is to develop a system that uses indoor positioning technology to locate the current indoor position of an on-site user, and download BIM-related information from the database. Finally, a 3D model of BIM components and the corresponding properties are superimposed on the building elements via augmented technology, providing immediate feedback to the user. This system provides the following benefits: (1) Immediacy: The system can instantly locate the user’s current location and provide immediate feedback to the user. (2) Synchronization: The models of the BIM components look as if they really exist on the site, achieving synchronization with the user. (3) Convenience: This approach is more convenient for on-site viewing of BIMs. The information, stored in a cloud-based database, is able to simultaneously support multiple users, which greatly improves the efficiency of on-site construction or maintenance staffs. Application scenarios indicate that the proposed on-site BIM viewer by integrating AR and indoor positioning technologies can improve the existing view model of BIM to obtain information efficiently, and effectively reduce the required operations. Moreover, the immediate feedback of BIM components provided to users for viewing, as well as superimposing it on the actual scene in a single synchronized screen, should be able to support the on-site operations of construction and maintenance.

6. REFERENCES

Bae, H.J., Golparvar-Fard, M. and White, J. (2012). Enhanced HD4AR (hybrid 4-dimensional augmented reality) for ubiquitous context-aware AEC/FM Applications, In T *Proceedings of the 12th International Conference on Construction Applications of Virtual Reality*, Taipei, Taiwan,.

Behzadan, A.H. and Kamat, V.R. (2011). Integrated Information Modeling and Visual Simulation of Engineering Operations using Dynamic Augmented Reality Scene Graphs, *Journal of Information Technology in Construction (ITcon)*, Vol. 16, 259-278.

Park, C.-S., Lee, D.-Y., Kwon, O.-S. and Wang, X. (2013). A framework for proactive construction defect management using BIM, augmented reality and ontology-based data collection Template, *Automation in Construction*, Vol. 33, 61-71.

Shin, D.H. and Dunston, P.S. (2008). Identification of application areas for Augmented Reality in industrial construction based on technology suitability, *Automation in Construction*, Vol. 17, No. 7, 882–894.

A CONCEPTUAL WORKFLOW FOR BIM BASED PREFABRICATION DESIGN VISUALIZATION WITH AUGMENTED REALITY

Shu Tang, Llewellyn Tang*, Zhuoqian Wu, Weiqing Zheng, Chao Chen

Department of Architecture and Built Environment, University of Nottingham, Ningbo,315100, China

ABSTRACT: *In recent decades, the architecture, engineering and construction (AEC) industry have been embracing prefabricated projects. Prefabrication shortened construction timeline, increased construction efficiency as well as reduced energy consumption. These superiority saved cost, promoted competitiveness and reputation for enterprises within the AEC industry. As building information modeling (BIM) drastically spread over the AEC industry, designers enjoyed the convenience of BIM application to improve the design quality and prefabricated rate of projects. However, the constructability of prefabricated projects is limited due to the gap between design drawings and fabrication drawings. As manufacturers usually involves in late design stage, there is lack of communication between manufacturers and designers. This situation may result in unreasonable design or unable to produce prefabricated components. Moreover, conceptual design of irregular architecture is becoming popular, the curved surfaces on the irregular buildings expand the difficulty to design and produce prefabricated components. Although with the aid of detailed 2D drawings manufacturers are able to fabricate components with high accuracy, the in-factory tested components could not able to guarantee inerrancy assembly process. In addressing these limitations, this paper proposes a conceptual workflow include several applications that integrate BIM and augmented reality (AR) so as to enable visualization of prefabrication design optimization* ***and installation.*** *To be effective, assembly modeling of project models as well as prefabricated component models is fundamental step. It is suggested that, the workflow requires a throughout involvement of AR in conjunction with labeling, tracking and sensing technologies. This visualized design workflow could eliminate the gap between project design and prefabrication design, facilitate communication and information exchange between manufacturers and designers, overcome the barrier of design prefabrication components for complex shaped buildings, and ensure an exactness installation.*

KEYWORDS: *Building Information Modeling, Augmented Reality, Prefabrication, Design Visualization*

1. Introduction

Old-fashion construction modes have been criticized for low productivity, poor quality, wasteful resource and energy consumption, unreliable safety issue and gigantic environment pollution (Zhang et al., 2016). With the development of innovative technology, fast economic growth has encouraged the development of high quality and sustainable constructions which adopted prefabrication or modularization design. Although with the infusion of new operation and strategic method, the new design construction workflow has been blended with conventional ways, so that the gaps between project design and prefabrication design is significant. Moreover, with traditional 2D design drawings and information sheets, it is a challenge to convert massive information into 3D components with reliable accuracy. Furthermore, on-site constructability is another concern for complex project prefabricated component installation. The integration of building information modeling and augmented reality into the design process can ease the way to expedite the development of prefabrication or modularization.

2. Building Information Modeling and Prefabrication Design

2.1 Building Information Modeling

Building information modeling (BIM) is a set of interacting policies, processes and technologies that generates "a methodology to manage the essential building design and project data in digital format throughout the building's life cycle" (Penttilä, 2006). Building Information Modelling, also called smart construction, is earliest proposed by Chuck Eastman professor in Georgia Institute of Technology in 1976. It is also defined by National Institute of Building Sciences (NIBS) that Building Information Modeling (BIM) is a digital representation of physical and functional characteristics of a facility. A BIM is a shared knowledge resource for information about a facility forming a reliable basis for decisions during its life-cycle; defined as existing from earliest conception to demolition. BIM is also the model which supports and reflects the collaborative work through importing, extracting, updating and amending relevant information at different stages. Usually BIM starts with a 3D model which contains attribute information and relationships of objects, with the addition of time element and cost element into the object attribute information database, more dimensions are added to the model. Furthermore, there is a distinct shift to expand BIM into an "N"D environment where simulation, calculation, analysis and other functions are enabled at different project stages. For example, these functions include scheduling, costing, accessibility, safety, logistic, sustainability, energy simulation (Wang et al., 2013).

2.2 Prefabrication Design

Prefabrication design, also named modular construction design, is a new way to design facilities which are formed with many prefabricated units. These units are prefabricated in factories before deliver to construction site. The prefabricated units are transported to the site and assembled into a building as a whole. Compared with the traditional buildings, modular constructions show advantages in construction period reduction, excellent quality, manpower and material force savings.

According to the percentage of prefabricated components in a building, there are three type of prefabricated units namely pole unit, plate unit and module unit. Corresponding to the prefabricated units' types, prefabricated building structure system can be divided into direct assembly structural system, prefabricated structural system and modular building structural system. For direct assembly structural system, prefabricated members are cut based on design size as well as the openings on members are accomplished in factories. The prefabricated members are transported to the site, before connected by bolts or self-tapping screws. In this way, the advantages are that the prefabricated members can be modified on-site so that the requirement for logistic container is lowered, and more cost effective for complex construction. Contradictorily, the disadvantage is the relatively large amount of field work. In terms of prefabricated structural system, structure skeleton like wall panels, roof and roof panels are preformed with special mould in factories and transported to construction site for assembly. The advantages of this system are the expedition of construction progress as well as the robust quality. Although prefabricated structural system reveals high automation and low labor workload, the transportation cost and requirement for on-site equipment are high. Unlike other prefabricated building structure systems, modular building structural system produce single rooms as a module in the factory. These decorated rooms then transported to the site before lifting and connecting with main building. Modular construction system with high proportion of prefabricated components, so that material resources, manpower and time can be saved.

2.3 BIM enabled Prefabrication Design

BIM enabled prefabrication design is based on the modularization of building components (Zhang et al., 2016). Designers model prefabricated units such as wall panels, windows and beams as the first step. Depends on the module level, these prefabricated units can be assembled into room-level modules like kitchen and bathroom modules. As shown in Fig 2.3.1, the top hierarchy are unit layouts which consist of room-level modules that can be picked to design floor plans.

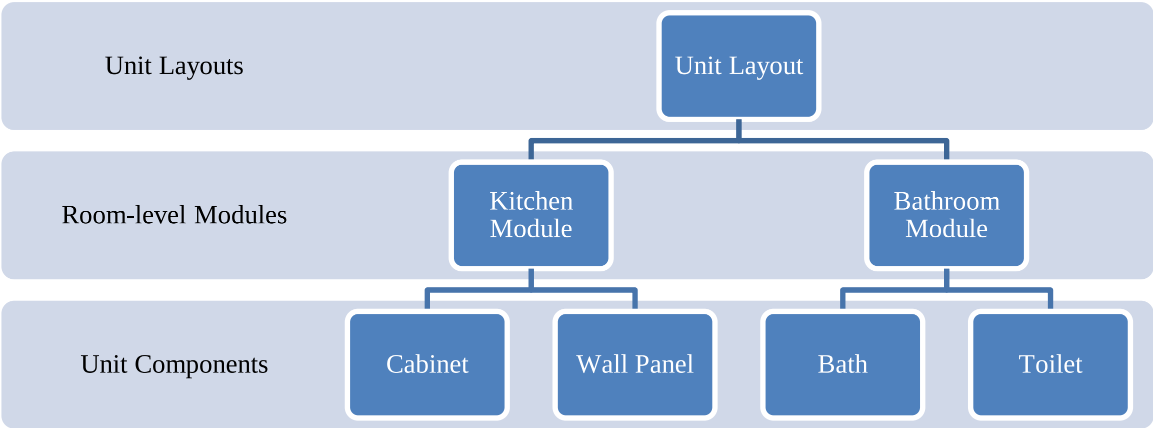


Fig 2.3.1 Modularization Hierarchy of Prefabrication Design

It is suggested that there are three procedures for the design process. Architectures confirm the floor plan by customizing dimensions of unit layout from their Unit Layout Library (ULL). Followed by structural engineers, a structure model can be created by modules from Structural Module Library (SML) before processing simulation and analysis. Meanwhile, MEP engineers can accomplish the building service systems by assemble units from MEP modules library.

3. Augmented Reality

3.1 Definition of Augmented Reality

Augmented reality (AR) is a technology that creates environment where computer-generated information is superimposed onto the user’s view of a real-world scene (Chi et al., 2013). The foundation of augmented reality is a real environment like an object or a space which incorporated with imaginary or contextual data based on the purpose of data application. Augmented reality has been widely adapted to various fields like medical imaging which enables doctors to superimpose imaging data from MRI onto a patient’s body or discover the exact location for surgeons; teaching, in which technology provides students or trainees with experience in real environment as well as important data about specific subject; tourism to a place where historical information is tagged to artifacts or constructions; games with assist of augmented reality provide players with excitement to explore in the reality. To sum up, augmented reality add audio commentary, location data, historical context, or other forms of content that can make a user’s experience in a real environment more meaningful based on their purpose.

3.2 Difference of Virtual reality and Augmented Reality Application in Architecture, Engineering and Construction Industry

As technology improve living condition, VR and AR technologist are becoming more popular in Architecture, Engineering and Construction (AEC) industry. The difference between augmented reality and virtual reality is that the objective of augmented reality adds information and meaning to a real object or an environment rather than producing a simulation of reality. To make a vivid understanding of difference between VR and AR application in AEC industry, this section provides several cases for explanation.

Fig. 3.2.1 Augmented Reality Application in AEC Industry Case (Autodesk, 2013)

It is suggested by Meža et al. in 2014, application of augmented reality in AEC industry can enable stakeholders to connect an array of complex information in the context of real environment. As shown in Fig. 3.2.1, augmented reality connects computer generated model with as built building both geometrically and visually. In that way, user would be able to pinpoint and visualize hidden pipelines and equipment beneath the physic surface.

Fig. 3.2.2 Virtual Reality application in AEC industry case (Graphisoft, 2013)

Virtual reality application in AEC has enjoyed a high popularity with BIM trend. As shown in Fig. 3.2.2, it is an example of BIMx virtual reality mode to display building information model. As stated by (Meža et al., 2014), the virtual reality display mode is similar with augmented reality display at first glance, but there is no connection between digital model with real surroundings. The approach is totally different, augmented reality requires camera to superimpose IT environment on to real buildings while virtual reality can roaming under all situation.

3.3 Augmented Reality and BIM

Currently, connecting building information modeling with augmented reality is usually implemented in two ways namely " BIM augmented reality" and "augmented reality enhanced building information modeler" respectively (Meža et al., 2014). BIM data is applied in an augmented reality in the first way which can be explained with the same example case in section 3.2, Fig 3.2.1. In the second way, modelers can edit building models in an augmented reality environment where sensors are applied to detect human behaviors. According to (Shin and Dunston, 2008), BIM and AR can applied to many procedures within the AEC industry. For instance, work tasks like coordination, conceptual design, excavation, positioning, defect inspection, conveying, commenting can all be BIM-AR assisted.

Recently, there has been a significant increase in AR application development due to the advancement of computational software and hardware. As architecture, engineering and construction industry focus is becoming more informatics and digitized, there has been a dramatic demand in digital information exchange efficiency approach development. As a result, the current trend in AR studies and approaches is to produce AR applications that can benefit the industrial field (Chi et al., 2013).

4. Integration of BIM and AR for Prefabrication Design and Installation

Fig 4.1 Conceptual Workflow for Prefabrication Design and Construction Process

4.1 Integrate Project and Manufacture Design Visualization

Usually, project design requires collaboration working, coordination meeting and understanding among all teams which involve multidisciplinary members with distinct level of project information maturity and handling ability. It is argued that construction industry has been experienced a low strategic and operational level of efficiency, poor profit margins, so that it is urged to infuse high technology and innovative utilization into the construction industry (Starzyk and Leon, 2013) .

There has been a high popularity in adopting prefabrication and modularization design in different types of facility like buildings, infrastructure and special projects, so that prefabrication and modularization design is playing a key role in the whole process of project lifecycle. As stated by (McGraw-Hill-Construction, 2011), there was 27% of prefabrication in building superstructure while the percentage of prefabrication in mechanical, electrical and public health system was 21%. Since prefabrication design has brought advantage in increase project productivity and reduce project schedule and cost, it is becoming dramatically popular in recent years.

In order to guarantee the success at the installation and construction stage, prefabrication design team need to participate during the design development process with project design team. It is suggested that, augmented reality for prefabrication design is an effective communication tool for collaborative design and information delivery (Behzadan et al., 2015). The reason can be concluded that "BIM and AR can provide a full 3D interactive solid model of the design, providing subcontractors with visual understanding of details"(Wang et al., 2013). For instance, an on-site design review process usually requires subcontractors to define a building into 3D components such as prefabricated slab, beams as well as MEP system components. With AR technology, a "walk-through" in the design models for subcontractors can be realized in order to undertake the prefabrication design process. It is also possible that subcontractors are able to 'zoom in and out' or 'rotate' the model to identify design quality, constructability issues and workflow.

4.2 Prefabrication component delivery flow tracking and management

Typically, the timeline is parallel between project construction and prefabrication component manufacture. When it comes to project component delivery, project schedule, safety and cost is directly impacted by the punctuality of project component delivery logistic. Any delay or early arrival of prefabricated components would arise costly construction delay or site storage issue. With assist of augmented reality, subcontractors are able to coordinate transportation between construction site and factories, so as to monitor on-site activity and manufacture plant progress (Starzyk and Leon, 2013) .

In Enterprise Resource Planning (ERP) system, project planning, procurement, manufacturing and delivery are executed through online procurement, management, and tracking system. By integrate BIM with ERP system, a unique barcode or radio frequency identification can be tagged and tracking on each prefabrication component, hence formed a mapping between ERP and components tags. AR is then applied to visualize the mapping system on site. With the unique ID tag, each prefabricated component status can be tracked and updated to ERP system, meanwhile visualization of these status on BIM models can be achieved by AR technology. Site managers can allocate work tasks by dynamic information from BIM and AR system (Wang et al., 2013).

4.3 On-site design collision control

Although the 3D clash detection and 4D construction simulation may avoid design collisions, on site real time dynamic collision still exists due to various reasons like poor installation, errors and modification of schedule. The crucial issue turn out to be the identification of dynamic collision and guarantee a fluent workflow. It is suggested that, “using AR, a site manager can address the potential for conflicts on site by retrieving and visualizing all the properties and details concerning the building elements from BIM”(Wang et al., 2013).

4.4 Installation Assist (On-site Assembly)

With assist of augmented reality during design stage, designers can assess complex components so as to develop an efficient assembly plan. In this way, designers, engineers and subcontractors can review assembly workflow before construction start, potential issues could be eliminated on the early stage, hence shortened the whole project time span.

During the installation process, workers conduct not only physical operations, but also mental comprehension on 2D design drawings. Usually, the 2D drawings are complex and information redundant for a specific task, as a result leveled up the easiness to understand assemble instruction (Wang et al., 2014). Apart from the information redundancy on 2D drawings, the paper based communication does not provide sufficient understand between designers and assemblers, hence hinders installation accuracy and project schedule (Starzyk and Leon, 2013) . In order to impede the problems stated above, AR can be applied as a resultful method. Firstly, actual construction site can be blended with digital information like models and assemble instruction. It arises an illusion that prefabricated components are exist, so that installation team can discuss and review future work of uninstalled components based on 3D visualization and completed work in reality. For example, underground construction without visualization of exist pipeline beneath the ground surface, the integration between augmented reality and BIM can support the visualization of pipeline during site excavation stage. Furthermore, augmented reality with BIM can create an installation schema demonstration (Wang et al., 2013). As shown in Fig 4.4.1 structure, architecture and MEP models can be shown through AR in to a real environment. Specialists can edit the sequence of model display, thus create a demonstration of step-by-step installation instruction.

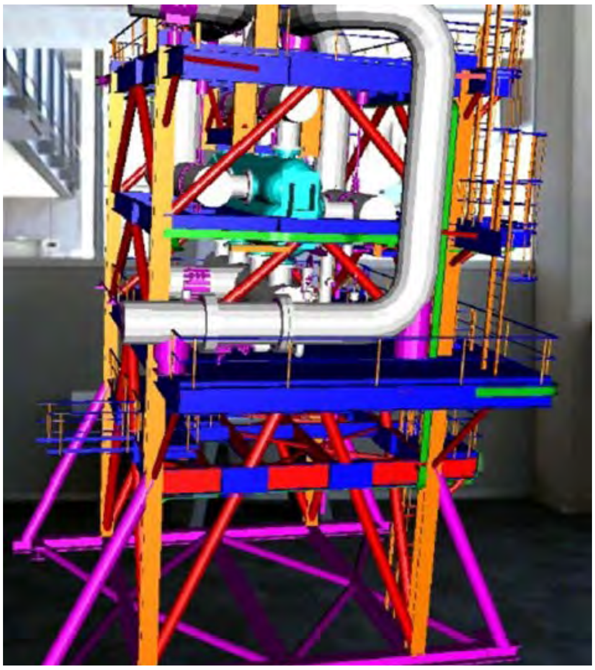


Fig. 4.4.1 AR visualization of models in real environment (Wang et al., 2014)

5. Conclusion

Building information modeling has surged into the construction industry, not only in the aspect of technology adoption, but also in the strategic management throughout projects' lifecycle. With the assist of information exchange and data integration of BIM, the AEC industry shows a great potential to improve the performance of prefabrication and modularization. However, the performance of BIM for on-site application can be seen as a foible. The newly emerged technology augmented reality can be a remedy for current short-coming of BIM on-site use in construction (Wang et al., 2013). In addressing the integration of BIM and AR into prefabrication and modularization, a conceptual workflow including several applications of BIM-AR integration is proposed in this paper. The workflow including BIM-AR aided design visualization, prefabrication component delivery management, on site collision control and installation assist can be an effective solution to unblock the barriers on the way to adopt prefabrication and modularization. The implementation of BIM-AR aided prefabrication and modularization in the near future, will unearth more benefits of the construction industry, such as innovative design, accurate manufactured construction product, cost and time saving, safer working site, reliable construction quality and more environmental friendly.

Acknowledgement

There work presented in this paper was undertaken under the aegis of the BIM-GIS Application in Green Built Environment Project, funded by Ningbo Science and Technology Bureau (2015B11011).

6. REFERENCES

AUTODESK. 2013. BIM for Infrastructure: A Vehicle for Business Transformation. Available: http://usa.autodesk.com/building-information-modeling/about-bim/ [Accessed 01Jun2016].

BEHZADAN, A. H., DONG, S. & KAMAT, V. R. 2015. Augmented reality visualization: A review of civil infrastructure system applications. *Advanced Engineering Informatics,* 29**,** 252-267.

CHI, H.-L., KANG, S.-C. & WANG, X. 2013. Research trends and opportunities of augmented reality applications in architecture, engineering, and construction. *Automation in Construction,* 33**,** 116-122.

GRAPHISOFT. 2013. Available: http://www.graphisoft.com/openbim/bim/ [Accessed 01Jun2016].

MCGRAW-HILL-CONSTRUCTION. 2011. Smart Market Report : Prefabrication and Modularization. Increasing Productivity in the Construction Industry. Available: http://www.nist.gov/el/economics/upload/Prefabrication-Modularization-in-the-Construction-Industry-SMR-2011R.pdf [Accessed 01Jun2016].

MEŽA, S., TURK, Ž. & DOLENC, M. 2014. Component based engineering of a mobile BIM-based augmented reality system. *Automation in Construction,* 42**,** 1-12.

PENTTILÄ, H. 2006. Describing the changes in architectural information technology to design complexity and free form expression. *Journal of Information Technology in Construction,* 11.

SHIN, D. H. & DUNSTON, P. S. 2008. Identification of application areas for Augmented Reality in industrial construction based on technology suitability. *Automation in Construction,* 17**,** 882-894.

STARZYK, I. & LEON, N. 2013. Improving delivery of building services systems by implementing Augmented and Virtual Reality technologies. Working Paper 5. Available: https://workspace.imperial.ac.uk/lorsystemscentre/Public/Working%20Paper%205%20Improving%20delivery%20of%20building%20services%20systems%20by%20implementing%20Augmented%20and%20Virtual%20Reality%20technologies.pdf [Accessed 01Jun2016].

WANG, X., LOVE, P. E. D., KIM, M. J., PARK, C.-S., SING, C.-P. & HOU, L. 2013. A conceptual framework for integrating building information modeling with augmented reality. *Automation in Construction,* 34**,** 37-44.

WANG, X., TRUIJENS, M., HOU, L., WANG, Y. & ZHOU, Y. 2014. Integrating Augmented Reality with Building Infoation Modeling: Onsite construction process controlling for liquefied natural gas industry. *Automation in Construction,* 40**,** 96-105.

ZHANG, J., LONG, Y., LV, S. & XIANG, Y. 2016. BIM-enabled Modular and Industrialized Construction in China. *Procedia Engineering,* 145**,** 1456-1461.

IDENTIFYING CONSTRUCTION RISK SOURCES BY VIRTUAL ENVIRONMENTS

Cem Sebzeci, Semra Comu & Isik Ates Kiral

Bogazici University, Istanbul, Turkey

ABSTRACT: *Workplace accident and fatality statistics show that the construction industry is one of the most hazardous industries in many countries around the world. The dynamic nature of the construction industry like changing work settings, using heavy machinery necessitates an appropriate safety management system. In order to set up an efficient safety management system, possible risk sources must be identified as an initial step. Today many construction companies still use traditional methods for risk identification. Yet, these methods do not sufficiently identify all the risk sources, especially project specific ones. Given the fact that unidentified risk sources are one of the leading reasons of accidents on construction sites, a more advanced risk identification method should be in effect. Accordingly, highly engaging virtual tools can be utilized to identify the risk source which leads to improve effective safety management. In this study, we used a virtual environment based safety training tool called V-SAFE (Virtual Safety Analysis For Engineering applications) which simulates and visualizes a tower crane operation. To evaluate the benefits of V-SAFE in terms of risk identification, we conducted a two-phase experiment using undergraduate students. In the first phase, students were asked to identify risk sources using traditional methods. In the second phase, same students identified risk sources by walking through the virtual environment of V-SAFE. The results of the comparative analysis showed that the participants were able to identify more of the risks they identify using conventional methods through the virtual environment. Therefore, virtual environment based safety training methods have a high potential in terms of improving the safety hazard identification level of the project participants.*

KEYWORDS: *Virtual Environments, Construction Risks, Risk Identification.*

1. INTRODUCTION

Workplace accident and fatality statistics show that the construction industry is one of the most hazardous industries in many countries around the world. According to Occupational Safety and Health Administration (OSHA) of United States, 20.5% of the fatal accidents were in the construction industry in 2014 (OSHA Records, 2016), although only 4.1% of the total workforce employed in the construction sector in 2014 (BLS Records, 2015). Occupational safety and health statistics in Hong Kong also presents a similar conclusion (Hong Kong Labor Departments Records, 2014), 9.5% of fatal workplace accidents occurred on construction sites, while, only 5% of the total employment was generated by the construction industry. Therefore, higher fatal accident rates are a worldwide problem in the construction sector. In other words, they do not depend on the countries' development indices or GDP's. Statistics reveal that risk management vulnerability is a common problem in the construction industry (BLS Records, 2015, OSHA Records, 2016).

In this respect, an effective risk management process could help the construction industry to reduce the high fatality rates. According to the Project Management Body of Knowledge (PMBoK, 2016), an efficient risk management process consists of five steps (i) risk identification, (ii) qualitative risk analysis, (iii) quantitative risk analysis, (iv) risk response planning and (v) risk monitoring and control. Among all the stages, risk identification is the most crucial stage of the risk management process since once the risks are identified adequately managing them becomes possible (Tchankova, 2002). Therefore, choosing the best risk identification method becomes even more important and challenging for the construction companies. Especially for the complex construction projects, not only the general construction risks, but also, the project specific risks must be clearly identified to provide a complete risk identification process. Moreover, conventional risk identification methods do not adequately identify all hazard sources. Most hazard identification methods rely on experience gained during similar projects in the past (Bajaj et al., 1997). Therefore, knowing that historical records and previous experience will not automatically imply new and project specific risk sources, more advanced safety hazard identification methods are necessary for the complex construction projects.

Conventional risk identification has been usually carried out through the examination of the two-dimensional contract drawings prepared by the project stakeholders. However, identifying all the risk sources solely based on the blueprints becomes problematic, since, they do not contain the location information of construction equipment and workers on construction sites. Consequently, this method possibly underestimates the safety hazards related to the construction component and process due to the lack of visualization. In order to integrate visualization into the risk identification process, virtual reality technologies can be utilized. Knowing that virtual technologies enhance spatial awareness (Rafi et al., 2005) and increase task performance (Ni et al., 2006), they can be conveniently used for the safety hazard identification stage. In this study, we aim to use virtual reality technology in the risk identification process and compare its effectiveness with the conventional methods.

2. BACKGROUND

The risk management process has a great significance in the construction industry since construction industry is one of the most hazardous industries around the world. It starts with the risk identification stage, which is the basis of risk management. In order to manage the risks adequately, all the risk sources, especially on-site construction safety hazards, must be identified. Bahn (2013) stated that workers are not aware of all the hazards in the workplace. In addition to that, Carter and Smith (2006) highlight that unidentified hazards present the most unmanageable risks. In general, traditional construction risk identification process is carried out through the examination of the construction projects' blueprints (Lu et al., 2009). However, due to the high accident rates in the construction industry; the effectiveness of the conventional risk identification methods is questioned. According to Bajaj and colleagues the most frequently used risk identification methods are top-down approach techniques, where the project is analyzed from an overall point of view, such as a case based approach, aggregate or bottom line approach (Bajaj et al., 1997). On the other hand, bottom-up risk identification techniques are not as popular as top-down approach except for questionnaire and check-list approach (Bajaj et al., 1997). Yet, commonly used top-down techniques mainly lead to guesswork regarding contingency for risks accepted by the construction shareholders (Bajaj et al., 1997). Conventional risk identification methods are based on the managers' expertise level and imagination which do not allow the visualization of the construction tasks. Due to the lack of the visualization, identifying all risk sources becomes challenging.

In order to enable the visualization of risk identification process, using virtual reality technologies could be an appropriate method. Virtual reality is a computer technology that is artificially creating a real or imaginary environment, and allows users to interact with the environment via their senses. Utilizing virtual reality technologies in different disciplines becomes trendy with the improvement of the technology such as; medicine (e.g. Marescaux et al., 1998), education (e.g. Kaufmann et al., 2000), design work (e.g. Ye et al., 2006) and training (e.g. Squelch, 2001). Particularly, virtual technologies have various advantages in terms of providing safe, risk-free and practical training environment. For this purpose, virtual environment based simulations have been used for many years in the training of pilots, drivers and surgeons (e.g. Hays et al., 1992; Lin et al., 2007, Seymour et al., 2002). Hays and colleagues (1992) conducted a meta-analysis of the studies related to aviation training. Based on their analysis and survey results, they concluded that aircraft training simulators significantly improve the performance of the trainees (Hays et al., 1992). Similarly, Lin and colleagues (2007) evaluated the cognitive capabilities of the drivers by quantifying the responses of the trainees. The study shows that adequate virtual training could significantly improve the drivers' cognitive responses. Seymour and colleagues (2002) examine whether virtual reality training transfers technical skills to the operating room environment. After the experiments, they prove that virtual reality surgical simulation significantly improved the operating room performance.

In recent years, the trend of using virtual reality technologies in the different fields of the construction has also become prevalent. There are several different applications of the virtual reality technologies in the construction literature such as space modelling (e.g. Frost, and Warren, 2000), interior design (e.g. Dunston et al, 2011), landscaping the site layout (e.g. Ball et al., 2005), palling and monitoring of the construction process and evaluation of construction scenarios (e.g. Huang et al., 2007). Moreover, many researchers also focused on virtual safety training in the construction industry (Lin et al., 2011; Li et al., 2012; Albert et al., 2014; Lucas and Thabet, 2008) including the safety hazard identification area (Zhao and Lucas, 2015; Hadikusumo and Rowlinson, 2004). For example, Zhao and Lucas (2015) developed a virtual reality-based environment which serves as a safe training environment for the workers and allows them to rehearse their task. Results show that virtual reality based interactive environment improves the cognitive abilities and risk awareness level of participants. (Zhao and Lucas, 2015). Similarly, Hadikusumo and Rowlinson (2004) integrated a virtual real construction model with its design for building a safety database. Thus, Hadikusumo and Rowlinson showed that virtual reality technologies have a high potential to transfer tacit knowledge via visualization. Lin and colleagues (2011) developed a virtual reality-based safety training tool to compare the conventional and virtual reality based methods in terms of risk identification process. Results show that students who participated in the virtual reality based training have a higher risk identification level compared to the students who had been trained with conventional methods (Lin et al., 2011). Other recent studies on virtual safety training also include conveyor belt safety training (Lucas and Thabet, 2008), tower crane dismantling training (Li et al., 2012) and hazard recognition (Albert et al., 2014). The results of these studies show that, using virtual reality technologies enables an effective training method to improve the safety performance of participants. Knowing that especially inexperienced workers are generally unsuccessful in the risk identification process (Bahn, 2013) and the dynamic environment of the construction industry makes the risk identification harder, we aim to merely focus on the risk identification process in this study. We use a virtual environment based crane operation training tool called V-SAFE (Virtual Safety Analysis for Engineering applications) in order to identify risks. Also, we examined the features of V-SAFE and added the necessities for effective risk identification process. Accordingly, we objected to provide an effective safety hazard identification process for the construction organizations.

3. METHODOLOGY

The main objective of this paper is to evaluate and enhance the participants' risk identification level via using a virtual reality-based safety training tool. For this purpose, we utilized a game engine based tool called V-SAFE (**V**irtual **S**afety **A**nalysis **F**or **E**ngineering applications). V-SAFE is developed based on "Unreal Engine 4" and "Unreal Software Development Kit". Unreal Engine supports the integration of the virtual reality into the gaming experience. Unreal Engine is not only utilized for gaming purposes, but also used for other expertise such as education, virtual training, urban transportation, movie storyboard (Unreal Engine Official Website, 2016). Warner Bros, Sony, Amazon are some of the licensees of the Unreal Engine (Unreal Engine Official Website, 2016).

V-SAFE is primarily developed for the safety training purposes via the simulation of a crane operation. In the initial step, V-SAFE simulates crane lifting operation in a 3D virtual environment (Figure 1). Main features of the simulation such as collision detection technology, reality integration and crane operation are involved in the environment. Thus, we aimed to provide a realistic training opportunity for the trainees. Secondly, as many researchers (e.g. Albert et al., 2014) highlight that effective hazard identification is a must in the effective safety training, V-SAFE could be also utilized as a training platform for the users to improve their risk recognition capabilities.

Fig. 6 – A site view of the V-SAFE during the tower crane operation

3.1 Experimental Design

In order to show the impact of visualization on the safety hazard recognition, we conducted an experiment with

16 junior and senior year students of Boğaziçi University Civil Engineering Department. In the experiment, we identified three different types of safety hazard sources as i) material-based, ii) safety knowledge-based and iii) behavior-based. All the risk sources are integrated into the tasks and objects encountered in the virtual environment of V-SAFE. Figure 2 represents some of the risk sources integrated into V-SAFE as; i) truck - traffic accident, ii) pit - fall from a height, iii) nails – stepping on a sharp object, iv) main electrical distribution panel - electrocute.

Students who participated in the experiments have completed at least 15 days of on-site internship. Therefore, they are familiar with the construction sites and they have previously encountered on-site safety hazard risks. In the first phase of experiment, schedules that include the details of workers' daily on-site assignments and project documents are provided to the students. Then we asked them to determine possible safety hazard sources based on both provided documents and their prior experience. Subsequently, the second phase of the experiment is conducted by utilizing V-SAFE. Participants log on the V-SAFE and they see the environment as a cloud spectator that can freely move when they use their movement keys. Then, students determined additional safety hazard sources by using the visual support of V-SAFE.

Fig. 7 Safety hazard source samples integrated into the V-SAFE

Participants were asked to write down each identified hazard source in their own words. For this reason, the evaluation requires the grouping the answers into different categories. In this respect, we followed the risk categorization format developed by Gurcanli and Mungen (2009). Gurcanli and Mungen (2009) grouped the occupational accidents on construction sites into ten categories which are "fall from height, contact with electricity, falling object, heavy equipment accidents, traffic accidents on site, building or structural collapse, cave-ins, fire or explosion and other causes of accidents". Afterward, we reviewed each risk source list written by test subject and matched each item with the relevant risk group. For example one of the students stated that "*Crane operator may* *fall when he is climbing the ladder"*, we accounted this risk source as fall from a height.

4. RESULTS

Table 1 shows the risk identification performance of each participant. The check marks in the table indicate that participants correctly identified the specified accident type. In the first part of Table 1, phase 1 results are presented. In the second part of the Table 1, risks identified by the students using V-SAFE are provided. Table 2 shows the difference between the first phase and the second phase of the experiment. Accordingly, the increase in the risk identification performance is by 68% on average.

Table 1 – The risk identification performances of the participants

Phase 1																
On-site Risk Sources	**P1**	**P2**	**P3**	**P4**	**P5**	**P6**	**P7**	**P8**	**P9**	**P10**	**P11**	**P12**	**P13**	**P14**	**P15**	**P16**
Fall from height		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Contact with electricity			✓									✓		✓		
Falling object	✓	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Heavy equipment accidents								✓	✓		✓			✓	✓	✓
Traffic accident on site		✓					✓									
Building or structure collapse					✓	✓			✓	✓	✓			✓		✓
Cave-ins			✓		✓								✓	✓		
Material bouncing to face or other parts of the body		✓		✓				✓				✓				
Fire or explosion				✓												
Other causes of accidents	✓	✓	✓		✓	✓	✓			✓	✓	✓	✓			✓
Total Number of Risks Identified	**2**	**5**	**5**	**4**	**4**	**4**	**4**	**4**	**4**	**4**	**5**	**5**	**4**	**6**	**3**	**5**
Phase 2																
On-site Risk Sources	**P1**	**P2**	**P3**	**P4**	**P5**	**P6**	**P7**	**P8**	**P9**	**P10**	**P11**	**P12**	**P13**	**P14**	**P15**	**P16**
Fall from height	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Contact with electricity	✓	✓	✓					✓	✓	✓	✓	✓		✓	✓	✓
Falling object	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Heavy equipment accidents								✓	✓		✓			✓	✓	✓
Traffic accident on site		✓				✓	✓	✓		✓	✓		✓	✓		✓
Building or structure collapse				✓	✓	✓	✓		✓	✓	✓			✓		✓
Cave-ins	✓	✓	✓	✓	✓	✓		✓		✓	✓		✓	✓	✓	✓
Material bouncing to face or other parts of the body		✓		✓		✓		✓	✓			✓	✓			✓
Fire or explosion	✓	✓	✓	✓				✓	✓	✓	✓	✓		✓	✓	✓
Other causes of accidents	✓	✓	✓	✓	✓	✓	✓		✓		✓	✓	✓	✓	✓	✓
Total Number of Risks Identified	**6**	**8**	**6**	**7**	**5**	**7**	**5**	**8**	**8**	**7**	**9**	**6**	**6**	**9**	**7**	**10**

Table 2: Safety hazard identification levels in the first and second phase of the experiment.

On-site Risk Sources	**Phase 1**	**Phase 2**	**Increase**
Fall from height	15	16	7%
Contact with electricity	3	11	267%
Falling object	15	16	7%
Heavy equipment accidents	6	6	0%
Traffic accident on site	2	9	350%
Building or structure collapse	7	9	29%
Cave-ins	4	13	225%
Material bouncing to face or other parts of the body	4	8	100%
Fire or explosion	1	12	1100%
Other causes of accidents	11	14	27%
Average	**4.25**	**7.13**	**68%**

In the first phase of the experiment, participants identified hazards based on a given work schedule, project documents and their experience. Participants identified on average 4.25 hazards out of 10 hazard sources. Falling from height and falling objects are the most commonly identified hazard sources in the first part of the experiment, 15 out of 16 participants have identified these two hazard sources.

In the second phase of the experiment, participants identified the hazards by utilizing V-SAFE. In this stage, participants identified 7.13 hazards on average out of 10 hazard sources, which indicates around 68% performance increase. In this phase every single participant has identified falling from height and falling objects as a hazard sources.

For every hazard we examined in this experiment, the safety hazard identification rate increases by a different percentage. We observe the most significant increase in the fire and explosion hazard type. While only a single participant could identify the fire and explosion hazard in the first phase, 12 out of 16 participants could recognize the hazard source when they utilize V-SAFE. The second significant increase observed in the on-site traffic accident. While only 2 participants could identify the accident risk in the first phase, 9 out of 16 participants identified the related risk source in the V-SAFE. Similarly, the hazard identification rates for contact with electricity, cave-ins and material bouncing to face or other parts of the body are more than doubled in the second phase of the experiment.

The t-test is a commonly used statistical method in the construction management literature for comparing two sample spaces. For example, Aksorn and Hadikusumo used the t-test in order to evaluate the general agreement about the critical success factors influencing safety program performance in the Thai construction projects (Aksorn and Hadikusumo, 2007). Similarly, Pheng and Chuan also utilized the t-test to test whether the various working environment variables are significant in terms of influencing the project performance of project managers (Pheng and Chuan). Accordingly, in order to compare the safety hazard identification performance of the students in the first and second phase of the experiments, we also used a two tail t-test. According to the t-test result, the p-value used to weigh the strength of the evidence is 2.7E-07 which is far below 0.05. Therefore, it is highly statistically significant that utilizing virtual environments improve the risk identification performance of the participants.

5. DISCUSSION

Occupational safety reports from different countries (OSHA Records, 2016; BLS Records, 2015; Hong Kong Labor Departments Records, 2014) reveal that the construction industry is one of the high-risk industries all around the world. Despite the precautions taken, fatal accident rates have remained high. As a result, safety management becomes even more crucial for the construction industry. In this regard, several recent studies (Carter and Smith, 2006; Bahn, 2013) focus on the risk identification which is the most important stage for the risk management process. If a potential risk source is not identified at this stage, it is not included in the further analysis. In other words, in order to manage all the potential risks, an efficacious risk identification process is essential. In this respect, Carter and Smith (2006) analyzed the risk identification level of three different construction projects in the United Kingdom. The study results highlight that unidentified risks are one of the major causes of accidents and 33% of the risk could not be identified adequately (Carter and Smith, 2006). On the same vein, Bahn (2013) evaluated the on-site hazard identification level of the workers during mining operations. In the study, Bahn (2013) grouped hazards under four categories which are i) obvious hazards, ii) trivial hazards, iii) emerging hazards and iv) hidden hazards. Moreover, Bahn also shows that the hazards identified by the trainees are less than the actual number of on-site safety hazard sources. In other words, not all the risk sources could be identified. Taken together, recent studies (Carter and Smith, 2006; Bahn, 2013) highlight that the risk identification level is less than targeted level and poor risk identification is one of the major causes of the accidents on construction sites. Therefore, an enhanced method for safety hazard identification on construction sites is required. In this sense, a recent study by Albert and colleagues (2014) shows that virtual reality based safety training has a great potential to improve the risk identification level of the workers. Similarly, we also utilized a virtual environment based safety training tool called V-SAFE and evaluated its effectiveness compared to the conventional risk identification methods. For this purpose, we conducted a two-phase experiment. In the initial stage, students listed all the risk sources given the project documents and based on their previous site experience. Then, students walked through the virtual environment and included additional hazard sources that they recognized. Results show that there is a highly statistically significant increase in the safety hazard recognition level of the participants when the virtual environment is utilized.

Falling from a height is the most common accident type on the construction sites (OSHA, 2016, Gurcanli and Mungen, 2009). 15 out of 16 participants identified falling from a height in the first phase of the experiment through examining the project information and the job description. Therefore, results indicate that participants are well aware of the most common hazard source. For this reason, the least improvement has achieved on the identification rate of the most frequently encountered accident type. Similarly, falling objects is the second most common hazard source which was identified adequately by the students in the first phase. Despite the fact that electrocution is the third most common accident type in the construction industry (Gurcanli and Mungen 2009), it is one of the least identified hazard source in the first phase of the experiment, only 3 out of 16 participants could identify the electrocution as a hazard source. On the contrary, once the visual support is provided 11 out of 16 participants identified the electrocution as a hazard source in the second phase, which corresponds to 267% improvement in the risk recognition level. Therefore, virtual reality-based risk identification methods have a potential to improve the risk identification level for the well-known accident type on construction sites.

Most significant risk identification improvement is related to the fire or explosion hazard sources. While only a single participant could identify it in the first phase, in the second phase of the experiment 12 out of 16 participants successfully identified the fire or explosion risk. Since, project blueprints and job descriptions do not cover all the construction components and processes (Hadikusumo and Rowlinson, 2002), it is easier to identify fire or explosion as a risk source once the visual elements are provided. In Table 1 and Table 2, “other” category covers sunstroke, toxication from chemicals and lightning. It is a strong evidence that virtual reality improves the risk identification level via improving the mental imagination and creativity. Because none of these risk sources were intentionally integrated into the virtual environment. Some of the participants interpreted the oil tanks filled with chemicals. Moreover, participants also considered lighting risk due to the high rise parts of the tower crane. Due to the sunny weather in the virtual environment, some of the participants also identified sunstroke which was not identified in the first phase of the experiment. Thus, we observed that the enhanced interpretation level of the trainees by the virtual reality technologies could increase the risk identification rate.

Despite the advantages of using V-SAFE, the current study has certain limitations. First of all, the experiment setting does not allow the performance decrease in the second phase. In the first phase of experiment, participants identify potential safety hazard sources based on provided work schedule, project documents and their prior experience. In the second phase of the experiment, participants involved additional safety hazard sources in their original list after walking through the virtual environment. Therefore, technically it is not possible to observe a lower risk identification level in the second part of the experiment. Also, participants were asked to write potential safety hazard sources down in their own words, after that participants' statements matched with the relevant groups of risk sources. For instance, subject stated that crane operator may fall down when he is climbing the ladder, we marked this statement as falling from a height. Generally, statements were clear, but some of the statements were vague. Vague statements double checked in order to prevent any misleading results.

6. CONCLUSION

The adequate risk identification method is essential for an effective construction site risk management system. The dynamic nature of the construction industry makes the risk identification process more challenging. More importantly, traditional safety hazard identification methods have vulnerabilities. This study aims to determine whether virtual reality technologies improve the safety hazard identification performance of the participants. For this purpose, we used V-SAFE as a virtual environment, which was developed as a tower crane operation training tool. A two-phase experiment was set up in order to measure the impact of the virtual reality on the risk identification performance. In the first phase of the experiment, participants identified safety hazard sources solely using traditional methods, while the second phase was supported by the virtual reality technologies. According to the results of this experiment, it is confirmed that using virtual environments significantly improve the risk identification rate of the participants. This study makes a variety of theoretical and practical contributions. First of all, the study presents the effectiveness of utilizing virtual reality technology to identify project specific risks in a dynamic work environment. Secondly, the results of this study showed that the participants were able to identify more of the risks they identify using conventional methods through the virtual environment. Therefore we can conclude that the study demonstrates potential advantages of using virtual reality environments to increase the risk recognition level of participants which leads to reduce on-site injuries and fatalities. Consequently, integrating virtual reality in the risk identification process can bring advantages to the construction industry. Further studies can be designed to examine the risk identification process of different work environments and construction projects.

7. ACKNOWLEDGEMENT

This material is based in part upon work supported by Bogazici University Scientific Research Projects (BAP) under Grant No. 7902. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of Bogazici University Scientific Research Projects (BAP).

8. REFERENCES

Aksorn, Thanet, and B. H. W. Hadikusumo. "Critical success factors influencing safety program performance in Thai construction projects." Safety Science 46.4 (2008): 709-727.

Albert, A., Hallowell, M.R., Kleiner, B., Chen, A. and Golparvar-Fard, M., 2014. “Enhancing construction hazard recognition with high-fidelity augmented virtuality.” Journal of Construction Engineering and Management,140(7), p.04014024.

Bahn, Susanne. "Workplace hazard identification and management: The case of an underground mining operation." Safety science 57 (2013): 129-137.

Bajaj D., Oluwoye J. and Lenard D. (1997) “An analysis of contractors' approaches to risk identification in New South Wales, Australia,” Construction Management and Economics, 15:4, 363-369,

Ball, J., N. Capanni, and S. Watt. "Virtual reality for mutual understanding in landscape planning." Development 2 (2005).

Bls.gov.uk (2015). Employment by major industry sector. [online] Available at: http://www.bls.gov/emp/ep_table_201.htm [Accessed 28 July 2016].

Carter, Gregory, and Simon D. Smith. "Safety hazard identification on construction projects." Journal of construction engineering and management132.2 (2006): 197-205.

Censtatd.gov.hk. (2016). Table 009: Unemployment Rate by Previous Industry | Census and Statistics Department. [online] Available at: http://www.censtatd.gov.hk/hkstat/sub/sp200.jsp?tableID=009&ID=0&productType=8 [Accessed 28 July 2016].

Dunston, P.S., Arns, L.L., Mcglothlin, J.D., Lasker, G.C. and Kushner, A.G., 2011. An immersive virtual reality mock-up for design review of hospital patient rooms. In Collaborative design in virtual environments (pp. 167-176). Springer Netherlands.

Frost, Peter, and Peter Warren. "Virtual reality used in a collaborative architectural design process." Information Visualization, 2000. Proceedings. IEEE International Conference on. IEEE, 2000.

Gürcanli, G. Emre, and Ugur Müngen. "An occupational safety risk analysis method at construction sites using fuzzy sets." International Journal of Industrial Ergonomics 39.2 (2009): 371-387.

Hadikusumo, B. H. W., and Steve Rowlinson. "Integration of virtually real construction model and design-for-safety-process database." Automation in Construction 11.5 (2002): 501-509.

Hays, R.T., Jacobs, J.W., Prince, C. and Salas, E., 1992. “Flight simulator training effectiveness: A meta-analysis.” Military psychology, 4(2), p.63.

Huang, T., Kong, C.W., Guo, H., Baldwin, A. and Li, H., 2007. “A virtual prototyping system for simulating construction processes.” Automation in Construction, 16(5), pp.576-585.

Kaufmann, Hannes, Dieter Schmalstieg, and Michael Wagner. "Construct3D: a virtual reality application for mathematics and geometry education." Education and information technologies 5.4 (2000): 263-276.

Li, Heng, Greg Chan, and Martin Skitmore. "Multiuser virtual safety training system for tower crane dismantlement." Journal of Computing in Civil Engineering 26.5 (2012): 638-647.

Lin, Ken-Yu (2011) “A pilot study of a 3D game environment for construction safety education”, Journal of Information Technology in Construction (ITcon), Vol. 16, pg. 69-84, http://www.itcon.org/2011/5

Lin, C.T., Chung, I.F., Ko, L.W., Chen, Y.C., Liang, S.F. and Duann, J.R., 2007. “EEG-based assessment of driver cognitive responses in a dynamic virtual-reality driving environment.” IEEE Transactions on Biomedical Engineering, 54(7), pp.1349-1352.

Lu, C.C., Kang, S.C., Hsieh, S.H. and Shiu, R.S., (2009). “Improvement of a computer-based surveyor-training tool using a user-centered approach.” Advanced Engineering Informatics, 23(1), pp.81-92.

Lucas, J., and W. Thabet. "Implementation and evaluation of a VR task-based training tool for conveyor belt safety training." (2008): 637-659.

Marescaux, J., Clément, J.M., Tassetti, V., Koehl, C., Cotin, S., Russier, Y., Mutter, D., Delingette, H. and Ayache, N., 1998. “Virtual reality applied to hepatic surgery simulation: the next revolution.” Annals of surgery, 228(5), p.627.

Ni, T., Bowman, D.A. and Chen, J., 2006, June. “Increased display size and resolution improve task performance in information-rich virtual environments.” In Proceedings of Graphics Interface 2006 (pp. 139-146). Canadian Information Processing Society.

Osha.gov. (2016). Commonly Used Statistics. [online] Available at: https://www.osha.gov/oshstats/commonstats.html [Accessed 28 July 2016].

Occupational Safety and Health Branch, Labor Department (August 2015) Occupational Safety and Health Statistics Bulletin Issue No. 15. Available at: http://www.labour.gov.hk/eng/osh/pdf/Bulletin2014.pdf

Pheng, Low Sui, and Quek Tai Chuan. "Environmental factors and work performance of project managers in the construction industry." International Journal of Project Management 24.1 (2006): 24-37.

Pmi.org. (2016). PMBOK Guide | Project Management Institute. [online] Available at: http://www.pmi.org/pmbok-guide-standards/foundational/pmbok [Accessed 28 July 2016].

Rafi, A., Anuar, K., Samad, A., Hayati, M. and Mahadzir, M., 2005. “Improving spatial ability using a Web-based Virtual Environment (WbVE)”.Automation in construction, 14(6), pp.707-715.

Seymour, N.E., Gallagher, A.G., Roman, S.A., O’Brien, M.K., Bansal, V.K., Andersen, D.K. and Satava, R.M., 2002. Virtual reality training improves operating room performance: results of a randomized, double-blinded study.Annals of surgery, 236(4), pp.458-464.

Squelch, A. P. "Virtual reality for mine safety training in South Africa." Journal-South African Institute of Mining and Metallurgy 101.4 (2001): 209-216.

Tchankova, Lubka. "Risk identification-basic stage in risk management. "Environmental Management and Health 13.3 (2002): 290-297.

Unrealengine.com. (2016). What is Unreal Engine 4. [online] Available at: https://www.unrealengine.com/ [Accessed 28 July 2016].

Ye, J., Campbell, R.I., Page, T. and Badni, K.S. (2006) 'An investigation into the implementation of virtual reality technologies in support of conceptual design', Design Studies, 27(1), pp. 77–97. doi: 10.1016/j.destud.2005.06.002.

Zhao, D. and Lucas, J. (2015) 'Virtual reality simulation for construction safety promotion',International Journal of Injury Control and Safety Promotion, 22(1), pp. 57–67. doi: 10.1080/17457300.2013.861853.

BIM TO MITIGATE HEALTH AND SAFETY RISKS IN THE CONSTRUCTION AND MAINTENANCE OF INFRASTRUCTURE

Mohammed Muzafar & Darshan Ruikar

University of Birmingham, United Kingdom

ABSTRACT: *BIM, an acronym for Building Information Modelling relates to the practice of creating a computer generated model which is capable of displaying the planning, design, construction and operation of a structure. The resulting simulation is a data-rich, object-oriented, intelligent and parametric digital representation of the facility, from which views and data, appropriate to various users needs can be extracted and analysed to generate information that can be used to make decisions and to improve the process of delivering the facility. BIM also refers to a shift in culture that will influence the way the built environment and infrastructure operates and how it is delivered. One of the main issues of concern in the construction industry at present in the UK is its record on Health & Safety (H&S). It is therefore important that new technologies such as BIM are developed to help improve the quality of health and safety. Historically the H&S record of the construction industry in the UK is relatively poor as compared to the manufacturing industries. BIM and the digital environment it operates within now allow us to use design and construction data in a more intelligent way. It allows data generated by the design process to be re-purposed and contribute to improving efficiencies in other areas of a project. This evolutionary step in design is not only creating exciting opportunities for the designers themselves but it is also creating opportunity for every stakeholder in any given project. From designers, engineers, contractors through to H&S managers, BIM is accelerating a cultural change. The paper describes the idea behind a research project that uses BIM as a platform to elucidate construction, operation and maintenance health hazards and using the principles of prevention devise mechanisms for their control.*

KEYWORDS: *Building Information Modeling (BIM), BIM Levels, Health and Safety (H&S), Asset Management, Risk Ranking, Health Hazards, Risk Matrix*

1. INTRODUCTION

Building Information Modelling (BIM) is a broad term with numerous definitions and explanations. Essentially it is a descriptive term used to describe the technologically advanced, collaborative and information centric processes used to drive design, construction and operation of the built environment. It is a digital representation of the physical and functional features of an asset that incorporates information about every component involved in the entire life cycle of a project from conception to construction, all the way through to demolition. The essence behind BIM is to promote value creating collaboration throughout a project via the exchange of intelligent data on a shared platform.

Often misconstrued as simply 3D modeling or a technological advancement that will be the norm in the future, BIM is overlooked as a platform for improvement that can be implemented immediately. It is crucial to recognise BIM as a shift in culture away from separate disciplines working in isolation to an industry that is based on the collaboration of all professionals on a uniform data exchange platform throughout the entire life cycle of an asset e.g. a building. This association between disciplines will benefit designers, clients and collaborators alike and create opportunities for improvement in facilities management, maintenance and retro fitting of buildings. Consequently this will lead to an improvement in the relationship between different parties in the construction industry; this paradigm altering collaboration will result in improved co ordination, cost management and health and safety (H&S).

Traditionally construction has been one of the worst performing industries in regards to its H&S record. Currently in the UK, the industry accounts for 5% of those in work, yet disproportionately accounts for 31% of all fatal injuries at work and 10% of reported major/ specified injuries (HSE, 2015). In an attempt to improve the H&S record, a Construction, Design and Management (CDM) co-coordinator role was created to monitor and co ordinate all H&S aspects of a project from design to completion. In order to maximise the benefit of having a CDM coordinator, the ‘safe by design’ initiative aims to encourage designers to eliminate H&S risks during the development stages of a project. The benefits of the concept have already been seen with a drop in fatalities in recent years, however there is still room for improvement; the key to finally eliminating the risks associated with construction H&S could lie with the successful adoption of BIM.

2. BIM ADOPTION IN THE UK

2.1 BIM Definition

BIM is a term that describes the practice of collating information concerning the planning, design, construction and maintenance of a structure into a digital, machine readable representation. The resultant computer generated simulation becomes a data rich, object orientated, intelligent and parametric digital representation of a structure which can be modified by a network of professionals at any point during the life cycle of an asset (Azhar et al. 2008). It is therefore more accurate to describe BIM as an activity rather than an object. Bazjanac (2006) defines the activity as a method of giving all collaborators a more holistic understanding of the project geometry, spatial relationships, material inventories, cost estimates and project scope via a virtual display. Each project can benefit in all of these aspects depending on the quality of the information within the model and the level of BIM at which the project is operating at.

2.2 Levels and Stages of BIM Maturity

Given the various definitions for BIM, it is understandably difficult to accurately define guidelines pertaining to the level of BIM at which a model is operating at. In an attempt to create a standardised understanding of what each level of BIM represents, Bew and Richards (2008) created a BIM maturity model which has been widely accepted as defining the benchmarks required to attain each level of BIM. This definition of the levels of BIM has been adhered to under best practice guidance and by the UK governments BIM adoption framework as outlined by the RIBA Outline Plan of Work (2007). The BIM maturity model presented in Figure 1 divides BIM into 4 distinct maturity levels which range from paper drawings to fully collaborative, intelligent models.

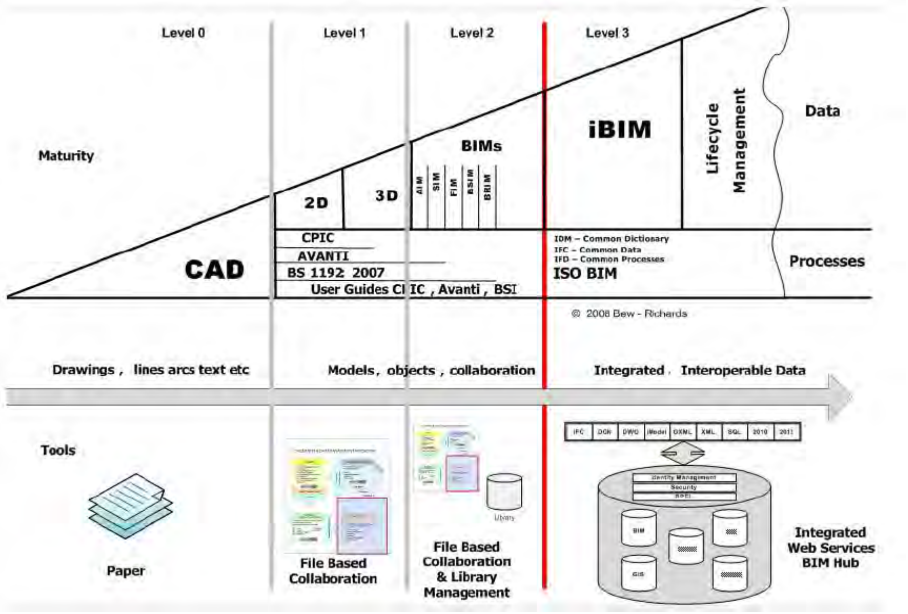


Figure 8: BIM Maturity Model (Bew and Richards, 2008)

2.2.1 Level 0- Pre BIM

In its simplest form, Level 0 refers to those operating using traditional methods used prior to the adoption of BIM. As defined by Figure 1, Level 0 is the use of 2D CAD files for production information without collaboration amongst different disciplines, thus leading to many inefficiencies in terms of communication and time management (RIBA, 2007).

2.2.2 Level 1- Object Based Modeling

Level 1 is the initial stage at which a project can be considered as having formally adopted BIM; it involves the utilisation of software such as Revit and AutoCAD as opposed to traditional 2D drawings on paper. At this level, only one party utilises BIM, thus not gaining the full benefits of the approach and not embodying the change in culture to a collaborative way of working. A single disciplinary model is incapable of improving collaboration between the disciplines and thus unable to lead to any significant improvements in communication.

There is legislation in place that requires all information to follow certain protocols and that the standard of work is carried out to BS 1192:2007 (NBS, 2014). The main benefit of working at this level is the potential to undertake the design and construction processes simultaneously, thus reducing construction times. The successful adoption of Level 1 can act as a catalyst to encourage the adoption of more advanced levels as users realise the potential benefits that stem from its use as a collaborative tool (Succar, 2009).

2.2.3 Level 2 – Model Based Collaboration

The key tenet that advances Level 2 is the idea of collaboration; this does not necessarily need to be on a single model provided there is a uniform platform where the exchange of information can take place. The software used requires collaboration to the extent that cost information, construction sequencing and asset maintenance can be factored into the design from the early stages; thus improving the efficiency with which the project progresses (Masons, 2014). The fragmentation between separate disciplines seen at pre- BIM levels begins to erode as a more collaborative approach is taken. In order for models to progress in an efficient way, it is important for all parties involved to operate following BS 1192:2007 (Collaborative production of architectural, engineering and construction information – Code of practice) which sets out standardised methods to exchange Construction and Design information, to ensure that all work is carried out to the required standards (RIBA, 2007). It should however be noted that the use of an integrated system has revealed deficiencies in the existing legal, contractual and insurance protocols and hence amendments to the current strategies are required to successfully implement Level 2 BIM (NBS, 2014).

2.2.4 Level 3 – Network Based Integration

Ultimately, those using BIM would aim to achieve Level 3, a data rich model which is created, shared and maintained collaboratively across the entire life cycle of the asset. Rather than being a collaborative project between disciplines, it becomes a fully integrated, interdisciplinary and multi dimensional model which allows complex analysis at early stages of the project (Succar, 2009). A single shared model allows for all parties to make adjustments to the design whilst removing the possibility of conflicting information and clashes due to the integration of clash detection software such as Solibri. At present most companies are operating at Level 1 and 2, a major reconsideration of the contractual relationships, legislations and guidelines is required before Level 3 can be implemented within the UK.

2.3 BIM in the UK

A key instrument in measuring the level of BIM adoption within the UK is the annual National Building Society (NBS) BIM Report; this is the main source of statistics for the both the government and industry. The NBS BIM Report 2015 found that 59% of the industry was now operating at Level 2 BIM, an increase of 8% from 2014, thus demonstrating the gradual change in perception about BIM (NBS, 2015). However, according to Shepherd (2015), the level of BIM adoption is often exaggerated due to a misconception of what each level of BIM entails. This was seen in the immediate aftermath of the governments BIM Strategy published in 2011, as many organisations claimed they were already operating at Level 2 when in actuality they were merely realising the benefits of cross referenced production drawings, rather than an integrated design process.

Due to the increase in quality of Publicly Available Standards (PAS) and British Standards (BS) specifically targeted at BIM adoption, it is easier for organisations to adopt BIM and become proficient in its use. These standards provide detailed information pertaining to various aspects contained within BIM such as the security of information, defining required outcomes and the use of an information exchange platform (NBS, 2014). As detailed in BS 1992-4:2014, the Construction Operations Building information exchange (COBie) provides a uniform structure for the exchange of information about new and existing facilities. This allows for the retention of information from the source, working its way up through the supply chain; an example of this would be a manufacturer detailing the specifications of a steel beam in an excel file, which would then be sent through the supply chain to where it is fitted, this information would then be passed on to any maintenance contractors so the information is available throughout the life span of the Asset.

Adopting such techniques leads to an increase in communication between those involved in a project, thus overcoming the inefficiencies of the traditional paper based exchange of information. As BIM is still very much an emerging phenomenon, there are still many barriers to its complete adoption within the UK; principle amongst which is the fragmentation amongst individual professions which impedes progress towards a collaborative system. Amongst smaller organisations, there is also an issue of individuals not willing to change the current system in place due to training and implementation costs as well as the potential contractual issues pertaining to intellectual rights and design responsibility (HSE, 2015).

Overall the industry has responded positively and proactively with large scale adoption of BIM for use on a variety of projects. Due to the government led impetus, the UK is internationally seen as a leader in BIM adoption due to its centrally led programme. It is estimated that the adoption of BIM in the UK has led to a saving of £2bn per annum for the government and its clients (BIM Task Group, 2012). Even thought the UK is held in high esteem for its BIM adoption, many other countries have been more successful in their BIM adoption. An example of this is Singapore, which in 2013 had a 76% BIM adoption rate, predicted to rise to 96% by the end of 2015 (CIOB, 2015). It is slightly easier to implement BIM in Singapore due to its size, however one of the main reasons for its rapid adoption is due to the governments BIM fund which provides finances for the cost of training, consultancy, software and hardware (CIOB, 2015). In the UK, the Construction Industry Council (CIC) has been at the forefront of collaborating with the government to ensure that there are initiatives in place to support the supply chain in meeting the mandate to have all centrally procured construction projects using Level 2 BIM by 2016 (BIM Task Group, 2012).

3. HEALTH AND SAFETY IN UK CONSTRUCTION

The construction industry is notorious for its health and safety record in comparison to other industries. For decades, construction has been the most dangerous industry to work in despite the drastic improvements that have been made over the years. The information in the table below shows the rapid decline over the past decades in the amount of incidents that have occurred on site. This has been as a result of many changes that have been made, including the establishment of RIDDOR (Reporting of Injuries, Diseases and Dangerous Occurrences Regulations (Reporting of Injuries, Diseases and Dangerous Occurrences Regulations), CDM Regulations, and documents such as the Egan and the Latham Reports (HSE, 2013). The graph below shows the number of injuries that occurred on site up to 2013, although there is a steady reduction in the number of work related injuries, the number of incident compared to other industries is still extremely high (HSE, 2013). The graph (figure 2) illustrates that there is still room for development; it is here where BIM could potentially play a role in eliminating major injuries and fatalities on construction sites.

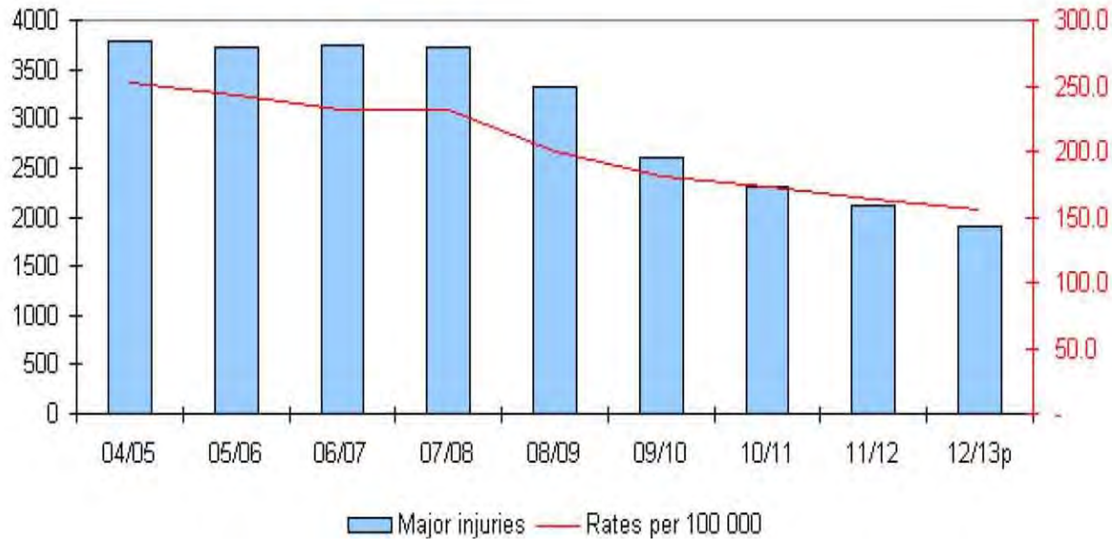


Figure 9: Rate of major injuries in construction (HSE, 2013)

Being such a major source of employment in the UK, it is crucial that the industry is regulated in a way to manage injuries to ensure the sector is operating in an efficient way. The HSE (2015) statistics reveal that 69,000 construction workers reported a work related illness or an illness being made worse by working in the construction industry. This resulted in 1.7 million working days being lost with a financial cost of £0.9 billion, equating to 7% of all work place injury costs (HSE, 2015). These statistics reveal the dire need for the improvement of the health and safety record within the UK construction sector. A survey conducted by the European Survey of Enterprises on 'New and Emerging Risks' (ESENER, 2014) documented the perceived risk by employees of companies employing more than 5 people. The results as displayed in figure 3 below which reveals that 8 out of 9 risks perceived by more than 50% of those asked are factors which can be mitigated through the use of pre-planning tools. In 2014, the HSE issued 1900 prohibition notices to employees who were not following the correct H&S procedures on site; if an incident was to occur as a result of malpractice, it would still be classed as a work place injury, regardless of whether the fact that it was a result of operator misconduct (HSE, 2015).

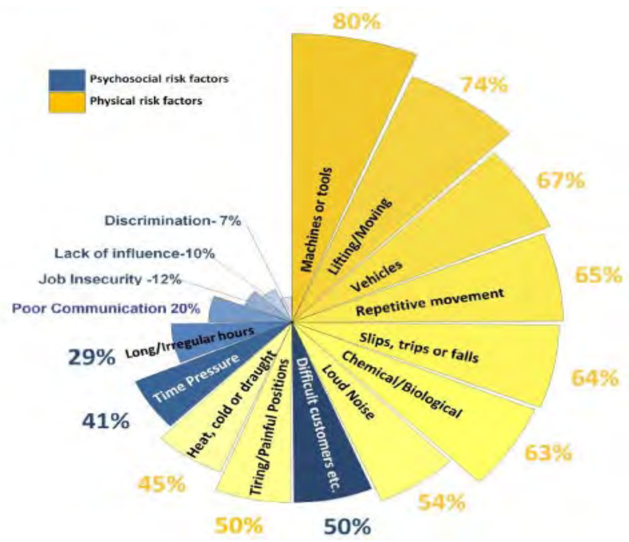


Figure 10: Perceived risks whilst on construction sites (ESNER,

3.1 Current Integration of BIM and H&S

As with any industry, it is crucial for the construction industry to keep advancing by adopting the latest technologies available. Research undertaken in Finland noted how BIM technologies are moving away from only being utilised in engineering and architect disciplines to the arenas of construction companies and construction management (VTT, 2011). The amount of fiscal investment construction companies are putting into BIM technologies is representative of the perceived benefits that can be derived from its adoption. According to Mott Macdonald who are presently using BIM for safety planning, many of the risks associated with construction are greatly reduced when site layouts are designed using BIM (MacDonald, 2014). Asides from site planning, simulations can be created to replicate prevention techniques that can potentially reduce incidents such as falls from height. An example of such a technique is an adjustable barrier that has been designed to prevent falls from height, the unique aspect that was specified within BIM is its ability to be used in multiple locations without additional support. By designing such an object within BIM, it is possible to ensure that it is safe and secure to be used anywhere on the site (VTT, 2011).

There are also other instances where BIM has been used to benefit H&S. Currently in Germany there is a programme in place to document house fires, which are then used to develop a database which is used to help understand the way in which a fire spreads through a residential building. This information is subsequently used to help designers make houses safer as well as inform the residents of a property the best way to escape a fire. The model can also be passed onto the emergency services who can plan the safest way of tackling the blaze (Schatz, 2011). This same technology can be evolved to assist with site inductions as well as provide a real-time model of any hazards that are currently on site.

In the UK however, the concept of integrating BIM and H&S is still being realised. With the introduction of new regulations which focus on the idea of collaboration, there is a framework in place to help companies integrate

BIM and H&S. Although the collaboration refers more to the management and coordinating roles, the 2013 versions of PAS 1192 has assigned a Principal Designer to coordinate the H&S during the design stages of a project, this replaces the CDM Coordinator, as a result the role is no longer assigned to a third party consultant and undertaken by a professional that can easily be integrate into the project team (PAS 1192:2013).

The 2025 Construction Strategy set out by the UK Government outlines its four main objectives as a reduction of initial cost, reduction in overall construction time, reduction in carbon footprint and a reduction of the trade gap (NBS, 2015). Although it mentions there is a need for improved H&S, there are no specific targets set out and no mention of how the improvement could potentially happen. However, they have gone as far as commissioning a working task group called BIM4regs which aims to integrate BIM models with building regulations, planning and health and safety requirements. Having been commissioned by the Government BIM Task Group, the initiative will aim to embed information so that all disciplines are able to see if their input meets the necessary regulations and H&S requirements. Creating an automated system will eliminate the possibility of human error and ensures that all parties are in compliance with the required standards. Following on from this, the inclusion of hazardous materials could be embedded into the BIM model. For example the refurbishment of a building could include the location of asbestos, thus allowing workers to take the necessary precautions before hand and reducing the risk of coming into contact with the hazardous substance.

4. BIM AND H&S

In construction, traditional safety planning relies on frequent manual observations, meaning it is labour intensive and time consuming and thus highly inefficient. Safety knowledge is difficult to transfer by safety regulations alone as it is reliant on an individual’s understanding and experience. Construction site safety often remains the sole responsibility of the contractor, thus alleviating the responsibility of H&S from others on site. Based on the schedule, construction sites change daily with new safety issues emerging and others being resolved as the work on site progresses (Zhang, 2013). All the hazardous risks possible to occur as a result of these sequences need to be foreseen and safety planning should be completed before the construction work begins. Safe construction necessitates care and planning throughout the project life cycle, from the initial concept, through construction planning and construction execution, extending into operations and maintenance. BIM offers a clear simulation of all these stages, thus enhancing the transfer of knowledge and methods to provide standardisation of a safe working environment. Furthermore, BIM based modeling and 4D simulation may offer many benefits to safety and logistics applications. The three areas where BIM can influence H&S management are: Evaluation of site conditions for workers; identification of potential safety hazards; and analysis, planning and validation of safety measures.

Using BIM processes, it is possible to identify potential safety hazards before any construction has taken place. This is one of the crucial factors that helps develop improved safety measures. Working with a 3D model from the beginning of the project improves object visualisation and allows all parties to gain a better understanding of the asset. BIM objects should be modelled taking into account its installation/maintenance space requirements and its health and safety too. This can be achieved by adding to their BIM models a CDM BIM object that allows you to place a warning tag within the model to identify hazards. Each tag could denote a potential hazard which could be assigned an Excel Link which is connected to an Excel version of a Risk Register. This allows all contributors to see the risk associated with a particular tag in a common and easy to use format.

Rajendran and Clarke (2011) undertook research which identified several areas in which BIM could help mitigate some of the risks associated with construction. The first area identified was in the introduction of new employees to the site. By using a BIM model to provide a site induction, new workers would be able to gain a better understanding of the potential risks before actually stepping foot on the site. Another area that could benefit would be pre-task planning where contractors are able to identify construction sequences before construction begins allowing for the provision of the necessary tools and materials as well as safety equipment. This also links in with undertaking a job hazard analysis to develop safe methods of working; this is particularly beneficial for subcontractors who may be coming on site to perform a high risk activity. Aside from the benefits that can be seen in terms of pre-construction planning, there is also the opportunity to use the same technology to analyse accidents after they occur; the virtual reality work space will allow for a better understanding of what happened and allow for a better analysis to ensure that such incidents do not occur again.

A case study undertaken by Azhar et al (2012) on a new $50 million (USD) Recreation and Wellness Centre at Auburn University aimed to see the perceived benefits of BIM in H&S on a real life project. After a discussion with various focus groups, it was decided that BIM would be used to address the “fatal four” construction risks, i.e. falls from height, electrocutions, struck by objects and caught in between. These risks were particularly noticeable in certain activities and as a result, these activities were modelled to see the potential outcomes. The first was to introduce a crane management plan which identifies the swing radius of a crane to ensure that it was not in danger of coming into contact with power lines, and if it were to topple, that it does not come into explosive substances. The image in Figure 4 displays how such information could be seen in a BIM model.

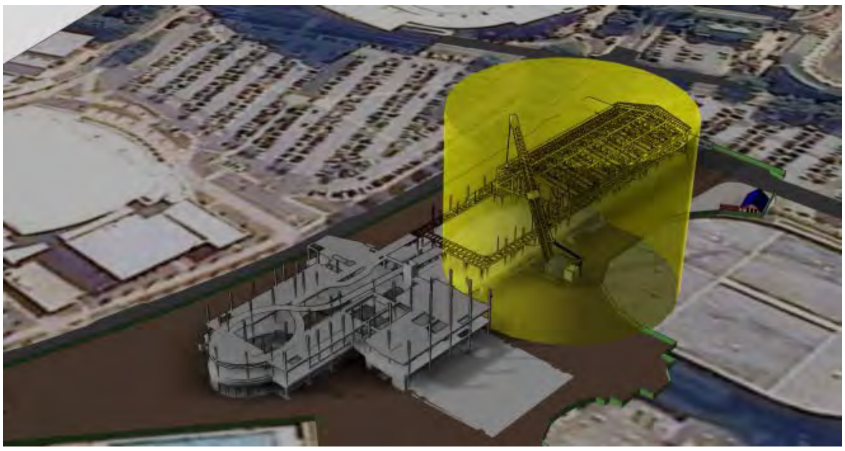


Figure 11: Crane radius shown in a BIM model (Azhar et al 2012)

The second construction activity that was modelled was earthworks as excavations were up to 8ft deep and sheet piles were required to avoid cave-ins. The construction sequencing was modelled to ensure that there was adequate space to work and that the necessary safety barriers were in place to avoid workers falling in. The safety barriers in place were also similar for the fall protection plan, where barriers were modelled wherever an edge was exposed. Barriers are not easily seen in 2D plans so it was important to model them around stairwells, balconies, skylights etc. The final activity that was modelled was a 4D emergency response plan which aimed to help workers orientate themselves on site and to avoid areas of high risk and areas of particularly high traffic. In the validation process of this case study, Azhar et al (2012) received feedback from a Focus Group of BIM professionals who noted the benefits as 1) The improved communication of the safety plan amongst those on site and 2) Pre-construction planning including details of logistical issues. Overall, the case study was seen as a success and identified areas that can be improved on future works.

5. CONCLUSIONS AND PROPOSED RESEARCH PROJECT

Based on the potential use of BIM for H&S in construction as documented in the paper, proposed research will examine the approach to using BIM as a platform to elucidate construction, operation and maintenance health hazards and using the principles of prevention devise mechanisms for their control. This will be done by developing an algorithm within the Industry Foundation Class (IFC) data schema; this is an open data schema that is compatible with many CAD programs. The aim of the algorithm will be to automatically identify risks that are identified within a BIM model, i.e. fall from heights and potential trips hazards. The hazards identified by the algorithm will then be flagged up within the BIM model, with a potential solutions provided; it is then up to the design team to choose the most appropriate solution. Further development of this concept would aim to include a suitable health rating system that can be applied to give all operatives an indication as to the potential risk involved to those on site. This system will be similar to a risk matrix where a high ranking indicates a high risk exposure and a vice versa for a lower number.

It is proposed that all projected health & safety related data that is required to achieve the project aim and objective resides in an Asset Information Management System (AIMS), with the building CAD only storing the associated Asset ID and linking through to AIMS.

To achieve the above, the following steps could be used:

1. Select a structure suitable for 3D modelling
2. Structure the model according to the Asset Hierarchy
3. Capture information about the materials used and any know hazards
4. Through construction sequencing, identify and visualise any known health hazards (vibration, noise, carcinogen exposure etc.)
5. Facilitate a health risk identification process that for each asset evaluates the health hazards and identifies controls.
6. Once the health risk identification process is complete undertake a similar assessment for the operation and maintenance of the structure

7. Devise a simple visual rating system that can be applied to the structure

The overall strategy with regards to information management is to keep the CAD data light in terms of attribution, but to utilise the AIMS which holds the definitive set of information about building assets (refer to figure 5). To further extend this, a spatial view of the health risks is required as a "heat map" within a 3D Viewer. To achieve this, the following steps are required:

1. Perform a gap analysis of existing 3D data (from the BIM model) to AIMS

2. Create a relationship between the individual assets (at entity level if feasible) and the BIM features (on the Asset ID)

3. Develop a heat map based on health risks and their categorisation for display in 3D visualisation

4. The conceptual architecture of the proposed system can be seen in Figure 4 below.

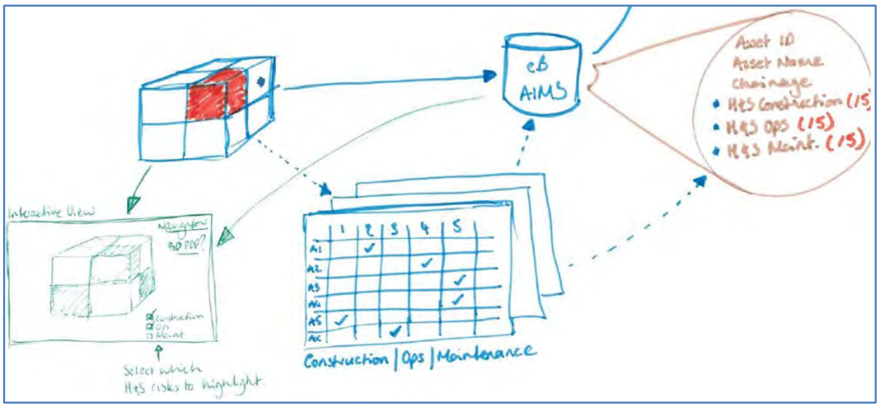


Figure 12: Conceptual Architecture and Information Flow

The aim of taking such an approach is to keep all those on site informed of the potential risks posed to construction workers. By incorporating information in such a visual format, the information is more compact and easily interpreted. All such developments epitomise the concept of collaborative working as site safety is the responsibility of all parties on site and so should be available on a uniform platform. Regardless of the nature of the project, by taking the correct preventative steps prior to construction, the H&S record of the industry will inevitably improve and remove the stigma associated with the industry as being a high risk environment.

6. REFERENCES

Azhar Salman, Michael Hein and Blake Sketo (2008) 'Building Information modelling (BIM): Benefits, Risks and Challenges ', McWhorter School of Building Science, pp. 6-12 Available at: ascpro.ascweb.org/chair/paper/CPGT182002008.pdf

Azhar Salman, Alex Behringer, Anoop Sattineni, Tayyab Maqsood (2012) *BIM for Facilitating Construction Safety Planning and Management at Jobsites* , USA

Bazjanac, V. (October 23, 2006). Virtual Building Environments (VBE) – Applying Information modelling to Buildings http://repositories.cdlib.org/lbnl/LBNL-56072

Bew, M. and Richards. M. *Bew Richards Maturity Model*, 2008.

BSI, PAS 1192-2:2013 Specification information management for the delivery phase of construction projects using building information modelling. London: British Standards Institution. 2013

BTG (2013) 'BIM Task Group Newsletter ', BIM Task Group, (PAS 1192-3), pp. [Online]. Available at: http://www.bimtaskgroup.org/articles/digital-library/

CIOB The Chartered Institute of Building (2015) *BIM Around the World,* Available at: *http://www.construction-manager.co.uk/agenda/bim-around-world-country-country/*

Egan, J. Rethinking Construction: Report on Construction Task Force. London: HMSO, 1998

ESENER European Survey of Enterprises on New and Emerging Risks (2014) Surveys & Statistics , Available at: https://osha.europa.eu/en/surveys-and-statistics-osh/esener

HSE (2007) Health and Safety, The Construction (Design and Management) Regulations 2007', [Online]. Available at: www.hse.gov.uk/construction/cdm.htm

HSE (2015) H&S in the construction industry, http://www.hse.gov.uk/construction/

Latham, M. Constructing the Team: *Final Report of the Government/Industry Review of Procurement and Contractual Arrangements in the UK Construction Industry*. London 1994

Mott Macdonald (2014) Building Information modelling, Available at: https://www.mottmac.com/article/2385/building-information-modelling-bim

NBS. *NBS National BIM Report 2014*. Newcastle upon Tyne: NBS. 2014

RIBA Royal Institute of British Architects (2013) *RIBA Plan of Work 2013,* Available at: *www.ribaplanofwork.com*

Sathy Rajendran and Brian Clarke (2011) *BIM Safety Benefits & Opportunities*, Professional Safety: American Society of Structural Engineers.

Schatz Kristian, Uwe Rüppel, (2011) Designing a BIM-based serious game for fire safety evacuation simulations, Available at: http://www.sciencedirect.com/science/article/pii/S1474034611000589#

Succar, B. (2009) Building information modelling framework: A research and delivery foundation for industry stakeholders. In: Automation in Construction, 18: (3): 357 – 375

UK GOV (2012) Government Construction Strategy, Available at: https://www.gov.uk/government/.../government-construction-strategy 2012

VTT (2013) *BIM Baser Safety Management,* Available at: *www.vtt.fi/sites/bimsafety/en*

Zhang, S., Teizer, J., Lee, J., Eastman, C.M., Venugopal, M. *Building information modelling (BIM) and Safety: Automatic Safety Checking of Construction Models and Schedules*. Automation in Construction, 29, pp. 183195. 2013

BIM-BASED SMART FACILITY MANAGEMENT VIRTUAL REALITY VIA INDOOR LOCALIZATION TECHNOLOGY

Rui LIU

Assistant Professor, M.E. Rinker, Sr. School of Construction Management, University of Florida, USA

Yishuai CAO

Master Student, Engineering School of Sustainable Infrastructure & Environment, University of Florida, USA

Xiaolin LI

Director, NSF I/UCRC Center for Big Learning, University of Florida, USA

ABSTRACT:

Despite Building Information Modeling/Model (BIM) supported Facility Management has been explored in the past, it has not been successfully implemented. One of the existing challenges is to enable easy accessibility of BIM and the embedded information in the model while the facility management field workers are off their desk and in the field. Such information is available in the as-built BIMs but hidden behand in the physical environment. It reduces re-visit times if the facility operation/maintenance workers can localize the information while they are on the field. Accurate localization is a key challenge for the accurate presentation of BIM visualization and the related non-geometry data. Localization accuracy is required for partial BIM model extraction for the field workers in a real-time manner especially for confined areas. To tackle this challenge, this paper presents a BIM-based smart facility management virtual reality (SFMVR) via indoor localization technology. The adopted technology improved the indoor localization accuracy down to centimeter-level. This paper illustrated how the integration of high-precision indoor localization and BIM can assist facility management activities. A prototype application has been demonstrated that SFMVR can simultaneously synchronize the location information and communicate with the BIM server for the real-time model visualization in the facility maintenance field. It makes the real-time model extraction a mission possible. Successful implementation of SFMVR will improve the localization and visualization of FM and reduce field re-visit times and the labor cost.

KEYWORDS: *BIM, Facility Management, Indoor Localization, Opportunistic sensing, Smart Mobile Devices*

1. INTRODUCTION

Current BIM implementation in the AECO industry focuses on design and construction practice. The utilization of BIM in facility management (FM) lags behind BIM implementation in earlier project phases. BIM (Building Information Model/Modeling) is defined as “a digital representation of physical and functional characteristics of a facility” and should serve as “a knowledge resource for information about a facility forming a reliable basis for decisions during its life cycle from inception onward.”(Smith 2008). Every developed BIM should contain critical facility life cycle information. Although benefits of implementing BIM for FM can be significant, there are still many challenges (Liu 2012, Liu and Issa 2013, Liu and Issa 2014, Liu 2016). One of the challenges for BIM for FM practice is to provide accessibility of building information models to facility management field professionals during operation and maintenance work. Real-time visualization of the model and accurate localization of a specific utility or the field professional in an unfamiliar physical facility can be difficult and time consuming. Some research has explored the indoor localization options such as passive RFID technology. However, there is a challenge for the accuracy of localization. Previous studies stated that an accuracy of one meter or less is the future goal of such research, their greatest system accuracy achieved was 1.66 m (Costin and Teizer 2015). In order to provide the right information from the BIM and provide BIM visualization for the field users, a higher localization accuracy is necessary. Depending on the size of different rooms, highly accurate indoor localization is needed at meter level at least. In some special cases such as confined spaces, centimeter level is required.

2. RELATED WORK

This section briefly presents the challenges and benefits for the utilization of BIM in facility management and previous related researches about indoor localization.

2.1 BIM for Facility Management

Even though BIM can benefit FM in many ways, 57.4% of the FM industry is not sure what BIM actually is (Ashworth et al. 2016). In addition, although some owners required adoption of BIM for their new construction projects, it was rarely used for facility management purpose (Liu 2016). Previous studies have shown that the AECO industry has already recognized the existence of silos between different parties (Liu and Issa 2014). With the development of computer technologies, the unfamiliarity of the body of knowledge between different parties should be diluted especially when BIM is implemented through the life cycle of a construction project. Investigation of the business needs and objectives of the facility management team, the final users of BIM delivery, are of critical importance to BIM-integrated project life cycle management. Research efforts are needed to facilitate seamless integration of building information into facility management practices. It would increase efficiency in facility management activities if facility operation and maintenance (FOM) teams could use “as-built” information for maintenance activities without extensive effort. It would increase efficiency in facility handover if FOM practitioners could extract required information from BIMs directly in real time (Liu 2016).

2.2 Location Awareness and Context-Aware Computing

Achieving real-time visualization of partial BIM through smart mobile devices in the field requires both location awareness and context awareness. Location awareness means each mobile host uses a positioning device to determine the current physical location (Yu-Chee et al. 2001). In another word, location awareness is an implementation of context-awareness (Schmidt et al. 1999). Context is defined as any information that can be used to characterize the situation of a person, place or object (Abowd et al. 2001). Context-aware system is a system that can provide the user with task-relevant information and/or services by using context. By the implementation of context awareness, when the user put ultra-mobile device on the specific location, the mobile host can identify the surrounding environment and provide the user with the information from the BIM model like pipe or ducts behind the wall.

2.3 Localization Via Hybrid Approaches

In order to achieve a comprehensive understanding of localization of related information within a BIM and the virtual environment, different localization technologies have been investigated to locate asset and users. These technologies include the use of GPS, Wi-Fi, ZigBee, Radio Frequency Identification Devices (RFID), Ultrawideband (UWB), Bluetooth, Acoustic Signals, and other technologies that fall in-between these categories. Table 1 shows relative applications and accuracies that have been identified with various localization technologies included within this research. Several single and hybrid approaches are discussed as follows.

Wireless localization technologies are relatively inexpensive and readily available to the general public without additional hardware installation requirements. Some wireless technologies, such as wireless local area network (WLAN) technique, are not primarily designed ranging and localization applications, but studies show the feasibility of using these systems. For example, WLAN based system, “Ekahau”, allows location to be determined within an x, y, and floor level with an accuracy up to 1-3 meters (Curran et al. 2010). One of the wireless technologies, wireless fidelity (Wi-Fi) system, provides wide coverage, easy availability and are relatively stable. While, another wireless technology, the ultra-wide band (UWB) technology. requires low energy consumption for data transmission(Choliz et al. 2011). While time difference of arrival (TDOA) is a powerful and commonly used technique that relies on time synchronized infrastructure to estimate the range of a mobile device, combining UWB with TDOA (Time Difference of Arrival) algorithm achieved the accuracy from 15 cm to 28cm (Long et al. 2016).

Based on the comparison with six techniques of accuracy, power supply, data storage, affordability, device lifetime and other aspects, RFID was proposed for indoor positioning by Li and Becerik-Gerber (2011). RFID does not require lines of sight environment and can work in noise construction site. In addition, with the integration of the application of particle swarm optimization-based back propagation (PSO-BP) neural network into RFID, RFID localization systems can reduce the average error to 0.3448 meter (Wang et al. 2016). BP neural network can provide with predictive accuracy to deal with the nonlinearity problem, PSO can help determine these parameters and Gaussian filter to process the data and received signal strength values.

Another localization technology is the application of Bluetooth technology (Di Flora et al. 2005). A way to take advantage of a Bluetooth transmitters short range output was to use predetermined zones that the signals work out of. In the research of indoor localization based on Bluetooth Low Energy RSSI (received signal strength index) system with triangulation showed that the precision was 0.2-0.5 meter Chai et al. (2016). Moreover, ZigBee devices use a wireless mesh network technology addresses remote monitoring and control applications (Shen et al. 2008). Compared to other positioning technologies, these devices provide low data rate, low power consumption, low complexity, high reliability and security. A recent research utilized ZigBee with cluster tree topology in the framework to achieve about 5 meters precision (Kuo et al. 2016).

Acoustic signals were explored in the indoor positioning research too. Escort was a proximity based system using only audio beacon (Constandache et al. 2010). Beacon placement did not change the stability of Escort’s too much, but it required dense sensors and the precision can’t meet the requirement. A modified acoustic indoor positioning system was achieved with the implementation of receivers synchronized with a Wi-Fi network (Ens et al. 2015). With the height defined, the positioning error was less than 30 cm.

Guoguo system used high-band acoustic signals based anchor network (Liu et al. 2013). High-density pseudo-codes was applied to the transmission scheme for not using radio assistance. With the integration of anchor nodes and cloud server, the work place can be made a context-aware environment in which a high precision indoor localization ecosystem has achieved centimeter level accuracy.

Table 1: Indoor and outdoor location technologies and accuracies.

Technology	**Indoor**	**Outdoor**	**Accuracies**	**Sources**
Cellular Data	✓	✓	200 m +	(Shen et al. 2008)
A-GPS	✓	✓	15-50m	(Burnham 2001)
Wi-Fi	✓		3-30 m	(Chen et al. 2012)
ZigBee	✓		5 m	(Kuo et al. 2016)
GPS		✓	1-5 m	(Koyuncu and Yang 2010)
Bluetooth	✓	✓	0.2-0.5 m	(Chai et al. 2016)
RFID	✓		0.35 m	(Wang et al. 2016)
UWB	✓		15-28 cm	(Long et al. 2016)
Redpoint Positioning	✓		20 cm	(Redpoint Positioning 2016)
Guoguo	✓		5-10 cm	(Liu et al. 2013)

3. METHOD

This section will show how to achieve BIM-based facility management with the high-precision indoor positioning.

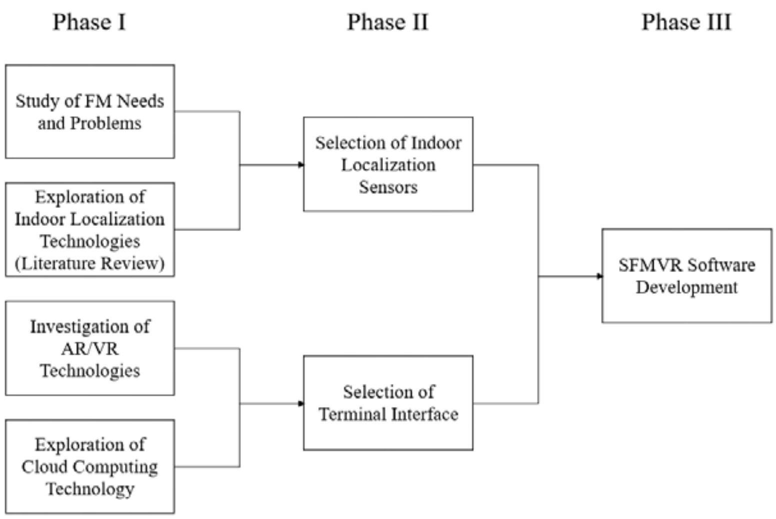


Fig. 1: System Development Research Workflow

Anchor Network. Anchor nodes are placed in indoor places to ensure the smartphone can have at least four beacon signals, which are acoustic with high detection sensitivity. The deployment of anchor nodes should follow the symbol-interleaved beacon structure requirement. After that, using a radio chip for the controller beacon and synchronize all the anchor nodes to it. Then utilizing other beacons to provide ranging and synchronization information to the smartphone. The smartphone can calculate the relative time-of-arrival (TOA) (Liu et al. 2013).

Terminal. The acoustic signals are detected from nodes by the sensor in the terminal which can be a smartphone, IPAD and many other mobile devices. With the sensor in the smartphone, the acoustic signals can be detected from anchor nodes to match the demodulated digital symbols to verify beacons' identification and position. Through the process of the measurement of TOA signals, pseudo-ranges are acquired. Then the accumulation of the distances from various acoustic beacons is utilized to calculate the location (Liu et al. 2013).

Cloud Server. The terminal transmits a ranging result from the original data to server application, and it calculates the location. After the calculation in the server, the server application sends the localization information to the terminals. Then, it can be located in the current location. BIMs were stored in the cloud server. When the building identification and the location information is determined, server locates the corresponding BIMs and extracts the partial BIM visualization view for the client server.

Smart Facility Management Virtual Reality (SFMVR) Software. The SFMVR software is created to integrate the BIMs with location information for the facility management purposes. Once a user moves into a signal coverage that acoustic beacons provide, a link is made connecting to the SFMVR software. Then the localization process runs in the background. When the terminal is located specifically, the real-world location information is transmitted to locate correspondingly in BIM model through the cloud server. After accurately extracting the related information from architectural, structural, mechanical, electrical, plumbing (MEP) or other model information, the SFMVR software visualizes it into a 3D model on application program interface (API). This study is divided into three phases. In the first phase, four main aspects are implemented: overview of challenges and opportunities of current FM, analyzing various indoor localization technologies, investigating AR/VR technologies and exploring cloud computing technology. In phase II, with the proposal of integrating indoor localization and visualization technology into FM, this study selects appropriate indoor localization sensors and terminal interface. Then the SFMVR software, combining localization of terminal and in BIM model as well as visualization of BIM model, is developed in phase III.

4. PILOT STUDY

The proposed method was demonstrated the accuracy of the application created for BIM software to integrate a user's location through a mobile device to the model. This study focused on indoor localization technology to fine-tune the application accuracies and extracted information from BIMs. The proposed system should have sufficient accuracy and provide the end users with the corresponding partial BIM visualization.

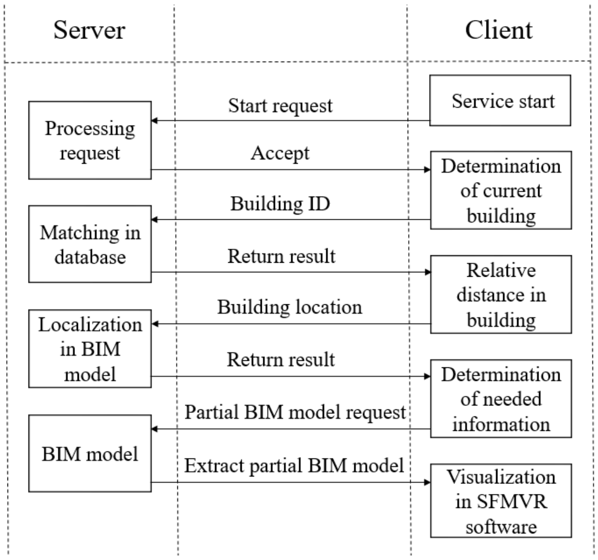


Fig. 2: Server-Client Model

In the case study, the building was zoned based on the spacing of acoustic beacons and their relative signal strength due to interruptions of interior partitions and other building components. Acoustic beacons were placed with four of them in each room or corridor. Then, the server was developed to store BIMs and the user's position data which was collected from the location devices. The user installed the SFMVR app on the smartphone before entering the building. SFMVR was used to communicate locations between BIM server and extract the corresponding perspective from the model. Once the user entered the building, locations were taken at multiple instances. These locations had been previously documented in terms of x, y, and z coordinates to provide constants to the base of the accuracies. The locations were taken down when the user clicked the button on the software to process the localization. Then a connection was made with the ZigBee devices and sent to the server for filtering and recording. When this was achieved, the location was shown up on the base station BIM model. After that, this partial model was transmitted back to the smartphone through Wi-Fi connectivity. A way to achieve this was through the SFMVR software itself, where once the location was transmitted to the server, BIM model, which was already synched to the SFMVR software could have relative location concurrently showing through the user's SFMVR application on their device. Then the software located the user and had an updated BIM model of the building they are navigating through. Fig. 2 shows the server-client model which is applied in this case.

The client is a terminal which can be a smartphone, PDA or other mobile device. The server is a backend processor which powers the indoor positioning system and provides the storage of BIM models. The client starts service and sends request to the server. The server accepts the request. Then the client provides the current building ID. The server searches in the database which contains many BIMs and then pairs with the corresponding model. Next, with the detection of signals from anchor nodes, the client provides the location information which is performed by the senor in the terminal. The server can locate the corresponding visualization in the BIM. Finally, the client can request corresponding BIM perspectives from the server and visualize it in the SFMVR software.

An implementation example of the SFMVR is shown in Fig. 3. Fig. 3-Ashows the user's relative location to the whole building, Fig. 3-B shows the location with appropriate section which demonstrates the location with the reference of floor and walls. Fig. 3-C is the ceiling section view with the terminal's location. Fig. 3-D is a rendering view illustrating the end user's view on the mobile device through the SFMVR software. The walls and ceilings are peeled to expose the pipes, ducts and other systems that are hidden in the physical world.

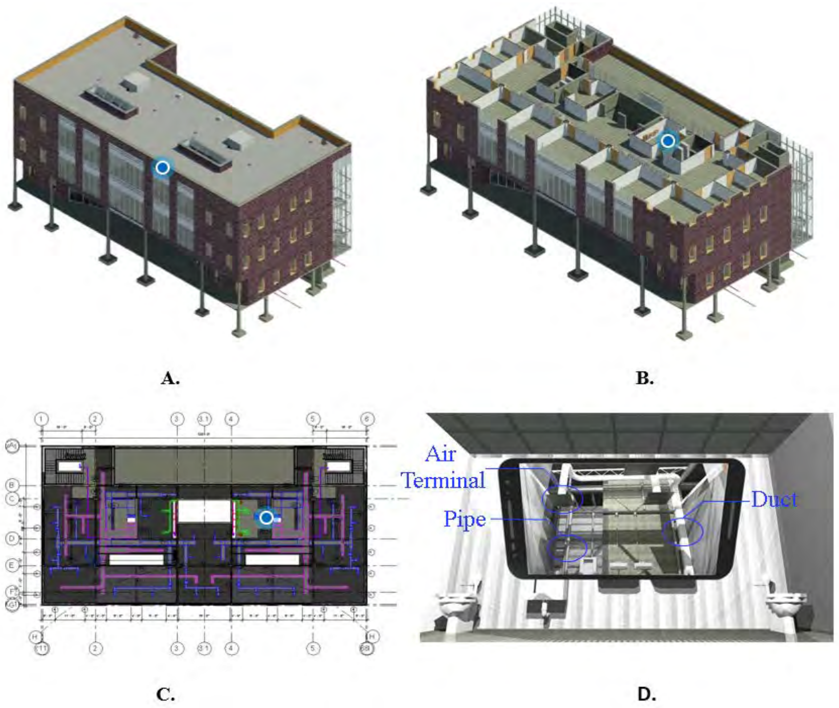


Fig. 3: Demonstration of SFMVR Visualization.

The SFMVR software can aid a user to "see through" the walls and ceilings with the functions to hide/peel different layers and objects in the virtual world. In addition, this tool can assist the end users to determine other non-geometry product information such as the materials, colors, pipe connections and many others stored in the BIM cloud server.

5. DISCUSSION

Facility Operation and Maintenance tasks are usually backlogged due to inefficient means and methods of approaching individual tasks, especially for giant organizations with complex organization structures. A lack of information, communication and virtual presentation of documents for the field workers to perform their daily job is one of the reasons for the backlog. With the development of BIM implementation, as-built BIM model can provide most of the information FM field workers need including geometry information (dimensions) and non-geometry information such as material, color, manufacture and contact. This study proposed to use current indoor localization technology to facilitate the end users' need for accessing information in the as-built BIMs. Success implementation of such technology can improve field maintenance worker's efficiency of their working process, reduce the backlog of maintenance work, and eventually reduce the FM cost.

One of the problems of this technology implementation is the unavailability of accurate “as-built” BIMs. Although BIM has been required for US GSA, Air Force and many other owners at handover, the usage of BIM for FM purposes is rare (Liu 2016). In addition, the quality of “as-built” BIM model at handover is insufficient to meet facility operation and maintenance requirement due to the incomplete and invalid information stored. Moreover, communication and collaboration among different departments in the organization is a challenge. In a case study published by Fiatech, field workers do not know the existence of BIMs and they showed no interest in understanding them and obtaining information from them(Liu 2016). Although they need the information to perform their work, they would prefer to visit the site and collect information on their own. Each department performs their job according to their traditional ways. Thus, the easy-to-access virtual environment has the potential for the end users (field workers) to change their working process and pattern of behavior.

Future studies can focus on the following areas. First of all, the process to generate “as-built” BIMs. Although several existing studies proposed some processes, adoption of such process in the AECO industry is difficult. Minor missing details within the BIMs can cause a flux in communication between different software platforms. Using information technology such as reminders, social media, email communications to enhance the communication between stakeholders’ personals is worth studying. CMMS (computerized maintenance management software) and BIM software interoperability should be studied and improved. Secondly, the organization structure and project structure should be investigated in order to adapt to the technology improvement. Thirdly, knowledge sharing among the same organization and across different organizations is also important especially between stakeholders at different phases. Moreover, augmented reality technology can be embedded into this current proposed framework in the future.

6. CONCLUSION

This present study demonstrated a BIM-based smart facility management virtual reality (SFMVR) for indoor localization with a higher accuracy to better meet the requirement of facility operation and maintenance. The proposed SFMVR integrated of indoor localization technologies and BIMs, therefore it provides easy accessibility of BIM and the embedded information that the facility management field workers need. SFMVR also simultaneously synchronizes the location information and communicates with the BIM server for the real-time model visualization to facilitate facility maintenance field tasks. A pilot study has been performed to validate the proposed system. Successful implementation of SFMVR will improve the localization and visualization of FM and reduce field re-visit times and the labor cost.

7. REFERENCES

Abowd, G. D., Dey, A. K., Brown, P. J., Davies, N., Smith, M., and Steggles, P. (2001). *Towards a Better Understanding of Context and Context-Awareness*.

Ashworth, S., Tucker, M., Druhmann, C., and Kassem, M. (2016). "Integration of FM expertise and end user needs in the BIM process using the Employer`s Information Requirements (EIR)." *European Facility Management Conference 2016*, IFMA, Milan.

Burnham, J. P. (2001). *The Essential Guide to the Business of U.S. Mobile Wireless Communications*, Prentice-Hall PTR, Upper Saddle River, NJ.

Chai, S., An, R., and Du, Z. (2016). "An Indoor Positioning Algorithm Using Bluetooth Low Energy RSSI." *International Conference on Advanced Material Science and Environmental Engineering*, 276-278.

Chen, Y., Lymberopoulos, D., Liu, J., and Priyantha, B. (2012). "FM-based indoor localization." *Proceedings of the 10th international conference on Mobile systems, applications, and services*, 169-182

Choliz, J., Eguizabal, M., Hernandez-Solana, A., and Valdovinos, A. (2011). "Comparison of Algorithms for UWB Indoor Location and Tracking Systems." *IEEE Vehicular Technology Conference*, IEEE 73rd, 1-5.

Constandache, I., Bao, X., and Azizyan, M. (2010). "Did You See Bob?: Human Localization using Mobile Phones." *Proceedings of the sixteenth annual international conference on Mobile computing and networking*, 149-160.

Costin, A. M., and Teizer, J. (2015). "Fusing passive RFID and BIM for increased accuracy in indoor localization." *Visualization in Engineering*, 3(1), 1-20.

Curran, K., Furey, E., Lunney, T., Santos, J., Woods, D., and McCaughey, A. (2011). "An evaluation of indoor location determination technologies." *Journal of Location Based Services*, 5(2), 61-78.

Di Flora, C., Ficco, M., Russo, S., and Vecchio, V. "Indoor and outdoor location based services for portable wireless devices." *Proc., Distributed Computing Systems Workshops, 2005. 25th IEEE International Conference on*, IEEE, 244-250.

Ens, A., Höflinger, F., Wendeberg, J., Hoppe, J., Zhang, R., Bannoura, A., Reindl, L. M., and Schindelhauer, C. (2015). "Acoustic Self-Calibrating System for Indoor Smart Phone Tracking." *International Journal of Navigation and Observation*, 2015, 1-15.

Koyuncu, H., and Yang, S. H. (2010). "A Survey of Indoor Positioning and Object Locating Systems " *IJCSNS International Journal of Computer Science and Network Security*, 10, 121-128.

Kuo, W.-H., Chen, Y.-S., Cheng, K.-T., and Lu, T.-W. (2016). "Signal Strength Based Indoor and Outdoor Localization Scheme in Zigbee Sensor Networks." *IAENG International Journal of Computer Science*, 1-10.

Li, N., and Becerik-Gerber, B. (2011). "Performance-based evaluation of RFID-based indoor location sensing solutions for the built environment." *Advanced Engineering Informatics*, 25(3), 535–546.

Liu, H., Gan, Y., Yang, J., Sidhom, S., Wang, Y., Chen, Y., and Ye, F. "Push the limit of WiFi based localization for smartphones." *Proc., Proceedings of the 18th annual international conference on Mobile computing and networking*, ACM, 305-316.

Liu, K., Liu, X., and Li, X. "Guoguo: Enabling fine-grained indoor localization via smartphone." *Proc., Proceeding of the 11th annual international conference on Mobile systems, applications, and services*, ACM, 235-248.

Liu, R. (2012). "BIM-based life cycle information management: Integrating knowledge of facility management into design." University of Florida.

Liu, R. (2016). "Guidlines for BIM Supported Information Exchange for Facility Sustainment Management System." Fiatech.

Liu, R., and Issa, R. "Issues in BIM for Facility Management from Industry Practitioners' Perspectives." *Proc., ASCE Computing in Civil Engineering (2013)*, ASCE, 411-418.

Liu, R., and Issa, R. R. (2014). "Design for Maintenance Accessibility Using BIM Tools." *Facilities*, 32(3/4), 153-159.

Liu, R., and Issa, R. R. A. (2016). "Survey: Common Knowledge in BIM for Facility Maintenance." *Journal of Performance of Constructed Facilities*, 30(3), 04015033.

Long, C., Shen, C., Feng, G., Zhu, Y., and Wang, Z. (2016). "Research on Network Scalability Based on UWB Indoor Localization System." *MATEC Web of Conferences*, 42, 07003-p.07001-07003-p.07005.

Redpoint Positioning

Part V: Big Data and IT in Construction

LABOR SENTIMENT ANALYSIS FOR THE CONSTRUCTION INDUSTRY: A CASE STUDY OF TWITTER IN THE USA

LiYaning Tang*

Department of Civil and Environmental Engineering, West Virginia University, USA

Yiming Zhang*

Lane Department of Computer Science and Electrical Engineering, West Virginia University, USA

Fei Dai

Department of Civil and Environmental Engineering, West Virginia University, USA

Yoojung Yoon

Department of Civil and Environmental Engineering, West Virginia University, USA

Yangqiu Song

Lane Department of Computer Science and Electrical Engineering, West Virginia University, USA

Radhey S. Sharma

Department of Civil and Environmental Engineering, West Virginia University, USA

** Equal contribution*

ABSTRACT: *Construction industry is a labor-* intensive *industry. Sentiment or mood of worker is a key issue in this business. To analyze this issue, using traditional ways such as questionnaire survey to collect data is both time- and cost-consuming. Recently, with the rapid development of social media services, data can be collected and extracted for sentiment analysis to provide officials and managers with fresh perspectives on labor in the construction management. In this paper, a labor sentiment analysis systematic framework is proposed. This system collected user messages from social media sites, establishes and compare different clusters emotion dictionaries by location, time, etc. This paper generated valuable information and knowledge in the construction domain. As an initial trial, this study selected social media of Twitter because of its wide usage in the United States. Four clusters which include construction workers, construction companies, construction unions, and construction media were analyzed. For each user identified in the four clusters, the 3,200 most recent twitter messages were collected. This research then analyzed these data in the following aspects to dig out sentiments behind data: hourly, daily, monthly, and locations. Detailed findings, benefits and barriers to incorporating social media data analytics in the construction industry, along with future research, were discussed. This paper benefits the academia by testing an alternative way of studying the construction population, which further will help decision makers better understand the real situations of the construction industry.*

KEYWORDS: *The construction industry; Social media; Sentiment analysis; Twitter; Big data; United States*

1. Introduction

Construction as a practical industry, issues about labors in the construction industry are always hot topics for researchers. Due to the increasing use of the Internet, never-ending growth of data are generated from the social media. All these sources of information could potentially assist in obtaining valuable administrative data and could even find new social phenomena. The construction industry might not be readily associated with the use of social media, but many construction companies are using social media to improve visibility and build brand awareness. Lots of construction workers are using social media to connect with friends and get information on projects and career. Social media has played a prominent role in current information society. The use of social media provides the opportunity to extract data that might be of benefit to the construction industry in a rapid and inexpensive manner.

In recent years, more and more research has focused on sentiment relevant topics. Construction industry as a labor-intensive industry, sentiment of workers is necessary to study. For example, negative feelings of workers would cause serious safety problems during working. Moreover, understanding sentiment of workers can benefit project management a lot. To this end, sentiment analysis using data extracted from social media is applied in this research to provide officials and managers with fresh perspectives on labor in the construction management.

This paper begins with the background of social media usage and sentiment analysis in the construction industry. Then the data representativeness and collection are explained for how data will be analyzed. Four clusters, i.e., construction workers, construction companies, construction unions, and construction media, are main subjects in this paper. The next part is data analytics of construction relevant tweets in the USA as a case study. The paper concludes with a discussion of promising future research directions enabled by incorporating social media data analytics in the construction industry at the end.

2. Background

Collecting empirical data in the construction industry is expensive. Traditional data collection methods including questionnaire survey, focus group meeting, etc., have downsides, for example, the limited survey population and the uncertain validation of collected data (Tang et al., 2015). Data from social media could overcome these problems. Almost all of the social media platforms allow users to post text messages to share their opinion, emotion, or comments to personal activities, news, and burst events. There are also some research on using social media for better communication among the participants involved in different construction development phases. For example, Fox et al. (2010) found developed technologies of media including social media have enabled changes in the means and locations of communication. El-Diraby (2013) used social media to create a new era in the evolution of urban infrastructure that shifts it from the realm of professional practices to a sociotechnical realm. The research mentioned that infrastructure is being transferred from a technical/business project into a sociotechnical project that is part of the evolving knowledge economy and e-society. Leung et al. (2013) pointed out that social media sites such as Facebook can be used to publish public engagement information for improving public engagement in construction development projects. Miles et al. (2014, 2016) found social media is a good way for communication during power outage to disseminate and find information. Russell et al. (2014) encouraged construction companies to use social media pages including Facebook, Twitter, Google+, Pinterest, and LinkedIn to showcase what they do and how they do it, and to build relationships with current and potential clients. Tanielian (2014) found social media can be used to spur radical change in energy consumption habits, share ideas, and broadcast theories. Bakht and El-Diraby (2015) said citizens, empowered with apps and an unfettered access to open knowledge, were eager to lead the idea generation on equal footing with professionals. They also wanted decision-making rights equal to those granted to government officials and/or project owners. That made social media play a more active role beyond discussing already-designed projects in public meetings. Standohar-Alfano et al. (2015) used social media for understanding the choices people made to seed refuge from the tornado. It showed social media is a good way to find out that people knew which neighbors had residential shelters and that they were welcome to go to those site when it became necessary. Tortajada (2015) studied the better communication via social media. The emergence of social media has also revolutionized the who, how, and where of the discussions. This has substantially increased the number and type of actors, although discussions are not necessarily rich in content. Arnette and Zobel (2016) research on disaster control and used social media to keep impacted populations apprised of the latest developments to fundraising and donation management. They found using social media in disaster control is a new operational context, not just for donations management, but also for communication in the context of overall disaster relief effort management. Jonkman et al. (2016) found disseminating the warning message through social media was still not been fully harnessed, and suggested agencies should continue to raise public awareness about the region's hazards and are harnessing ness outreach opportunities such as social media.

Social media platforms have been used as sources to analyze diverse disciplines that traditional social science did not have enough data to analyze. For example social media has been used for analyzing social customer relationship management (Cumby et al., 2005; Bollen et al., 2011), political science (O'Connor et al., 2010; Ghani, 2013; Tumasjan et al., 2010), and emergency crisis or disaster management (Kelly, 2014; Linna and Goodchild, 2010; Sabrina et al., 2013; Annamalai et al, 2014), etc. Sentiment analysis and opinion mining have been studied for years in computer science community (Pang and Lee, 2008; Liu, 2012; Liu, 2015). The goal of sentiment analysis and opinion mining is to predict the polarities of the natural language showing on the Web, including reviews for online shopping and messages on social media. There are different aspects of sentiment and opinion, e.g., the positive and negative polarity of opinion, or different emotions like anger, disgust, fear, happiness, sadness, and surprise (Pang and Lee, 2008). Moreover, there are different levels of sentiment analysis, i.e., document level analysis, sentence level analysis, and aspect/attribute level analysis (Liu, 2012; Liu, 2015). One can use either rule based methods or machine learning based method to predict the sentiment from texts (Liu, 2012; Liu, 2015).

3. Data Representatives and Collection

Twitter is a social media platform allowing users posting information about their daily living or social activities, or their opinion about certain political events, news about companies, products, or celebrities and so on. More than 140 million active users post over 400 million 140 character "Tweets" every day. It has been one of the most important social media platforms for people to use all over the world.

The following data collection and processing modules are used to acquire all the data we need from Twitter. First, data collection is performed to get Twitter data. Then data processing is used to process and mine knowledge from data.

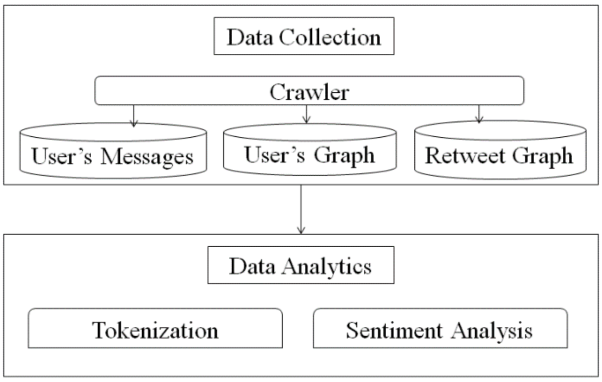


Figure 1. Data collection and processing flowchart.

3.1 Data Collection

In data collection, the Twitter APIs were used to collect data. When searching, the APIs opened by Twitter only allow us to get up to 1% of the public Tweet in a certain period (e.g., one week) when submitting a query.[5] Therefore, a new Web-based data crawler was developed instead, to parse the html Web pages we can browse at Twitter. By using the developed crawler, we were able to get more data as a user browsing the Twitter Website. This is one of the most comprehensive data set that can be collected out of Twitter for the construction domain. For statistics and user dependent tweet collection, the APIs were used. The API for tweet collection only allows us to get 3,200 tweets per user, which might be one of the bottleneck of our data collection process.

From Twitter social media platform, three different kinds of information were collected, i.e., user's messages, user's graph, and retweet graph.

- User's messages are the short 140-character messages that users post on Twitter. Each user can post a message at any time s/he likes. By using the Web search based crawler, all the tweets of interested users were collected in the period of 05.16.2008~03.10.2016.
- User's graph is the user's following and being followed connections. In Twitter, a user A follows a user B where A is called follower and B is called followee. All the user connections up to 03.15.2016 were collected in construction domain.
- Retweet graph is the graph that a user's message refers to another user. Previously Twitter allows re-post other users' messages and distinguishes the original post and the re-post. However, current Twitter interface does not allow users to see this information. Therefore, a surrogate method is used to obtain the retweets, which is to detect the "@" key. When a user use "@" to mention another user, a retweet is regarded as happened.

For the data considered in construction domain, four clusters of social media users are of interests, i.e., construction workers, construction companies, construction unions, and the public media who consistently posting news about construction related topics. Originally, a heuristic based method is used to obtain seed users from Twitter. The

[5] https://twittercommunity.com/t/potential-adjustments-to-streaming-api-sample-volumes/31628

heuristic rules include whether a user post messages containing keywords such as "construction" and "project," whether a user is follow a construction company or union. After obtaining the seeds, a propagation is performed to get more users. Then two annotators were asked to label whether the collected users are falling into the four categories. The mutual agreement is above 90%, and only the agreed users were retained. Statistics about the four types of users is shown in Table 1.

Table 1: Results of the collection of all Twitter data.

Dataset	Accounts (03.15.2016)	Tweets (05.16.2008~03.10.2016)
Construction Worker	397	275,325
Worker-Followers	8,051	49,578
Worker-Following	27,032	/
Construction Company	43	53,029
Company-Followers	2,043	/
Company-Following	3,359	/
Construction Union	67	48,880
Union-Followers	3,288	/
Union-Following	4,853	/
Construction Media	20	53,036
Media-Followers	747	/
Media-Following	1,580	/

To compare with the data collected by the Web based crawler, the Twitter API is also used to get the most comprehensive statistics related to the four clusters. Comparing Tables 1 and 2, it shows that the percentage of tweets obtained by the developed approach is less than 1% compared to the total 3,215,091 tweets for workers, while the percentages of company, union, and media are 58.7%, 53.8%, and 28.7% respectively. This means that the user's tweets are missed a lot, compared to other categories. The reason is that crawling API can only retrieve up to 3,200 tweets per user due to Twitter's policy. There are about half users posting much more tweets than 3,200 in the construction worker category. Whereas, in the other categories, the numbers of users posting more than 3,200 tweets is much less. From Table 2, it shows workers and media post more tweets everyday than companies and unions. Moreover, there are a lot of retweets shown in the numbers in Table 2 for users. Empirically, more than half of the tweet numbers of workers are retweets. For the other clusters, the numbers of retweets are much less.

Table 2: Statistics of Twitter users obtained by Twitter APIs.

Dataset	Total # tweets	#tweets per user (Mean)	# tweets per day/user (Mean)
Worker	3,215,091	1,116	1.2
Worker-followers	35,496,963	1,866	/
Worker-following	510,077,335	5,520	/
Company	90,369	1,280	0.5
Company-followers	9,031,812	529	/
Company-following	37,526,293	2,816	/
Union	90,904	454	0.3

Union-followers	17,359,156	543	/
Union-following	50,583,117	2,157	/
Media	184,918	5,119	2.5
Media-followers	2,613,514	422	/
Media-following	11,316,293	1,561	/

3.2 Data Analytics

The data analytics step significantly leverages the existing techniques developed in natural language processing. In natural language processing, two key techniques are considered, namely tokenization and sentiment analysis.

- Tokenization is applied to split the 140 characters into tokens (or words). A simple whitespace based tokenization is performed. Moreover, the hashtags (marked with "#") and user mentions (marked as "@") are also detected based on regular expressions.
- Sentiment analysis is a powerful tool for business analysts to understand the public opinion of social users on social media. In this work, the StanfordNLP[6] is used to perform sentiment analysis. Sentiment analysis has been successfully used for opinion mining and business analytics for news articles (Pang & Lee n.d.; Balahur et al. 2013). Then it has been extended for short texts such as tweets (Kiritchenko et al. 2014). The way used in StanfordNLP is based on deep learning, which has been recently proven to have similar state-of-the-art performance (Socher et al. 2013).

4. Case Study: Data Analytics of Construction Relevant Tweets in the USA

For each tweet posted on Twitter, StanfordNLP can use its existing models to classify it to be "positive," "negative," and "neutral." Some examples of the tweets with different sentiments are shown as follow.

- **Positive** tweets like "Nice day in the sun! Rendering is always good! #rendering #plasterer #southwest," "So it was a success and I have enjoyed working on the project is what I would like to do for a living. Well done every one and may be soon," and "Hot Houses @***… How cool to have the home we built for @*** firefighters - FS10 - featured in ..." (mentioned ids are anonymized).
- **Negative** tweets like "Doing construction you're always tired and you never get enough sleep.. " and "@*** but a very bad auction pricing system @***."
- Some of the tweets are also **neutral**, which means that there is no clear sign of positive or negative. For example, "Anyone know of any labouring work going in the south west at the minute? #labouring #work #southwest #building " and "Sub-bids requested for NIKE Westfield Parking - site work, electrical, landscaping, temp fence... ."

By applying the sentiment classification into the three categories to all the tweets in the four clusters, the statistics is shown as Table 3. From Table 3, it is shown that most of the tweets are without polar of sentiment. Especially, the tweets posted by Media users are mostly (63%) neutral. Moreover, workers tend to have more negative proportion of tweets compared to the other clusters.

Table 3: Sentiment analysis of all tweets collected

Types of attitudes	Worker		Company		Union		Media	
	Total number	Percentage (%)	Total number	Percentage (%)	Total number	Percentage (%)	Total number	Percentage (%)
Negative	56,859	20.7%	6,705	12.6%	9,530	19.5%	7,111	13.4%
Neutral	154,425	56.1%	30,558	57.6%	27,153	55.6%	33,392	63.0%
Positive	64,040	23.3%	15,766	29.7%	12,197	25.0%	12,533	23.6%

[6] http://nlp.stanford.edu/sentiment/

All	275,324	100%	53,029	100%	48,880	100%	53,036	100%

To show more details about the sentiment analysis results, the hourly, daily, and monthly number of positive, negative, and neutral tweets are shown in Figs. 1, 2, and 3 respectively.

In Fig.1, it shows that compared to the other clusters, workers post tweets consistently over time. Only around 3:00am-5:00am in the early morning, they post less messages. In the night, the peak of posting is around 9:00pm-10:00pm. This means that they may feel more free to spend time on social media to share their experience during night. The sentiment of workers is pretty even, where both positive and negative tweets are increasing and decreasing consistently. The other clusters, companies, unions, and media only post tweets in working time. For companies, there are two peaks of posting, i.e., 9:00am and 2:00pm. There is a drop of number during lunch time. This shows that the companies' accounts are handled by some certain employees who may work in personal relationship departments and are responsible for the company open account. They will treat posting tweets as work for their daily job.

For the unions, similar patterns have been found. However, comparing the sentiment, there are much more positive tweets than negative tweets posted by companies while there are relatively more negative ones posted by unions. This means that unions not only post positive tweets for themselves like companies, but also post some critiques about other events with negative opinions. By looking at the data, it seems that they care about fair employment and political issues for construction workers. Therefore, it is possible that they post negative opinions to attack more attention. For media accounts, it seems the peak of posting delayed compared to companies and unions. This may be because media will wait for the events or news happened in the daytime, and post through their account by a time delay. Thus, there will be a lag of time for them to collect the news of the day.

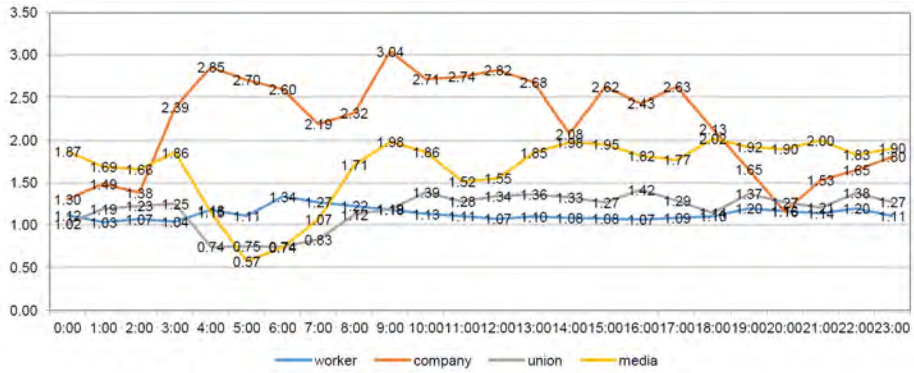
To compare the differences among different clusters, the ratio of positive and negative numbers are compared in Fig. 1 (e). In the figure, it shows that in general companies is the most optimistic cluster, which consistently posts positive tweets more than negative tweets. Workers are the least optimistic cluster. There are two relative higher period of time of a day, i.e., 6:00am in the morning and 7:00pm-10:00pm at night. This may show that during work, they are stressful because of early work and pretty tired after work. For companies and unions, there is drop around 5:00am. However, they post too few tweets at that time so that to make the statistics meaningful.

(a) Workers

(b) Companies

(c) Unions

(d) Media



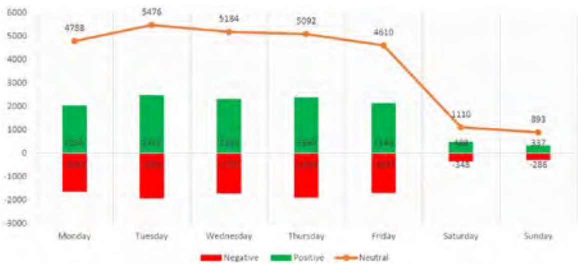
(e) Positive/Negative Ratio

Fig. 1: Hourly visualization of sentiment analysis for construction clusters.

The daily number of tweets are shown in Fig. 2 (a)-(d). In this figure (a), it shows that construction workers consistently post tweets every day. Whereas the other clusters post tweets only working days and the number significantly drops over weekend. To compare the different clusters, the ratios of positive numbers over negative numbers are also shown in Fig. 2 (e). It shows that workers are generally consistent over days. The ratio is slightly lower on Monday and Friday, and slightly higher during weekend. This may be because on Monday they face back to work, and on Friday they get tired and need some rest. Whereas, the companies' tweets are more positive on Monday and Friday. Maybe because on Monday and Friday the companies tend to post their achievements and encourage the employees.

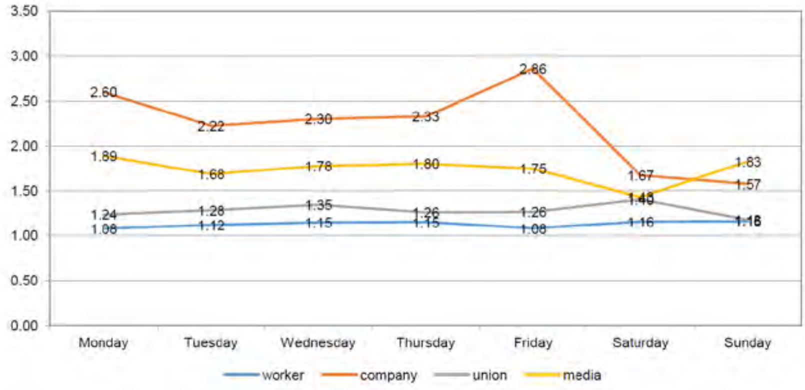
(a) Workers

(b) Companies



(c) Unions

(d) Media

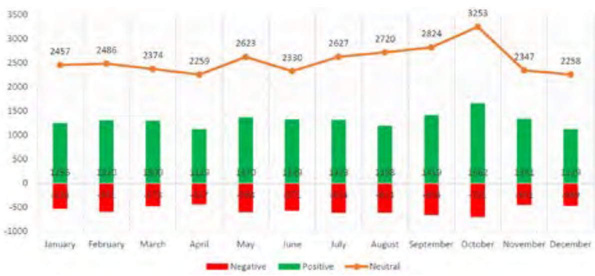


(e) Positive/Negative Ratio

Fig. 2: Daily visualization of sentiment analysis for construction clusters.

In Fig. 3 the monthly sentiment analysis over time is shown. In general January is the month with most tweets published. Maybe because all the users demonstrate their New Year plan and emotion in January. For workers, December is also a peak month, because of Christmas and end of year events. Whereas, for companies and media, the other peak is October. And in November and December, companies, unions, and media consistently decrease on the numbers. This may be because the construction markets are usually not that active around October due to season changes to winter, and the whole industry is preparing for winter and next year. It is also interesting to see that in spring, there is fewer posts published by media. Maybe it is because the news about projects, technologies, and events are gradually exposed during the year when projects proceed, and they will retweet their posts periodically over the year. The positive and negative ratios are also shown in Fig. 3 (e). There is no clear clue about which month is the best month for workers and unions. However, it is clear that November is the best month for companies. Maybe it is because companies try to finish projects on or before October when the bad weather is coming, and in November to celebrate their success.

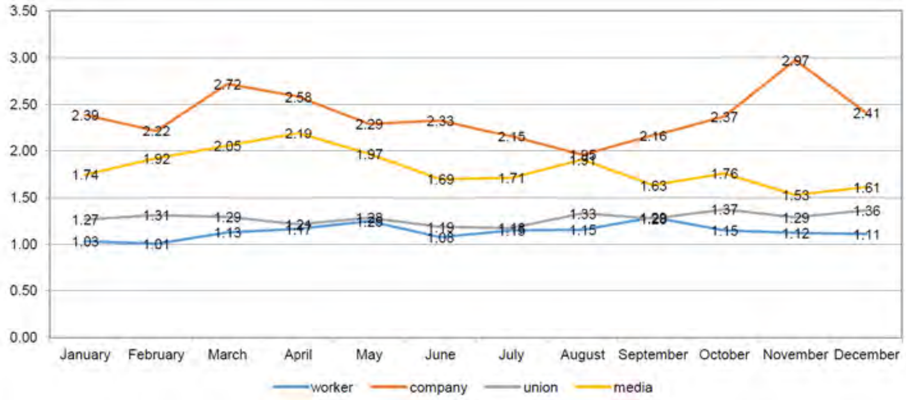
(a) Workers



(b) Companies

(c) Unions

(d) Media



(e) Positive/Negative Ratio

Fig. 3: Monthly visualization of sentiment analysis for construction clusters.

Another contribution to the construction industry using geo-location analysis is to predict construction market activity in each state. By combining sentiment of workers, positive or negative attitude of workers can be presented on map. The sentiment analysis results of workers over different states are summarized in Figs. 4 and 5. Fig. 4 shows that the number of posted messages across different states is very diverse. For some of the states, e.g., New Jersey, Ohio, Mississippi, Minnesota, Illinois, California and Washington, we can collect relatively more tweets than other states. This may be because there are more worker or projects in these states, but it is also highly likely that the workers and companies like to post messages on Twitter than other states. Thus, the conclusion cannot be made from our sampled data crawled from Twitter. However, there are indeed some findings. For example in Fig. 5, among the top states in number, the Ohio state is the most negative state while California, Nevada, Minnesota are relatively more positive states. This would be caused by reasons such as salary, job stableness, supports from unions, etc. This information is useful to investors and state governments for their considerations of investments and policy making on construction projects.

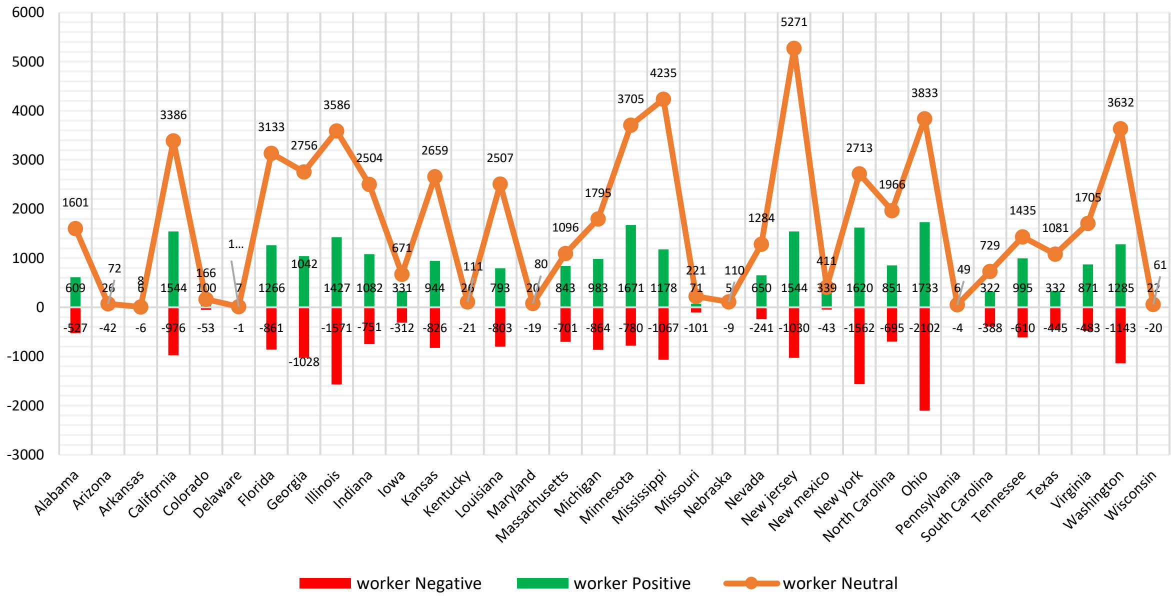


Fig. 4: Location chart of sentiment analysis for construction workers.

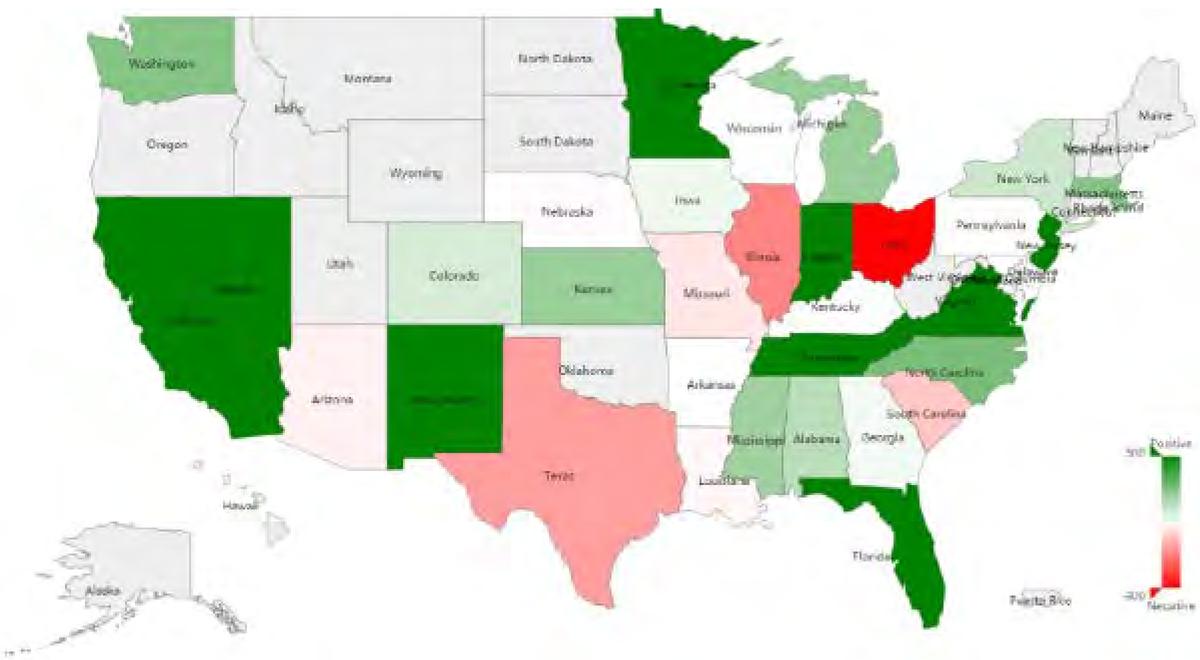


Fig. 5: Location visualization of sentiment analysis of construction workers on the U.S. map.

5. Conclusions

This paper gives a new perspective of collecting data for research in construction. Twitter was selected as a case study, and by using collected data, labor sentiment analysis was studied in this research. By analyzing hourly tweets which are relevant to construction, it shows that the sentiment of workers is pretty even, where both positive and negative tweets are increasing and decreasing consistently. There are much more positive tweets than negative tweets posted by companies while there are relatively more negative ones posted by unions. This means that unions not only post positive tweets for themselves like companies, but also post some critiques about other events with negative opinions. By analyzing daily tweets which are relevant to construction, it shows that the ratios of positive numbers over negative numbers of workers are generally consistent over days. The ratio is slightly lower on Monday and Friday, and slightly higher during weekend. Whereas, the companies' tweets are more positive on Monday and Friday. By analyzing monthly tweets which are relevant to construction, it shows that January is the month with most tweets published. There is no clear clue about which month is the best month for workers and unions. However, it is clear that November is the best month for companies. By analyzing tweets in different locations, it shows that some states, e.g., New Jersey, Ohio, Mississippi, Minnesota, Illinois, California and Washington, we can collect relatively more tweets than other states. Among the top states in number, the Ohio state is the most negative state while California, Nevada, Minnesota are relatively more positive states.

This study had several potential limitations. First, there may be some statistic bias (e.g. numbers of tweets collected during a period of time) according to private policy of Twitter on collecting data. It may be that some long-term patterns can be observed only by analyzing a database from an extended time scale. Secondly, patterns of four clusters observed in Twitter might not apply in other areas owing to different populations. Validating the applicability of Twitter in the study of situations of four clusters has opened multiple future research avenues, such as (1) collect additional data from different social media to validate the methodology internally and externally; and (2) conduct social influence analysis of construction projects. This expanded approach will enable investigation of several of identified civil engineering grand challenges.

References

Annamalai C., Koay S. S., and Lee S. M. (2014). Role of Social Networking in Disaster Management: An Empirical Analysis. *Journal of Computation in Biosciences and Engineering*, Vol. 1, No. 3, 1-5.

Arnette A.N. and Zobel C.W. (2016). Investigation of Material Convergence in the September 2013 Colorado Floods. *Natural Hazards Review*, Vol. 17, No. 2, 05016001.

Balahur A. et al., 2013. Sentiment analysis in the news. arXiv preprint arXiv:1309.6202.

Bakht M.N. and El-Diraby T.E. (2015). Synthesis of Decision-Making Research in Construction. *Journal of Construction Engineering and Management*, Vol. 141, No. 9, 04015027.

Bollen J., Mao H., and Pepe A. (2011). Modeling public mood and emotion: Twitter sentiment and socio-economic phenomena. *Proceedings of the Fifth International AAAI Conference on Weblogs and Social Media*, 17–21.

Cumby C., Fano A., Ghani R., and Krema M. (2005). Learning Individual Consumer Models for Personalized Promotions: A Data Mining Case Study. *Workshop on Data Mining for Business* — held with the European Conference on Machine Learning (ECML/PKDD 2005).

El-Diraby T.E. (2013). Civil Infrastructure Decision Making as a chaotic Sociotechnical System: Role of Information Systems in Engaging Stakeholders and Democratizing Innovation. *Journal of Infrastructure Systems*, Vol. 19, No. 4, 355-362.

Fox S., Leicht R.M., and Messner J.I. (2010). Assessing the Relevance of Media Synchronicity Theory to the Use of Communication Media in the AECO Industry. *Journal of Architectural Engineering*, Vol. 16, No. 2, 54-62.

Jonkman S.N., Hiel L.A., Bea R.G., Foster J., Tsioulou A., Arroyo P., Stallard T., and Harris L. (2016). Integrated Risk Assessment for the Natomas Basin (California) Analysis of Loss of Life and Emergency Management for Floods. *Natural Hazards Review*, Vol. 13, No. 4, 297-309.

Kiritchenko, S., Zhu, X. & Mohammad, S.M., (2014). Sentiment Analysis of Short Informal Texts. *Journal of Artificial Intelligence Research*, Vol. 50, 723–762.

Leung M.Y., Yu J.Y., and Liang Q. (2013). Improving Public Engagement in Construction Development Projects from a Stakeholder's Perspective. *Journal of Construction Engineering and Management*, Vol. 139, No. 11, 04013019.

Linna L. and Goodchild M.F. (2010). The role of social networks in emergency management: A research agenda. *International Journal of Information Systems for Crisis Response and Management*, Vol. 2, No. 4, 49-59.

Liu B. (2012). Sentiment Analysis and Opinion Mining. Morgan & Claypool Publishers, May.

Liu B. (2015). Sentiment Analysis: Mining Opinions, Sentiments, and Emotions. Cambridge University Press, June.

Miles S.B., Gallagher H., and Huxford C.J. (2014). Restoration and Impacts from the September 8, 2011, San Diego Power Outage. *Journal of Infrastructure Systems*, Vol. 20, No. 2, 05014002.

Miles S.B., Jagielo N., and Gallagher H. (2016). Hurricane Isaac Power Outage Impacts and Restoration. *Journal of Infrastructure Systems*, Vol. 22, No. 1, 05015005.

O'Connor B., Balasubramanyan R., Routledge B.R., and Smith N.A. (2010). From tweets to polls: Linking text sentiment to public opinion time series. *Proceedings of the Fourth International AAAI Conference on Weblogs and Social Media*, 122–129.

Pang B. and Lee L. (2008). Opinion mining and sentiment analysis. Foundations and Trends in Information Retrieval, 2(1-2), pp.1–135.

Ghani R. (2013). Targeting and Influencing at Scale: From Presidential Elections to Social Good. Talk Abstract – KDD'13. *Proceedings of the 19th ACM SIGKDD International Conference on Knowledge Discovery and Data Mining*, 1137.

Russell J.S., Menassa C.C., and McCloskey E. (2014). Lifelong Learning to Leverage Project and Career Success: 21st-Century Imperative. *Practice Periodical on Structural Design and Construction*, Vol. 19, No. 1, 137-141.

Sabrina P., Freberg K., and Saling K. (2013). Emerging Media Crisis Value Model: A Comparison of Relevant, Timely Message Strategies for Emergency Events. *Journal of Strategic Security*, Vol. 6, No. 2, 20-31.

Socher R., Perelygin A., Wu J.Y. Chuang J., Manning C.D., Ng A.Y., and Potts C. (2013). Recursive Deep Models for Semantic Compositionality Over a Sentiment Treebank. *Proceedings of the Conference on Empirical Methods on Natural Language Processing*, 151–161.

Standohar-Alfano C.D., Freyne S., Graettinger A.J., Floyd R.W., and Dao T.N. (2015). Performance of Residential Shelters during the May 20, 2013, Tornado in Moore, Oklahoma. *Journal of Performance of Constructed Facilities*, Vol. 29, No. 5, 04014143.

Tang, L.Y.N., Shen, Q.P., Skitmore, M., and Wang, H. (2015). Procurement-Related Critical Factors for Briefing in Public-Private Partnership Projects: Case of Hong Kong. *Journal of Management in Engineering*, Vol. 31, No. 6, 04014096

Tanielian A.R. (2014). Balancing Harmful Impacts of the Petroleum Industry with Internal Dispute Prevention and External Sustainable Development Initiatives. *Journal of Legal Affairs and Dispute Resolution in Engineering and Construction*, Vol. 6, No. 2, 03013003.

Tortajada C. (2015). Dams: An Essential Component of Development. *Journal of Hydrologic Engineering*, Vol. 20, No. 1, A4014005.

Tumasjan A., Sprenger T.O., Sandner P.G., and Welpe I.M. (2010). Predicting elections with twitter: what 140 characters reveal about political sentiment, *Proceedings of the International AAAI Conference on Weblogs and Social Media*, vol. 10, 178–185.

REAL-TIME SIMULATION OF CONSTRUCTION WORKER USING HUMAN BODY AND HAND TRACKING FOR ROBOTIC CONSTRUCTION WORKER SYSTEM

Manoj Kurien, Min-Koo Kim & Ioannis Brilakis

University of Cambridge, United Kingdom

ABSTRACT: *In the United Kingdom, deaths and serious injuries amongst construction workers are significantly higher than all other industries. This has considerable adverse effects in terms of human cost, financial cost and the industry's reputation. Methods in literature to address these concerns do not fundamentally solve the primary causes of workplace injury and death at a construction site which are fall from heights, musculoskeletal disorders and being struck by objects. This paper develops a novel approach to solving the health and safety hazards of human construction workers at a construction site. A new concept of 'robotic construction worker' is presented and two systems essential for the robotic construction worker, (1) combined body and hand tracking and (2) virtual construction environment, are developed to demonstrate, test the concept. The results illustrate the proof-of-concept of the robotic construction worker and display this technique's promising path towards eliminating the health and safety risks to human construction workers.*

KEYWORDS: *Construction site safety, combined 3D body and hand tracking, virtual construction.*

1. INTRODUCTION

The construction industry is one of the largest industries in the world. Employing two million people in the UK, it is the country's biggest employing industry (HSE, 2004). Unfortunately, it also has one of the worst safety records. According to the Health and Safety Executive UK (2004), deaths and serious injuries amongst construction workers are unacceptably high and more frequent than in any other sector of the United Kingdom economy". Construction workers are prone to accidents that lead to work place injuries, material losses, disabilities and to fatalities. The worker fatal injury rate in the construction sector is alarmingly over 3.5 times the average rate across all industries (RIDDOR, 2015). The rate of work-related illnesses in this industry is 20% higher than the average rate across all industries, and about 80% of non-fatal injuries were due to fall from heights, trip fall, lifting/handling and being struck by object. For fatal injury cases, fall from heights accounts for nearly 50% of the cases. Considering workplace illnesses, about 65% of cases were occurred due to musculoskeletal disorders (MSD's).

One of the most important procedures in managing site safety is performing periodic inspections of the entire construction site. Safety inspectors walk through the site, conduct inspections and evaluate site conditions based on safety criteria. This helps manages site safety but increases overhead costs, inefficiency and is time consuming. Lifting and moving was the one of the most commonly reported risk factors in workplaces. Current practice realises this risk and hence 90% of workplaces where this risk is present provide equipment and machinery for lifting and moving (HSE, 2015). The protective gear worn by construction workers such as helmets, steel-toed boots etc. help reduce the impact of falls, trips and being struck by objects on their body. However, this increases worker discomfort, does not protect against MSD's and can be ineffective against large falls, heavy equipment, moving vehicles etc. that are common place to the construction site.

The involvement of the workers in the decision-making processes of evaluating workplace risks help identify and manage risks effectively (SFC, 2007). As the workforce has direct experience of site conditions, they are most aware of potential hazards. This helps plan and manage the overall safety of a site. The advances in technology, regulation and awareness have reduced the rate of construction site injury. However, this rate has plateaued in recent years (HSE, 2015). This reveals the pressing need for a new approach to tackle the problem.

This paper develops a novel approach to solving the health and safety hazards of human construction workers at a construction site. A new concept of 'robotic construction worker' is presented in this study and two essential systems, (1) combined body and hand tracking and (2) virtual construction environment, are developed.

In Section 2, a review of the state of research is presented to identify the gaps in knowledge that this paper aims to answer. Section 3 presents the proposed system framework of this study. Section 4 presents a validation test and the derived results. Finally, Section 5 presents a conclusion and recommends future work.

2. BACKGROUND

2.1 Related previous methods

2.1.1 Site safety planning

Advances in Building Information Models (BIM's) enable automatic identification of construction safety issues. Malekitabar et. al (2016) identifies a set of five safety risk drivers related to the environment and design factors that can increase the probability of an accident. This enables the automated checking of potential safety risks with BIM's. Wetzel and Thabet (2015) present a BIM-based framework to support safe maintenance and repair practices during the facility management phase. Most falls from heights are due to insufficient risk assessment and preparation to address these risks. BIM for simulation and planning enables detailed preparation, training, simulation of the construction site. While this approach can reduce the risk of fall from heights and being struck by objects, it is however unable to address the risks of MSD's and pilot studies to assess the functionality of such a system and its effectiveness are limited.

2.1.2 Computer vision techniques

Seo et. al (2015) identify that continuous monitoring of conditions and actions at the construction site is essential to eliminate potential hazards in a timely manner. Computer vision techniques enable an automated means of monitoring the site to overcome the current limitations of slow and unreliable manual inspection by safety managers. These techniques can reduce the risks of being struck by an object or vehicle and fall from heights. There are, however, challenging issues and limitations to this approach due to continuously changing environments and diverse machinery and objects on-site issues such as occlusion and identifying good camera positions. Furthermore continuous monitoring can also cause negative effects such as privacy concerns and reduced motivation by construction workers. Lee et. al (2012) investigated using the Microsoft Kinect to collect prior models of unsafe actions and then identify similar actions in site videos. They address safety at heights by extracting 3D skeletal models using the Kinect from videos of workers climbing ladders and evaluating their behaviour. The main drawback this approach is, however, that it is very difficult to form representative priors of unsafe actions due to the large motion ranges of human movement and due to the varied nature of construction site activities.

2.1.3 Robotic techniques

Automation with robotics is an approach that can increase productivity, reduce the risk of MSD's and reduce the risk of humans being present in a hazardous environment. One such robot is SAM, short for semi-automated mason, a robotic bricklayer (Sklar, 2015). A human mason can lay about 300 to 500 bricks a day, while SAM can lay about 800 to 1,200 bricks a day. Fundamentally, however, an automated robot does not have the fine skills, adaptability that human construction workers provide and they would still be required on-site (e.g. SAM requires a human construction worker to tidy up the mortar and place bricks in difficult areas such as corners). In addition, the simplest construction task of automating bricklaying itself poses an immense challenge and leaves much to be desired. One method to overcome the challenges of automated robots at a construction site is the remote/ teleoperation of construction robots. A remote controlled trench compactor reduces the need for repeated strenuous actions by workers in trenches, reducing the risk of MSD's. However, the machinery increases the risk of other hazards such as being hit by them.

2.2 Gaps in knowledge

The previously proposed methods do not fundamentally eliminate the risks to the construction worker. The best solutions in literature have risen from using the technologies of computer vision and in teleoperated robotics as they can reduce worker involvement on-site. There are however still significant gaps in knowledge that:

- A framework that tracks both the hand and body of a construction worker is yet to be developed. The independent tracking of the body and of the hand has been developed but methods to address worker safety are limited due to their incapacity to fully track the human motions. Song et. al (2011).make plain that current technology in vision based tracking is limited with "*body and hand signals typically considered separately, restricting the expressiveness... making interaction less natural*".

- A robotic solution to address all construction operations, ranging from using fine tools to heavy machinery has not been developed. Existing robotics (e.g. bricklayer robot, teleoperated crane and remote controlled trench compactor) can only carry out a very small portion of the tasks necessary at a construction site.

3. METHODOLOGY

3.1 System overview

A robotic construction worker would copy the motions of a human construction worker to carry out construction tasks. The human construction worker on-site can control the robotic construction worker, essentially removing the human from the hazardous construction site. As a first step for the ultimate goal, this study develops two essential systems that illustrate this solution: (1) A novel framework to combine vision based 3D hand and body tracking; and (2) A real-time simulation to demonstrate combined tracking in a virtual construction environment. Fig. 1 shows the proposed framework for the system.

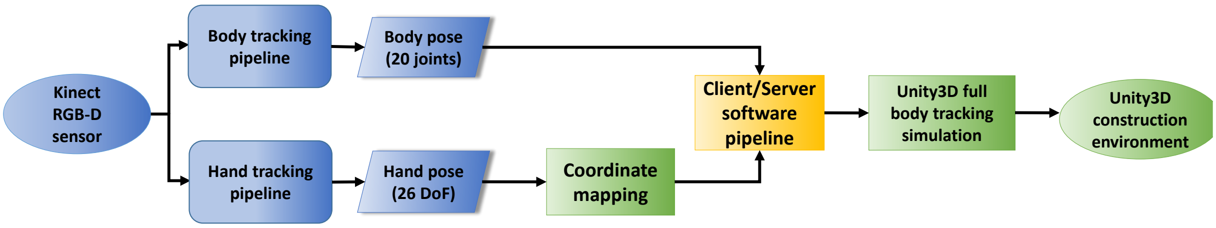


Fig. 1 The proposed framework of this project colour coded to illustrate the author's contribution. Blue -systems used as is. Green - newly developed systems. Yellow - existing systems extensively modified.

Vision based body tracking is performed using the Microsoft Kinect sensor. It enables a relatively inexpensive approach to acquiring and processing RGB-D data. The Kinect Software Development Kit (SDK) is a well-known system, capable of tracking 20 human joints and is readily available to be programmed in C# environments. The skeletal tracking pipeline available in the Natural User Interface (NUI) library calculates the 3D joint position and bone orientation.

Vision based hand tracking uses the same Kinect sensor and processes RGB-D data using the FORTH Hand Tracker library developed by a research group (Oikonomidis et al., 2011). This produces a monocular solution to hand and body tracking. The FORTH Hand Tracker calculates a 27-D parametrized representation of the 3D hand configuration and can be decomposed into joint coordinates in 3D homogeneous coordinates. The coordinate system of the hand tacking is mapped to the coordinate system of the body tracking.

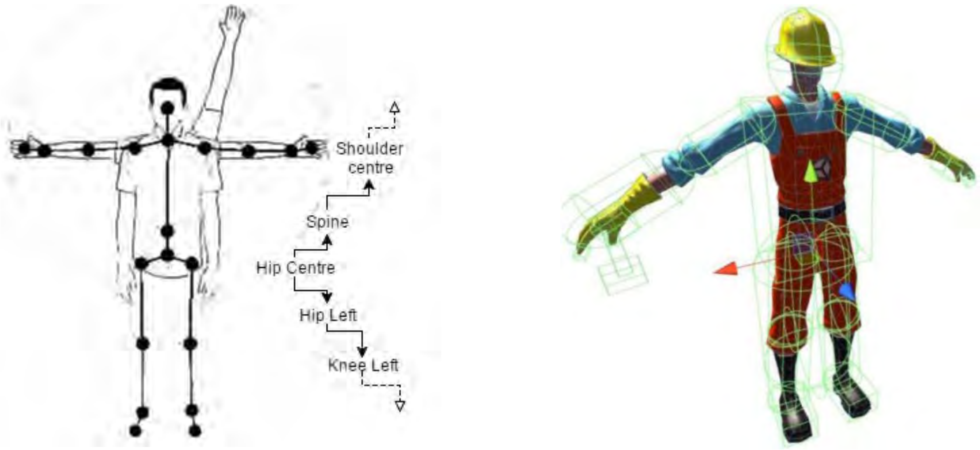
Combining the two systems of hand tracking and body tracking requires the development of a software pipeline. A pipeline consists of a chain of processing segments arranged such that the output of each segment is the input of the next. The Hand Tracker pipeline is in the programming language Python, whereas the Kinect SDK pipeline is in C#. A Client-Server software pipeline enables a real-time communication channel between these systems. This enables the two independent body and hand tracking pipelines to run separately, simultaneously and seamlessly and enables data to be transferred to a simulation platform.

In order to verify the real-time simulation of combined body and hand tracking, the construction environment and virtual construction are developed in the Unity3D (2016) game engine. Unity3D has substantial ready-made components necessary for virtual reality simulations with the Kinect. Furthermore, existing Unity3D toolkits have ready-made human characters that can be controlled to demonstrate full body tracking.

3.2 Technical details

3.2.1 Body tracking

The Kinect SDK performs body tracking by calculating real-time 3D joint coordinates and orientations. This is presented in a hierarchical structure (parent-child) as shown in Fig. 2a. A standard 3D model (Takala and Pugliese, 2015) of a construction worker was utilized to demonstrate tracking and control of a virtual construction worker. This is composed of a graphically rendered mesh, *character joints*, and *colliders* placed on the body (Fig. 2b). The *character joints* are managed in the same hierarchical system used by the Kinect SDK, enabling one-to-one joint mapping. The *transform* component which defines 3D position and orientation is then updated with the skeletal tracking data to move the character model. The results of the virtual construction worker tracking the user's movements are shown in Fig. 5.



(a) (b)

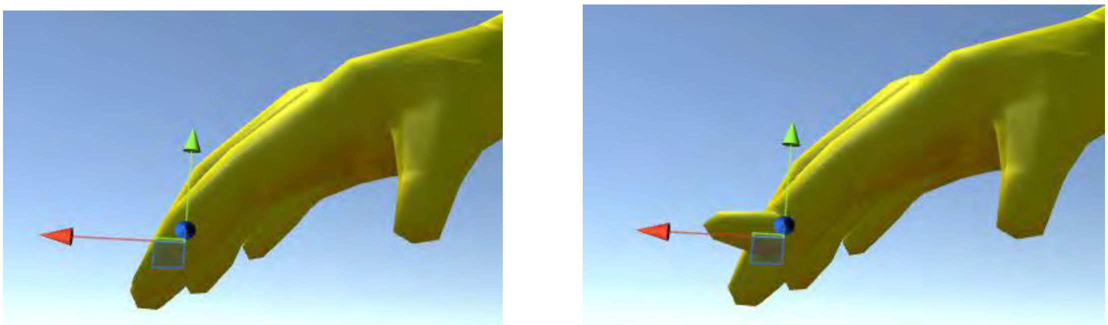
Fig. 2 Body tracking setup: (a) The hierarchical relationship of the different joints tracked and their orientation (image modified from Microsoft. (2016)). The Hip Centre joint is set as the root and the hierarchy then extends to the feet, head, and hands; (b) The Unity3D character model with shown as a wire frame.

3.2.2 Combined hand and body tracking

The pipe server programmed in C# maintains a real-time communication channel to the FORTH Hand Tracker (Python pipe client) and to Unity3D (C# pipe client). The pipeline designed and developed enables the FORTH Hand Tracker to send hand coordinates to the pipe server, which then sends the coordinates to Unity3D, in real-time. The FORTH Hand Tracker calculates hand coordinates in a different coordinate system (3D homogeneous coordinates) to the one used in the Unity3D simulation (3D scene coordinates). A coordinate transformation was used to convert the output from the Hand Tracker to Unity3D.

In addition to the 3D joint coordinates, the orientations of hand and finger segments are essential in developing the simulation. The hand tracking libraries do not explicitly calculate the orientation of each modelled segment. This can lead to spurious simulations. This problem can be visualised in Fig. 3 where both finger-tip 3D positions are correctly transformed but the lack of orientation information can lead to incorrect representation of the tracking.

The orientation of finger segments can be defined by two orthogonal vectors - one to indicate the forward direction and the other to indicate the up direction. Defining the orientation of finger segments can constrain the 3D position of the segment if their positions are restricted by hierarchical joint position updates. At each time step of the simulation, this new technique calculates the current orientation vectors of segments, the new orientation vectors and then updates the simulated hand and fingers with rotations.



(a) (b)

Fig. 3 An illustration of how fixing only the 3D position does not constrain the orientation of the segment in 3D space: (a) Correct coordinate transformation to fix the 3D position of a finger segment in 3D space and with the correct orientation of the segment; (b) Correct coordinate transformation to fix the 3D position of a finger segment but with incorrect orientation which leads to inaccuracies.

3.3 Virtual construction environment

3.3.1 Overview

The Unity3D simulation is developed by preparing various Scenes. In each Scene, the objects, algorithms, 3D models, camera and lighting are designed and built in a 3D virtual space. The 3D virtual environment to simulate a construction site, tools, objects and a construction worker is shown in Fig. 4.The Unity3D platform is built on object-oriented programming, meaning that every entity within the Scene is a *GameObject*, which is the base class. It contains a variety of parameters and functions and acts as a container class. This enables other classes to be parented to the base class with the use of *Components*. Parenting and creating child classes with this technique enables the grouping of objects in the scene and the *inheritance* of any transformations or algorithms that control the objects. This method is used to move objects in simulation that are held by the construction worker.

The *Transform Component* defines the position (x, y, z), orientation (x, y, z, w) and scale (x, y, z) in the virtual world. The Unity3D engine operates with vectors and quaternions. *Transform* has pre-built functions that enable the translation, rotation and scaling of the objects within the *Scene*. Unity has a *Prefab* asset type that allows one to store a *GameObject* object complete with *Components* and properties.

3.3.2 Simulated physics

Physics is enabled with *Rigidbody*, *Collider*, *Trigger* and *Joint Components*. *Rigidbody* enables mass to be added to an object and for it to respond to gravity. A *Rigidbody* enables the object to be moved by incoming collisions with the addition of *Collider Components*. The physics game engine typically calculates the motion of objects with

Rigidbodies. In cases where the user defines the motion of a *Rigidbody*, the motion is non-physical and is hence known as kinematic. This is performed with the *Rigidbody* property called *IsKinematic* to remove its motion control from the physics engine. This is the technique used to move objects once the virtual construction worker grasps them, as it tracks the motion of the human controller's arms and hands as shown in Fig. 5.

Collider components define the shape of an object for physical collisions. *Colliders*, which are invisible, need to conform to the shape of the graphical rendering, with rough approximations enabling more efficient calculations. The least processor-intensive *colliders*, the *Box Collider*, *Sphere Collider* and *Capsule Collider* were used to bring physical characteristics to the virtual construction worker and to the virtual construction site.

A *Trigger* enables the physics engine to detect when one *collider* enters the space of another, without creating the resulting `collision'. A *Trigger* does not behave as a solid by enabling other *colliders* to pass through it. This technique was utilized to enable easy, single-handed grasping of objects in the simulation.

Joints enable attaching one *Rigidbody* to another or to a fixed point in space. *Character Joints* are used to create the virtual construction worker to demonstrate body and hand tracking. They are a ball-socket joint, which allows the limitation of the joint movement on each axis.

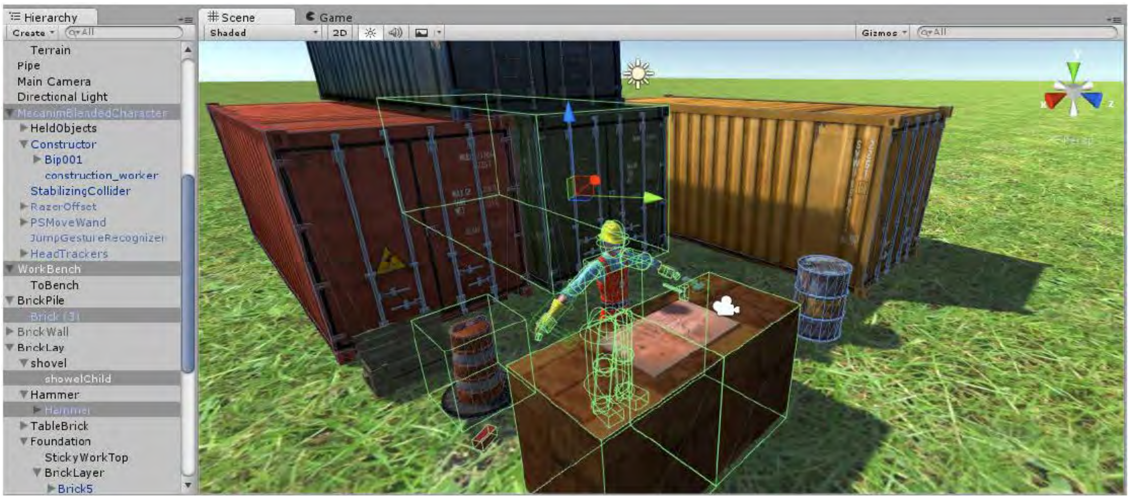


Fig. 4 The virtual construction environment developed with a human character model.

4. VALIDATION

In order to identify the feasibility of the proposed system, a validation test was conducted. Since picking up, moving and dropping an object are basic tasks to demonstrate construction works, the system of picking up virtual objects with a two-handed grasp was developed with the use of *Colliders* placed on the left and right hands of the virtual constriction worker. A virtual box was created to be lifted and moved. It uses *Rigidbody* physics such that if both hands are touching the box, it sets *IsKinematic* to true and the box *GameObject* becomes a child component of the Right Hand *GameObject*. Thus, movement of the box is enabled as the box *GameObject* inherits the position updates of the Right Hand *GameObject*. If both hands are not colliding with the box, then it is dropped. The simulation results were able to demonstrate the use of natural human motion OF picking up, moving and dropping a crate as shown in Fig. 5.

Fig. 5 An example of picking up, moving and dropping a large crate in simulation using the two hand interaction developed. Top left - shows the user's live motions in front of the Kinect.

5. CONCLUSION

In considering the larger goal of improving the health and safety of construction workers at a construction site, this paper focused on tackling three major risk factors - fall from heights, musculoskeletal disorders and being struck by objects. Reviewing the state of research and identifying the gaps in knowledge related to the promising fields of computer vision and robotics to address this issue, the author proposed a novel solution that effectively eliminates the risks faced by human construction workers. As a first step in establishing this solution, two essential systems of the robotic construction worker were developed, which are (1) combined body and hand tracking and (2) a simulation environment to demonstrate, test the system.

Using a single Microsoft Kinect sensor, a novel framework of combining vision based hand tracking (FORTH Hand Tracker) with body tracking (Microsoft Kinect SDK) was developed. This was developed with coordinate mapping and a software pipeline to enable the tracking systems to run independently and simultaneously. The framework demonstrated accurate and successful combined tracking in real-time. The Unity3D game engine was employed to develop a virtual construction site. This was used to illustrate the use of the combined tracking to carry out virtual construction - moving crates with two hands, picking and placing bricks with a single hand and the use of construction tools.

The limitations of the FORTH Hand Tracker lead to constraints on the speed of hand and finger movements for accurate tracking. To prevent loss of hand tracking, the movements must be relatively slow, smooth and minimize finger occlusions. Furthermore, the Hand Tracker operates accurately only within a one to two meter depth range from the Kinect sensor. These slow down the process of virtual construction and reduce the preciseness of moving and placing virtual objects.

To further develop the robotic construction worker system, suggestions for future work include: (1) Develop a haptic feedback system for the user using the developed simulation, (2) Demonstrate a wider range of construction tasks to develop a more detailed virtual construction environment. This enables testing and developing the key features and capabilities of the system, and (3) Develop a system based multiple Kinect sensors to enable 360 degrees of tracking the user. This address the problem of the current system coming from using a single Kinect sensor.

6. REFERENCES

Health and Safety Executive (HSE) (2004). Improving health and safety in the construction industry.

Health and Safety Executive (HSE) (2015). Health and safety in construction sector in Great Britain.

Lee S. H., Han S. U. and Pena-Mora F. (2012). *Proceedings of Construction Research Congress 2012: Construction Challenges in a Flat World*. 858-867.

Malekitabar H., Ardeshir A., Sebt M. H., and Stouffs R. (2016). Construction safety risk drivers: A BIM approach. *Safety Science*, Vol. 82. 445-455.

Microsoft. (2016). Microsoft Kinect for Windows Software Development Kit (SDK) 2.0.

Oikonomidis I., Kyriazis N. and Argyros A. (2011) Efficient model-based 3d tracking of hand articulations using Kinect. *Proceedings of The 22nd British Machine Vision Conference (BMVC).*

Reporting of Injuries, Diseases and Dangerous Occurrences Regulations (RIDDOR) (2015). Health and safety in construction sector.

Seo J. O., Han S. U., Lee S. H., and Kim H (2015). Computer vision techniques for construction safety and health monitoring. *Advanced Engineering Informatics*, Vol. 29, No. 2, 239-251.

Sklar J (2015). Robots lay three times as many bricks as construction workers. *MIT Technology Review*.

Song Y., Demirdjian D. and Davis R. (2011). Tracking body and hands for gesture recognition: Natops aircraft handling signals database. *Proceedings of Automatic Face & Gesture Recognition and Workshops IEEE International Conference.* 500-506.

Strategic Forum for Construction (SFC) (2007). Short guide to improving health and safety on construction sites through effective worker involvement.

Takala T. and Pugliese R. (2015). Reality-based User Interface System http://blog.ruisystem.net/about/.

Unity3D. (2016). Unity documentation. http://docs.unity3d.com/Manual/.

Wetzel E. M. and Thabet W. Y. (2015). The use of a BIM-based framework to support safe facility management processes. *Automation in Construction*, Vol. 60. 12-24.

THE ENERGY PERFORMANCE ANALYSIS OF RESIDENTIAL BUILDINGS IN SAUDI ARABIA

Ahmed Al Kenani[1], Nashwan Dawood [2], Mohamad Kassem[3]

[1] PhD Student, School of Science and Technology, University of Teesside,
Middlesbrough, TS1 3BA, UK email: A.Alkenani@tees.ac.uk

[2]Professor, School of Science and Technology, University of Teesside, Middlesbrough, TS1 3BA, UK email:
N.Dawood@tees.ac.uk

[3]Senior Lecturer, School of Science and Technology, University of Teesside, Middlesbrough, TS1 3BA, UK
email: M.Kassem@tees.ac.uk

Abstract

Energy demand in residential buildings in the Kingdom of Saudi Arabia is escalating and the electricity supply cannot sustain the demand especially in summer, when the demand rises by 50%. Air-conditioning for cooling is the crucial factor for this peak in residential electricity demand accounting for around 70% of the country's total consumption during the summer periods. Saudi Arabia's Central Department of Statistics and Information estimates that the country's population will grow by 2.6% in 2017 to more than 30 million residents, further increasing energy demand. Hence the kingdom has a pressing need to adopt innovative solutions over conventional energy efficiency practices. Therefore, a strong commitment and sustainable energy practices has been considered an imperative issue. Accordingly, this large consumption of electrical energy for buildings represents a major potential for reducing energy consumption. To cope with various factors placing increased demand on energy, the Saudi government has plans to diversify its power generation sources and promote energy performance and efficiency. However, challenges are also inherent in the design process adopted in Saudi residential buildings. A key challenge is the lack of energy policy regulations that either guides or regulates the design process of residential buildings.

This paper proposes a new design process which considers energy policies that are specifically tailored to the hot and arid climate of Saudi Arabia. The proposed process is suitable for residential markets, which is characterized by high energy requirements for air-conditioning and incorporates sustainable building regulations for the design phase of all types of residential buildings in the Kingdom of Saudi Arabia. The proposed process is expected to promote design practices that enable an efficient use of energy and contribute to significant reduction in the energy consumption and operation costs of buildings over their lifecycle.

Keywords: *Residential buildings, energy performance, design process, Saudi Arabia*.

Introduction

Energy consumption patterns depend on local climate conditions, the culture of the citizens and the policies of the country. Building performance is recognised as a key contributor to the high energy demand from fossil fuels use (Ghiaus, 2004). In recent years, the Kingdom of Saudi Arabia has been experiencing a tremendous economic boom. As it usually happens during such periods of financial growth, the built environment in the KSA is also experiencing an unprecedented development. However, in most cases, this expansion has relied upon unsustainable practices (Obaid, 2008; Taleb and Sharples, 2011; Hepbasli and Alsuhaibani, 2011).

Saudi Arabia is an oil producing country, with an economy based on the oil industry. It is also a country characterised by high energy consumption. The hot climate in the region and the design of residential buildings explain to a large extent the high levels of energy consumption (Taleb and Sharples, 2011). Energy consumption in the Kingdom of Saudi Arabia, in the form of electricity, has increased sharply over the last two decades (Al-Ajlan *et al.,* 2006). This increase is due to the rapid development of the economy in the absence of energy conservation polices. Electricity is currently generated in Saudi Arabia by burning fossil fuels (Al-Natheer, 2000).

The kingdom has a pressing need to adopt innovative solutions over conventional energy efficiency practices. Therefore, a strong commitment and sustainable energy practices has been considered an imperative issue. Accordingly, this large consumption of electrical energy for buildings represents a major potential for reducing energy consumption (Fasiuddin and Budaiwi, 2011). The Saudi Arabia Ministry of Electricity have stated that over half (51.1%) of electricity is consumed by the domestic sector (SAME, 2010), as all modern residential buildings in Saudi Arabia depend on air conditioning for interior cooling.

In view of the high energy consumption by the residential sector in Saudi Arabia, significant steps are urgently needed in order to reduce energy consumption. Such steps are to be proposed in a framework specifically designed for the environment and climate of Saudi Arabia. This framework, then, would provide solutions that reduce energy demand and guidelines for the design of future energy efficient homes in Saudi Arabia. Furthermore, the framework will support architects, civil engineers, building professionals and developers to control and manage future sustainable, low energy residential buildings in the design stage, which can then be validated and approved by using energy assessment software tools before the construction stage in Saudi Arabia on the basis of climate, culture and occupants needs.

Many developed countries have dealt with energy saving through the sustainable energy consumption codes and established energy consumption standards based on local climate conditions and citizen’s needs. Such codes are absent in Saudi Arabia and are essential to control energy consumption and accelerate the understanding and implementation of sustainable design and construction (Aldossary *et al.,* 2014; Taleb and Sharples, 2011; Chwieduk, 2003).

Hence, the theoretical challenge is to overcome barriers posed by both the technology and organisation and allow for the analysis of their interactive combination in generating conditions for Saudi construction organisational configuration and reformation. Accordingly, the central issue to be analysed and discussed in this research is how an enhanced understanding of energy efficiency and its implementation in Saudi construction industry can be gained. As a result, this research will attempt to study how to adopt energy efficient performance measures at the design phase in Saudi Arabia by developing a framework through the design and development of energy efficient buildings to foster energy-efficient approaches for building practices in Saudi Arabia.

The rate of residential building development in the Kingdom of Saudi Arabia has been high, consequently the intervention of the energy efficiency concept is essential due to the scarcity of essential resources and unfortunately, the issue of energy consumption in particular is not given serious consideration with regard to Saudi building designs. Research shows Saudi buildings severely lack the means to ensure energy efficiency. As a result of poorly designed buildings in Saudi Arabia nearly 80% of household energy is used for heating and cooling purposes (Akbari *et al.,* 1996; Ibraheem, 2007).

The concept of energy efficient residential buildings is concerned with integration of economic, environmental and social aspects under the hypothesis that minimizing the embodied energy is to assess the energy cost of construction versus the operational energy expenditure. Thus, by integrating energy performance assessment criteria in the building's design phase, this research proposes an investigation of case study of new construction based on software analysis for a comprehensive, concept-to-detail design analysis tool that provides a wide range of simulation and analysis functionality to perform whole building analysis, optimizes energy efficiency, and works toward carbon neutrality to investigate the influence on energy consumption, lifecycle energy cost and carbon emissions. As forecasting, the energy performance of a building during the early phases of its design is suggested as a method of informing the development of energy efficient buildings (Schade *et al.,* 2011, Loh *et al.,* 2010, InPro 2007, Kirkham *et al.,* 2007).

Literature Review

Oil wealth has made Saudi Arabia an economically prosperous country. This has led to the rapid growth in the population of Saudi Arabia which in turn has influenced the construction industry.

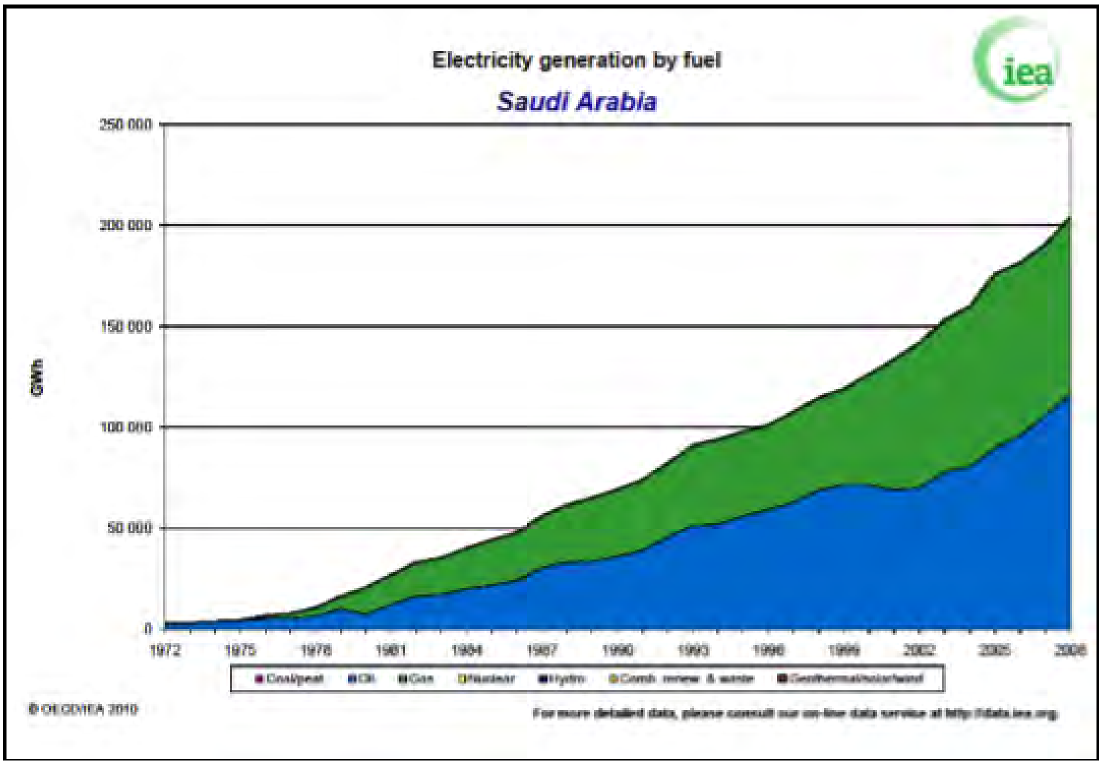


Figure 1 Electricity [GWh] generated in Saudi Arabia

Source: IEA, (2011)

The growth in the demand for new buildings has in turn resulted in a large consumption of resources, such as energy (Lahn and Stevens, 2011). Consequently this expansion has relied upon continuous unsustainable practices (Taleb and Sharples, 2011; Hepbasli and Alsuhaibani, 2011; Obaid, 2008).

This huge increase in demand for new and modern residential housing units has prompted the use of modern architectural construction methods and design styles in Saudi Arabia. Mubarak (1999) suggests that the prominent modern styles include the Western-styled villa and multiple story apartments.

Residential buildings account for the majority of energy consumption in every country, however, in Saudi Arabia the amount of energy consumed by buildings is considerable. Residential buildings in Saudi Arabia consume more than 50 per cent of the country's produced electricity, where the majority is consumed by air conditioning, due to the harsh dry local climate (Aluwaisheg, 2013).

Currently the residential building sector in Saudi Arabia is placing intensive pressure on the country's reserves of natural resources. It is estimated that about two-thirds of the electric energy generated in the Kingdom of Saudi Arabia is used by the building industry (Al-Sanea *et al.,* 2012). Hence, conventional construction operations impact seriously on the environment as a result of their excessive use of energy. Continuing in this manner is neither feasible nor sustainable. Viewing this statement from a frame of reference, in 1975 the total peak electricity load was 300 MW. By 2007, it had increased to 34,953 MW. By 2023, according to the forecast of current projections, total peak electricity is set to achieve 57,808 MW (SAME, 2010; Obaid, 2008). Moreover, it has been estimated that 2.32 million new residential buildings will be built by 2020, indicating an even more significant increase in electricity demand associated to residential buildings for the Kingdom of Saudi Arabia in the coming years (Alrashed and Asif, 2012).

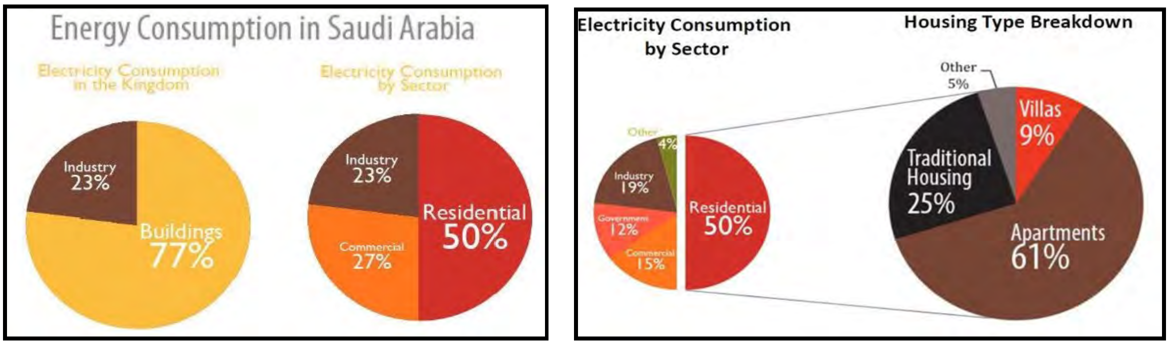


Figure 1: Energy consumption trend in Saudi Arabia (2016), where 50% of the electricity consumption in Saudi Arabia is attributed to residential buildings.

Source: Authors own illustration

Typically, Saudi residential buildings are designed in such a way that little regard is paid to principles of sustainability. Saudi residential buildings consist of fairly large reinforced concrete structures, with air conditioning units constantly running in each room (Taleb and Sharples, 2011). Al-Ibrahim (1990), asserts that in Saudi Arabia the energy performance of modern architecture is inferior to that of traditional architecture, and that modern residential building materials are not well suited to the hot, arid environment of Saudi Arabia.

Sustainable architecture is the result of an environmentally conscious attitude towards designing, implementing and maintaining buildings and is based on local requirements and needs, construction materials for buildings and reflection on local traditions (Niroumand *et al.,* 2013). This creates the need to design and apply energy-efficient techniques in Saudi residential buildings through the application of sustainable architectural principles (Karam, 2010). According to Aluwaisheg (2013), there are two reasons for this; the first is that there are no strict laws to bind builders to use a certain type of insulation, which can dramatically contribute to the overall conservation of energy. The second reason is that Saudi laws are set to a very low standard when it comes to cooling systems used in buildings, which contributes to high energy consumption levels.

Building envelope components of residential buildings such as walls, roof, floor and windows have other functions than just structural or architectural elements. Indeed, building envelope components can be designed to maintain safe and comfortable indoor environment. In particular, building envelope components affect the energy required for thermal comfort within buildings. For instance, heat storage capability of some building envelope components, such as walls, can help in controlling the indoor temperatures without the need of mechanical systems. So there are sustainable approaches to achieve thermal comfort in buildings without utilizing significant amounts of energy especially for cooling or heating (Alaidroos and Krarti, 2014).

However the lack of thermal insulation, and the absence of sustainable standards in the Saudi construction industry has led to an assortment of low quality buildings in the nation’s existing built environment. At the present time, there is no standard criteria for buildings to raise the level of quality and efficiency. This is due to the fact that energy efficiency performance of buildings was initially neglected by the Saudi Building Code since energy consumption was low and no serious threat from peak loads was expected. As a result almost 70% of buildings in the Kingdom of Saudi Arabia are not thermally insulated (SEEC, 2013; Alshenaifi, 2015).

As there are no regulations which are being adhered to, or compulsory building codes which sufficiently set out the energy performance guidelines for the residential sector in Saudi Arabia, which incorporate the principles of sustainable architecture in the country. It has been argued that setting a coherent set of such codes and standards is one of the most important and cost-effective ways to promote the widespread of sustainable practices, especially with regard to reducing residential energy consumption (Karam, 2010).

It appears from all of the above information that Saudi Arabia is heading towards consuming its only major income source before it can solve the problem and consume wisely. However, this can be averted if key stakeholders collaborate with each other to set new regulations and introduce new energy efficient construction methods. According to Hamed (2003), designing sustainable energy efficient residential buildings is no longer a luxury addition, but it is now vital to the survival of the present generation and those yet to come.

The use and implementation of innovative information and communication technologies, such as BIM, and related software in the analysis of energy for residential buildings is an important and effective strategy for energy saving and economic growth (Ishida, 2015). ICT can be applied both in the conceptual design and detailed design of residential buildings in Saudi Arabia for energy analysis, energy performance, and energy management and conservation purposes. ICT can play a significant role in energy conservation if employed in energy efficient homes in Saudi Arabia to manage energy consumption.

According to Wong and Fan (2013), BIM is a critical element in reducing industry waste including wasted energy, adding value to industry products and decreasing environmental damage. Their research on the extent of the contribution, which BIM can make to the energy performance of buildings, is well worthwhile, at the same time increasing awareness of the main capacities of this new technology and its potential contribution towards energy efficiency in residential developments. Their research claims that BIM has helped to promote energy analysis and performance in public housing development projects in Hong Kong (Hong Kong Housing Authority, 2011).

Through the use of highly energy efficient materials and building operation optimisation technologies the impacts to life cycle energy and emissions consumption from the operational phase can be shifted back to the material production and construction phase (Blanchard and Reppe 1998). Integration of LCA software and BIM energy analysis software to automate this process will not only for allow efficiencies in LCA assessment procedures but also enable design changes to be made prior to construction and assist building management in the optimisation of a building’s environmental footprint throughout its operation (Russell-Smith and Lepech 2012). Since BIM has great potential for promoting sustainable building design, it is inevitable that BIM should be more utilized in the Saudi construction industry. This is backed up by Azhar (2011), who states that the use of BIM for sustainable design can be broaden further than commercial buildings.

Consequently the rapid increase in residential energy consumption requires an immediate and serious strategy to reduce this energy consumption. This is essentially in order to improve and set out minimum standards for conventional design, construction practices and standards, as well as reducing the overall impact energy use of buildings upon the environment (Geyer 2012; Kubba, 2012; Kasim *et al.,* 2013). So together with practical innovation the residential buildings of Saudi Arabia could have a significant impact upon the energy performance whereby they will be more energy efficient, cost less to operate and promote the construction of high-energy performance buildings.

Research Methodology

The development of a framework is proposed for the implementation of energy analysis procedures during the conceptual details design phase of a construction project in order to reduce energy demand and specify guidelines for the design of future energy efficient homes in Saudi Arabia. The energy analysis framework will control and manage energy consumption in residential buildings at the design stage, and can be validated and approved using energy assessment software tools before the construction stage.

This stage also incorporates the proposed energy performance strategies for the Saudi residential sector that were identified in the literature review and during design experiments. The proposed framework is applicable and suitable for Saudi Arabia and the broader Middle Eastern region due to the hot local climate and the manner in which residential buildings are custom-built.

In order to validate the framework, a case study approach was undertaken. The case study involved analysis of a new two storey residential building in the city of Riyadh with the specific aim of assessing the current and potential improvements in terms of energy and consumption with regard to energy efficiency of the building. Riyadh is the capital city of Saudi Arabia which is located in the middle of the kingdom. It experiences extremely hot and dry summers and cold dry winters.

Case study description

The case study buildings will consists of a two storey residential building in each of the selected cities. With an average of 185 square meters on each floor of the building. The ground floor is used as the main living and entertaining space, whereas the first floor area is used as the bedroom space. The structure of the building consists of reinforced concrete for the floor and ceilings. The walls are made from concrete blocks without any insulation used in the walls and roof. The outer façade of the building is covered by a cement sand render.

The methodology involved an analysis of the properties' design and construction fabric and materials. Three dimensional models were designed for each property based on the design, and then assessed using energy simulation software (1) without the use of insulation materials and also (2) with the use of insulation material.

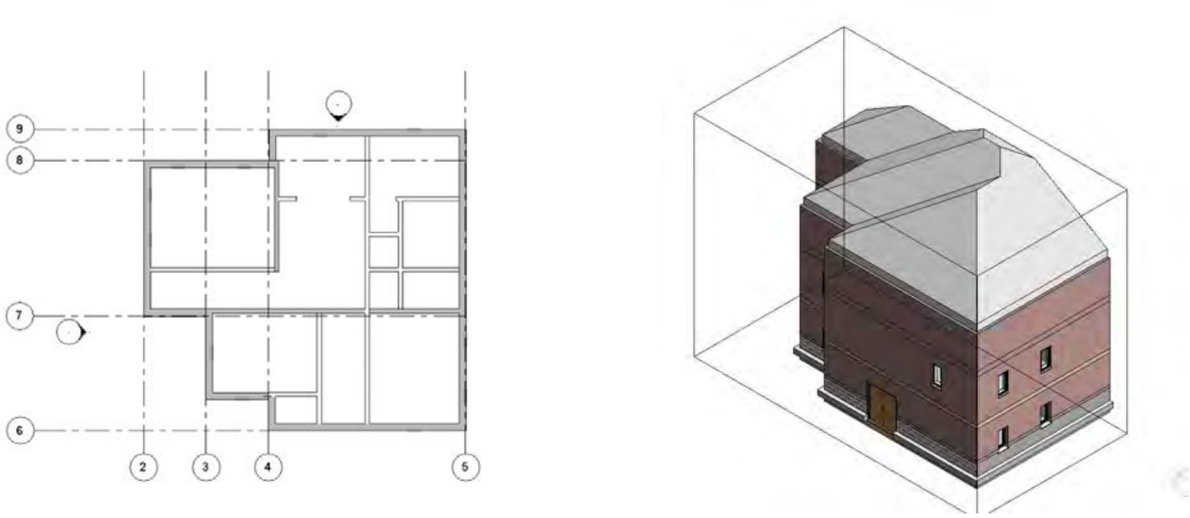


Figure 2: Case Study floor plan and 3D model

Use of simulation software tools

Energy simulation has been conducted using Sefaira energy simulation software in order to perform whole building energy analysis for the purpose of comprehensively studying the influence on energy consumption, daylight analysis and carbon emissions upon a residential building in the city of Riyadh in order to gain meaningful energy performance results. The philosophy of undertaking energy simulation upon residential buildings is to create a model where the user can specify in detail parameters that influence the building performance, with resulting performance predictions that are as close to reality as possible.

The simulated results provided real time climate data, energy consumption, daylighting metrics as well as the building geometry. As a result the analyses and the results from the energy simulations are likely to determine the optimal construction materials for both the maximum and minimum effect upon energy performance of residential buildings, as well as exemplify costs for energy savings in the residential building sector of Saudi Arabia.

Framework Development

The framework is based on the outcomes of a comprehensive literature review and the design experiments with energy performance measuring tools such as SAP (Standard Assessment Procedure) and GSAS (Gulf Sustainability Assessment System) used to implement the sustainable energy policies in the design phase.

The proposed framework takes into account the GSAS system for the development of energy policies and the use of energy based software such as Sefaira energy simulation software for the assessment and validation system which will then manage and regulate the use of energy in residential buildings. The framework will then provide engineering office the opportunity to employ technologies for energy consumption and management.

Currently the residential building design process follows the procedure set out in Figure 2 below.

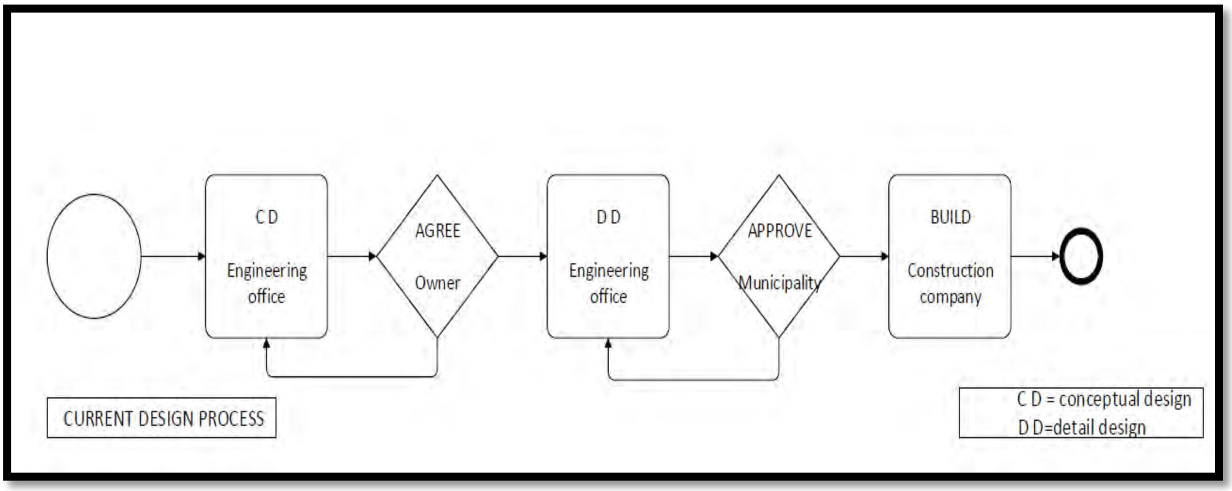


Figure 3: Current Design Process of new residential buildings in Saudi Arabia

Here the first step necessitates the land owner to go to the engineering office for a conceptual design of the residential building. This is known as the design phase. If the owner agrees with the design then the process moves along for the detailed design of the residential building. If the owner for some reason does not agree (s)he will then go back to the engineering office for a revised conceptual design of the residential building.

The detailed design then has to be approved by the local municipality in order to progress to construction. This is known as the approval phase. Once the detailed design of the residential building has been approved by the local municipality it can then progress to the construction phase. As soon as the construction is complete it should obtain final approval from the local municipality in what is known as the operational phase before being occupied.

The proposed residential building design process would follow the procedure set out in Figure 3 below.

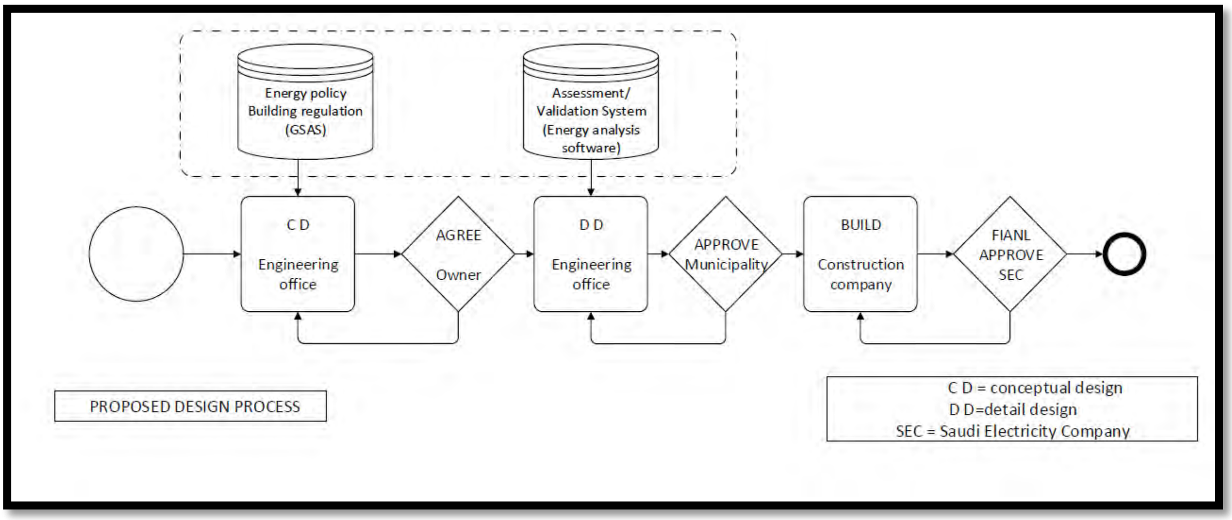


Figure 4: Proposed Design Process of new residential buildings in Saudi Arabia

This proposed design process is similar to the current design process up to the point where the final approval has to be gained by the Saudi Electrical Company (SEC) who will assess the residential building against its own energy standards before connecting the electricity supply to the new residential building. If for any reason the SEC do not give approval it will go back and inform the construction company of the necessary re-work to be done regarding the energy supply in particular the electricity supply to the residential building which should be sufficient to bear the load of modern energy efficient domestic appliances in order for the residential building to gain final approval.

In addition to this, during the design phase it is proposed that energy policies and building regulations and codes based upon the GSAS (Gulf Sustainability Assessment System) should be incorporated and adhered to for energy requirements of the residential building when setting out the conceptual design of the residential building as it is then utilized for analysis of energy efficiency and alternative comparisons to improve energy economy of the residential building.

Once in agreement and moving forward towards the detailed design of the residential building, it is proposed that an assessment / validation system is put into place utilizing energy analysis software to validate the residential building design based on energy performance. The requirements for energy analyses depend upon the detailed design. Energy analyses are required especially when there is a potential for significantly improving the energy performance of the residential buildings.

Framework Validation Using Case Study Analysis

The energy consumption was simulated and analysed using Sefaira real time energy analysis software. The results of the simulations for the energy consumed in the residential building in Riyadh city were evaluated according to the design of the case study residential building, including the building fabric used. The simulations provided energy consumption analysis, daylight analysis and information regarding energy demand for heating/cooling purposes.

At first energy simulation was conducted without the use of insulation materials in the external walls of the residential building and then the details of the design were changed by adding insulation materials to the external walls. The building energy consumption, and its associated daylight analysis were re-assessed in order to examine the potential improvements with the use of insulation materials in the external walls of the residential building which was applied as an energy efficiency measure.

The energy consumption data were then analysed and the results compared with and without the use of insulation materials to the external walls of the case study residential building in the capital city of Riyadh in the Kingdom of Saudi Arabia.

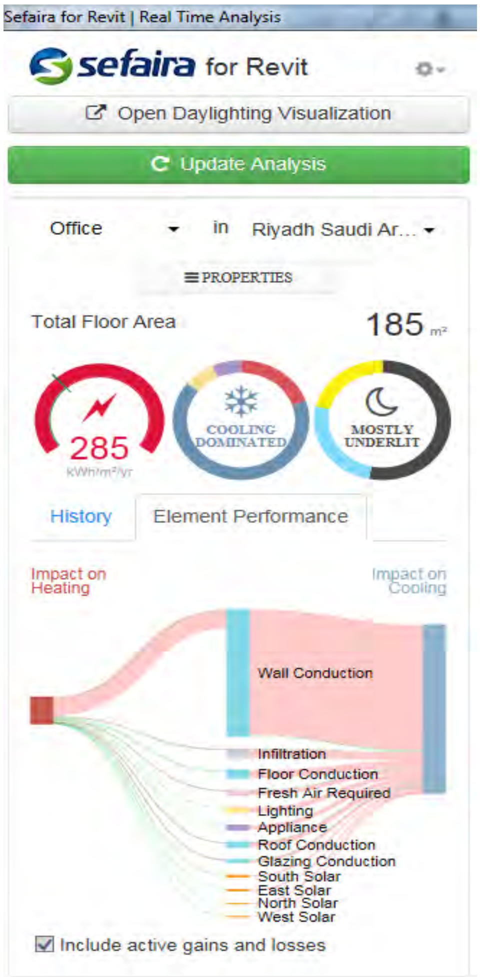


Figure 5: Energy consumption analysis on the case study residential building in the city of Riyadh KSA –without the use of insulation materials on external walls

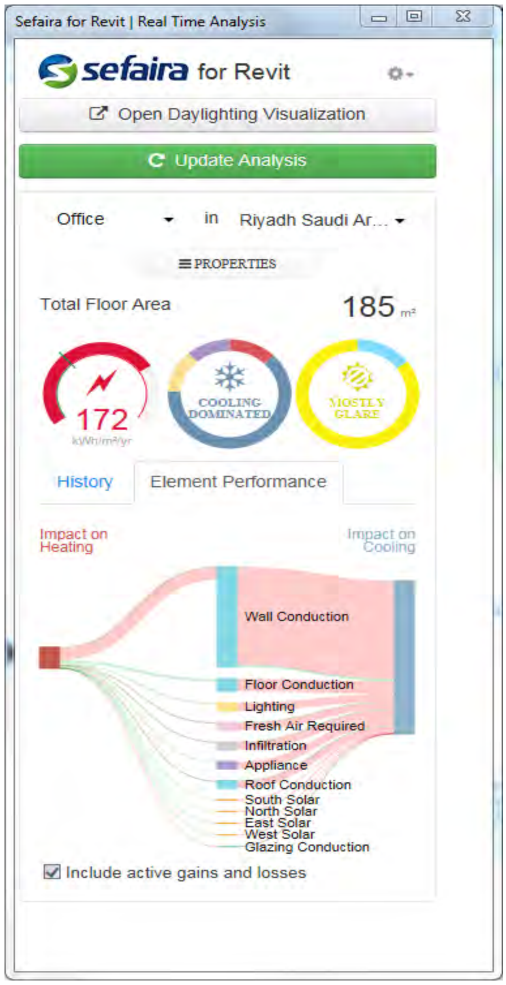


Figure 6: Energy consumption analysis on the case study residential building in the city of Riyadh KSA –with the use of insulation materials on external walls

Table 1:
Framework Validation Case Study Summary

Location	**Type of residential building**	**Total floor area of residential building**	**Occupies**	**Type of software used**	**Element performance tested**	**Wall Insulation material results**	
						With	**Without**
Riyadh KSA	Two storey residential building	185 m^2	3 to 5 people	Sefaira Energy Simulation Software	Wall Insulation	285 $kWh/m^2/yr$	172 $kWh/m^2/yr$

The results of the impact of wall insulation on the energy consumption of the case study on the residential building shows most of the optimized energy performance being achieved by adding the external wall insulation. The simulation results show that by adding wall insulation to the case study residential building in Riyadh it achieves 39% in energy savings in the total energy consumption. These findings are attributed to the fact that the lack of optimal architectural design and construction materials especially insulating materials has been the cause of the high energy consumption and demand.

From a comparison of the diagrams shown in figures 4 and 5, the results show an overall difference of 30% to 40% by the addition of insulating materials to the external walls. For future validation purposes it is prosed to test other variables which affect the building envelope such as roof, floor and windows as these also affect the energy required for thermal comfort within buildings.

According to Blom *et al.,* (2011), "Energy consumption in dwellings contributes significantly to their total negative environmental impact". It is evident that according to the energy simulations, there is high energy consumption in residential buildings in the city of Riyadh. With the biggest issue causing a high demand for energy is the high level of electricity consumption for cooling, Aldossary *et al.,* (2013), state amongst other energy conservation measures a lack of optimal architectural design and construction materials has been the cause of this high energy demand in residential buildings in Saudi Arabia. Preceding this Balaras *et al.,* (2007), has earlier specified that as an example, 33% - 60% of energy can be saved by using efficiently designed external walls.

Hence the in-depth Sefaira analysis has allowed an understanding of what the energy was consumed for. As illustrated the case of the highest energy consumption is for cooling purposes due to the extremely hot and arid climate of Saudi Arabia. Consequently in order to reduce this high demand for domestic energy consumption and for residential buildings to become energy efficient in the hot arid climate of Saudi Arabia it is important to enhance the building envelope performance to reduce cooling thermal loads through thermal insulation. As this illustrates the need to employ optimal insulation with the full use of architectural solutions as set out in the proposed framework.

Conclusion

The building sector in Saudi Arabia is currently placing intensive pressure on the country's reserves of natural resources. It is estimated that about two-thirds of the electric energy generated in the Kingdom of Saudi Arabia is used by the building industry (Al Sanea *et al.,* 2012). Hence, conventional construction operations impact seriously on the environment as a result of their excessive use of energy. Continuing in this vein is neither feasible nor sustainable.

However, this proposed framework for energy efficient Saudi residential buildings differs from other studies, as it takes into account the GSAS (Gulf Sustainability Assessment System) alongside the local Saudi climate, environmental conditions, and residential needs. The GSAS (Gulf Sustainability Assessment System) is used as a benchmark for the low energy consumption definitions, standards and policies that are incorporated into the proposed framed for Saudi Arabia.

This will lead to, (a) adherence to sustainable energy policies during the conceptual design phase and (b) a validation system during detailed design with the use of BIM Energy analysis software tools in the established framework. Consequently, this framework will act as a reference for developers, architects and civil engineers required to design energy efficient residential buildings in Saudi Arabia to meet all local requirements, needs and environmental challenges.

The results of the validation case study demonstrated high energy consumption, thus the energy optimization approach was based on energy performance to identify optimal and effective energy efficiency measures. These analyses and energy simulations offer the potential for a cost-effective solution for energy reduction and major savings in electricity use for cooling purposes, as well as elucidate the potentials for energy efficiency in the residential building sector of Saudi Arabia.

References

Al-Ajlan, S. A., Al-Ibrahim, A. M., Abdulk Haleq, M., Alghamdi, F. (2006), Developing sustainable energy policies for electrical energy conservation in Saudi Arabia. *Energy Policy*, 34, 1556-1565.

Alaidroos, A., Krarti, M., (2014), Optimal design of residential building envelope systems in the Kingdom of Saudi Arabia, *Energy and Buildings*, 86; 104–117

Al-Dossary, N. A., Rezgui, Y., Kwan, A., (2014), Domestic energy consumption patterns in a hot and humid climate: A multiple -case study analysis. *Applied Energy*, 114, 353-365

Al-Ibrahim, M.H., (1990), The Criticism of Modem Architecture in Saudi Arabia. College of Architecture and Planning, *Journal of King Saud University*, Riyadh, Saudi Arabia. vol. 2, pp. 63-80.

Al-Natheer, O., (2006), Environmental benefits of energy efficiency and renewable energy in Saudi Arabia's electric sector. *Energy Policy*, 34, 2-10.

Almatawa, M. S., Elmualim, A. A., Essah, E. A., (2012), Passive and active hybrid approach to building design in Saudi Arabia. In: *Eco-architecture IV: Harmonisation Between Architecture and Nature*, C. A. Brebbia, (Ed.), WIT Press, UK, pp. 163-174

Alrashed,F., Asif, M., (2012), Prospects of renewable energy to promote zero-energy residential buildings in the KSA, *Energy Procedia* 18 1096–1105.

Al-Sanea, S. A., Zedan, M. F., Al-Hussain, S. N. (2012), Effect of thermal mass on performance of insulated building walls and the concept of energy savings potential. *Applied Energy*, 89, 430-442.

Alshenaifi, M.A., (2015), *High Performance Homes in Saudi Arabia- Revised Passivhaus Principles for Hot and Arid Climates*, MSc Thesis, Philadelphia University, USA

Aluwaisheg, A. A., (2013), *Unemployment rises again amid rapid economic growth. Arab News*. Retrieved from http://www.arabnews.com.

Azhar, S, Carlton, W, Olsen, D, Ahmad, I., (2011), Building information modelling for sustainable design and LEED® rating analysis. *Automation in Construction*, 20(2), 217–224.

Azhar S., (2011), Building Information Modeling (BIM): Trends, Benefits, Risks, and Challenges for the AEC Industry, *Leadership and Management in Engineering,* pp241– 252.

Blanchard, S., Reppe, P., (1998), *Life cycle analysis of a residential home in Michigan*. Master's thesis, University of Michigan, Ann Arbor.

Blom I., Itard L., Meijer A., (2011), Environmental impact of building-related and user related

energy consumption in dwellings. *Building and Environment,* 46(8):1657e69.

Chwieduk, D. (2003), Towards sustainable - energy buildings. *Applied Energy*, 76, 211- 217.

Fasiuddin, M., Budaiwi, I., (2011), HVAC system strategies for energy conservation in commercial buildings in Saudi Arabia. *Energy and Buildings*, 43, 3457-3466.

Geyer, P (2012), Systems modelling for sustainable building design. *Advanced Engineering Informatics*, 26(4), 656-668.

Hamed, S.E. A., (2003). *Capacity Building for Sustainable Development: The Dilemma of Islamization of Environmental Institutions. Islam and Ecology*. Harvard University, Press.

Hepbasli, A., Alsuhaibani, Z. 2011. A key review on present status and future directions of solar energy studies and applications in Saudi Arabia. *Renewable and Sustainable Energy Reviews*, 15, 5021-5050.

Hong Kong Housing Authority., (2011), *Application of Building Information Modelling (BIM) in the Hong Kong Housing Authority's Public Housing Developments*, Accessed online 03 March 2016, http://www.hkifm.org.hk/psdas/presentation/AdaFung-2011-05-24BIMinHAforHKIFM26May2011-rev7.pdf

IEA, International Energy Agency. (2011). *Statistics and graph Saudi Arabia (OECD).* Retrieved 02 2011, from IEA (international energy agency): http://www.iea.org/country/n_country.asp?COUNTRY_CODE=SA&Submit=Submit

Ishida, H., (2015),The effect of ICT development on economic growth and energy consumption in Japan. *Telematics and Informatics*, 32, 79-88.

Karam, S., (2010), Special report: *Can Saudi Arabia fix its housing time bomb*? Reuters.

Kassim, T. *et al*., (2013), *Automated Sustainability Compliance Checking Process Proof Of Concept.* In proceeding of: CONVR 2013, 13th International Conference in Construction Applications of Virtual Reality

Kubba S., (2012), *Handbook of Green Building Design and Construction: LEED, BREEAM, and Green Globes*. UK: Butterworth Heinemann.

Lahn, G., Stevens, P., (2011), *Burning Oil to Keep Cool - The Hidden Energy Crisis in Saudi Arabia.* The Royal Institute of International Affairs.

M, A.-S. (2002), Greenhouse Gas Reduction: Scientific Concern, or Economic Rivalry? The Oil and Gas Industry. [Online]. Available: http://www.thecwcgroup.com

Mubarak, F. A., (1999), *Cultural Adaptation to Housing Needs: A Case Study, Riyadh, Saudi Arabia*. IAHS Conference Proceedings, San Francisco.

Niroumand, H., Zain, M. F. M., Jamil, M., (2013), A guideline for assessing of critical parameters on Earth architecture and Earth buildings as a sustainable architecture in various countries. *Renewable and Sustainable Energy Reviews*, 28, 130 -165.

Numan, M.Y., Al-Naim, M. A., Al-Shaibani, K. A. and Al-Maziad, F. A. (2001). The Impact of Dynamic Cultural Changes on the Design and Energy Performance of Residential Buildings in Saudi Arabia. Mediterranean conference for Environment and Solar, Beirut, Lebanon.

Obaid, R. R., (2008), *Present State, Challenges, and Future of Power Generation in*

Saudi Arabia. IEEE Energy2030. Atlanta, GA USA.

Russell-Smith, S., Lepech, M., (2012), Activity-Based Methodology for Life Cycle Assessment of Building Construction. In: *" CIBSE ASHRAE Technical Symposium",* Imperial College London, 1–13.

SEEC., (2013), Saudi Energy Efficiency Centre. Accessed online 03 March 2016, from http://www.seec.gov.sa/2013/03/27/ينابم/?lang=en

Saudi Ministry of Electricity, (2010), *Saudi Electricity Company Report 2010*. Ed. Saudi Arabia: Ministry of Electricity.

Taleb, H. M., Sharples, S. (2011), Developing sustainable residential buildings in Saudi Arabia: A case study. *Applied Energy*, 88, 383-391.

Wong, K., Fan, Q., (2013), Building Information Modelling (BIM) for sustainable building design. *Facilities*, 31 (4).

DYNAMIC MODELLING OF CRANES AND CONCRETE PUMPS DIFFUSION IN THE CONSTRUCTION INDUSTRY

***Samad M.E. Sepasgozar*[A] *& Perry Forsythe*[B]**

[A] *The Faculty of Built Environment, The University of New South Wales Australia, Sydney; Australia, Email: Samad.Sepasgozar@gmail.com*

[B] *Faculty of Design Architecture and Building, University of Technology Sydney; Australia, Email: Perry.Forsythe@uts.edu.au*

ABSTRACT: *Advanced technologies are increasingly being introduced to the construction industry. Several studies in the literature have examined the diffusion of advanced technologies such as communication technology; however, the diffusion process for hard construction technologies such as advanced concrete pumps, from an organizational diffusion perspective, has received very little attention. Moreover, project managers require an approach by which they can take the complexities within the construction industry into account. This paper presents a Dynamics of Technology Adoption Model (DTAM) which is based on the concept of system dynamics incorporating time lags for each activity, operation feedback effects and causal links among factors. The model demonstrates the relationships between different attributes such as individual, financial and technological factors in a visual context, in order to evaluate the diffusion patterns of advanced concrete pump technologies. The model is verified using the results of a survey of practitioners in the US and Australia. Finally, the paper discusses the implications of the model structure for fostering pump concrete diffusion, as a means of boosting productivity in building construction.*

KEYWORDS: *concrete pump, system dynamics, technology implementation, diffusion.*

1. INTRODUCTION

The success of the commercialization of a new technology relies on a thorough understanding of the adoption process (Ganguly et al., 2010; McCoy et al., 2010). Several adoption studies also illustrate a consensus on the importance of the process in ensuring the success of new technologies, and the market place where technology diffusion and adoption occurs (Kale and Arditi, 2005; Castro-Lacouture et al., 2007; McCoy et al., 2010; Abdelhameed, 2012; Sardroud, 2014). Position papers such as the Australian Construction Vision 2020 encourages the construction industry to partner with other industries in order to facilitate technology diffusion (MacGauran and Macfarlane, 2004). There is a rising desire among practitioners and academics to promote rapid technology adoption through widespread dissemination strategies to provide awareness and effectively communicate with customers.

The ability to know how, why and where construction companies adopt new technologies is also critical, because it gives the ability to expedite the rate of technology diffusion by facilitating adoption. According to Arts et al.

(2011), understanding this process is critical for managers involved in marketing innovation. However, investigation of the process in terms of considering dynamic factors influencing adoption decisions by which construction companies select and operate new construction technologies for their projects, remains an open question.

Models of the technology adoption process exist outside construction. However, these are not suitable for the construction industry, because construction is widely recognized as a complex and project driven system and distinctly different from other industries (Barlow, 2000; Dubois and Gadde, 2002; Straub, 2009; Hinkka and Tätilä, 2013; Ozorhon et al., 2013; Sardroud, 2014). There is therefore, a need to investigate the current industry practice of decision making in order to provide a dynamic system model to assist industry players in facilitating the process, and to hopefully become more successful at utilizing the most appropriate technology in the timeframe available.

Data from the Melbourne Institute of Applied Economics and Social Research (2010) shows that the construction innovation index lags significantly behind other industries (IBM, 2010). Construction even fell by 18.2% between 2005 and 2006. Previous studies discuss how the Australian construction industry is high cost/low productivity compared to USA (BCA, 2012; Loosemore, 2014). The general problem is by no means unique to Australia, and there is significant room to adopt many innovations (Loosemore and Richard, 2015). Possible causes of the slow rate of adoption are attributed to specific customer- and vendor-related attributes (Robertson and Gatignon, 1986; Gourville, 2005; McCoy et al., 2010). It is also frequently reported that the conservative attitude of construction companies affects their openness to consider new technologies as the whole industry continues to lag in technology adoption and is generally averse to change (Stewart et al., 2004; Nikas et al., 2007; Harty, 2008; Goodrum et al., 2009; Hardie, 2010; Hardie and Newell, 2011; Milliou and Petrakis, 2011; Heller and Orthmann, 2014; Love et al., 2014). According to Manley (2008), many construction companies are not aware of the best practice approaches to implementing innovations in Australian projects – this may apply to the construction industry in many other countries as well. Therefore, the need to study technology adoption in construction is particularly important as it has been significantly slow in up-taking new technologies.

This paper attempts to develop a systems dynamics perspective of construction technology adoption in three main steps. First, an extensive number of papers were reviewed to present a clear and important gap in knowledge of construction technology adoption. Second, a conceptual model is presented based on the previous studies with systems dynamic being at the core of the approach used. Third, the Dynamics of Technology Adoption Model (DTAM) is developed and presented.

2. LITERATURE REVIEW

Many studies have attempted to understand and predict the adoption process of information technology (IT) in construction. These studies often borrow general acceptance from diffusion models from IT disciplines (e.g. Adriaanse et al., 2010; Park et al., 2012; Son et al., 2012; Lee et al., 2013). For example, Park et al. (2012) and Rampersad et al. (2012) use and extend the technology acceptance model (TAM) to predict adoption of new information technologies in construction. TAM was developed by Davis et al. (1989) to predict individuals' intentions to use new information technologies and is based on psychological based behavioral traits. However, such studies seem to assume that the technology adoption occurs in a single stage, akin to an impulse purchase (Ulubeyli and Kazaz, 2009). Sepasgozar and Davis (2015) present a multi-stage decision making framework for construction technology adoption. They cover the interaction between the vendor and the purchasing organization, while other studies in the literature regarding technology adoption in the construction industry tend to focus either on customer related attributes or supplier related attributes (Robertson and Gatignon, 1986; Gourville, 2005; McCoy et al., 2010) without considering the interaction between these two parties. In particular, there is no published work dealing with the surrounding customer-vendor issues. Overall, little attention has been paid in the literature to investigating the whole adoption process considering the path a company passes through prior to and after making the decision to employ a new construction technology (particularly hard technologies such as equipment and tools).

Technology adoption has been studied in information systems for decades, but it has not been sufficiently developed, envisioned and tailored for the construction context. While image, demonstrable results and computer anxiety are determinants of information system adoption, safe operation, low downtime, and easy repair are likely to be important to a contractor to purchase and use advanced equipment and tools (e.g. cranes or concrete pumps). Another deficiency of the existing models relates to the level of analysis (e.g. individual vs organizational). For example, Lee et al. (2013) used TAM to measure “organizational intent to accept BIM” (Lee et al., 2013, P. 10) which is somewhat out of context given that TAM is a psychologically based model to predict individual user behavior. Not surprisingly, their results concerning hypothesized relationships concerning perceived usefulness, perceived ease of use, and organizational intent to accept BIM shows that neither perceived usefulness nor perceived ease of use have a direct relationship with organizational intent to accept BIM”. Organizational intentions cannot be predicted without considering other phases (i.e. all three phases of investigation, adoption, implementation) and factors such as company policy and vested stakeholders. In Lee et al’s study (Lee et al., 2013), mixing organizational and individual determinants to measure TAM’s constructs (e.g. Usefulness and Ease of use) resulted in a weak correlation (less than 0.3) between most of their proposed determinants. They concluded that “high individual intent to accept BIM and high consensus on appropriation are required in order to achieve high organizational intent to accept BIM”. Even so, there is no evidence that TAM can prove that the adoption in an organization is a consensus based decision.

This research therefore aims to advance the modelling of technology uptake with an emphasis on equipment oriented construction technology. It aims to take into account a wider array of dynamically occurring factors that impact on adoption decision making as well as focusing on organization level decision making (including both customers and vendors).

3. RESEARCH METHODOLOGY

The research method begins by using the literature to build a basic adoption behavior model using a Systems Dynamic Modelling approach. This is then elaborated further using data from an extensive interview process of equipment vendors and customers. It provides much greater context about linkages within the system and the weighting assigned to certain adoption features.

A group of factors such as project objectives, project obligations, and reliability were asked to the participants to rank issues using closed questions structured on the hierarchy recommended by Analytical Hierarchy Process (AHP) procedure (Saaty, 1988). AHP is a powerful tool that is developed to assist decision makers by ranking factors and evaluating alternatives (Saaty, 1980). Respondents were asked to rank the attributes considering the importance of each factor in the process of decision making for adoption of a new technology – at a project, technology, organization and vendor attributes. They were asked to score each position 'N/A', 'low', 'medium', and 'high'. The collected data was analyzed using AHP analysis technique to reveal the percentages of times that each factor ranked 'high'.

Data was collected through conducting 147 interviews. The interview participants were spread across Australia and North America. The spread of samples in two regions increases generalizability of the results and enables cross validation of the findings. Interviewing both customers and vendors also increases validity. Data were analyzed using coding and micro analysis of the interview transcripts.

Table 1. A summary of participants' profiles

Item	Description	Vendors	Customers	Total
Participants' experience (years)	5-10	29	6	35
	11-30	42	34	76
	>30	14	22	36
Total		85	62	147

The analysis provides factors and activities involving the adoption process which are used to develop and verify the Dynamics of Technology Adoption Model (DTAM). A system dynamics approach was used for modeling the process, because the inclusion of feedback effects can be considered in the model. This aims to advance previous studies which focused purely on an event or linear process and did not consider feedback and other dynamic factors effecting adoption decision making.

4. TECHNOLOGY ADOPTION SYSTEM DYNAMIC MODEL

In this section, a system dynamics model is presented for describing the technology adoption process in construction markets in four sub sections. The conceptual model which initially occurs as a single loop is developed, and the model is then extended with an additional loop including vendor attitudes. Next, the general detail model of technology adoption for construction technologies will be developed based on the qualitative analysis gained through interview.

4.1 Conceptual SD Model for Technology Adoption

The System Dynamics (SD) approach was selected as an appropriate option for modelling construction technology adoption since it is able to take the dynamicity of the construction industry into account and aims to improve on previous studies in technology adoption in construction (Sepasgozar and Davis, 2015) which are primarily limited to a linear model for construction technology adoption. The model explains how a contractor chooses a technology and implements it on a construction site. However, there are also dynamic attributes that should be considered in the process of predicting adoption such as the lag between activities and the inter-related influence of specific factors that impact on the process. For example, the question is which specific factors, such as parts availability can affect the purchase decision. Therefore, the system dynamics approach is used to develop a dynamic model for technology adoption to give an understanding of key factors. These include all adoption factors and diffusion factors that in the literature have been considered separately. The model is called Dynamics of Technology Adoption Model (DTAM).

According to Sepasgozar and Davis (2015), the construction technology adoption process includes three main phases of investigation, adoption, and implementation. Based on the overall concept, the core model developed in this study includes four main activities: need identification, adoption decision, operation, and information feedback as shown in Figure 1.

Figure 1. The conceptual dynamic adoption model.

In addition to the main activities, the vendors' role should also be considered in the model as their characteristics are known to be important in adoption decisions. Figure 2 shows that vendors' performance will affect the operation phase, as their support during this phase is critical and will prevent downtime. Their support will affect customer feedback and the word-of-mouth recognition by customers to others. Vendors also may offer new technologies for specific needs in construction projects, and therefore influence the needs identification by contractors.

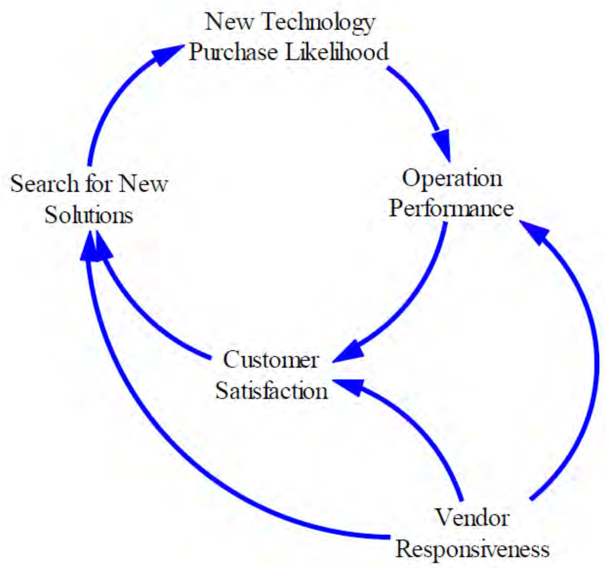


Figure 2. The dual core model including vendors' role.

Interviews revealed that there are two strategies pursued by vendors. Some vendors do not provide extensive maintenance support because they want to offer a competitive price (cheaper than competitors). On the other hand, some vendors seek to meet this need and tend to identify with being industry leaders. A large excavator vendor in the USA describes what their customers ask them: "Can I call you 24/7 for parts? Would you be there on Sunday afternoon?". Some customers additionally hold particular concerns regarding availability of a vendor to perform on-site repairs. While larger contractors and rental equipment companies often have expertise (e.g. mechanics), individual workshops and basic tools and parts to repair their machines, these customers still need technical information on how to repair unusual problems and major break downs. They are happy to get remote support (e.g. phone and email support) in order to repair broken machines by themselves, as long as they do not have to wait for long periods for remote support. A director of a large rental company in the US who bought an advanced hydraulic crawler crane (220 ton) just before being interviewed stated: "*They are very good at helping us, we are from North Carolina so we are rather remote. ... We have got fairly good at maintaining our equipment. So if we can get factory support direct that actually helps us…*"

4.2 Construction Technology Adoption SD Model

Figure 3 illustrates the Dynamics of Technology Adoption Model (DTAM) including twenty one factors. Each factor has a negative or positive influence on the other factor. The main purpose of the model is to predict what factors may affect the adoption decision (purchase decision). Figure 3 shows two main groups of factors, which influence decisions in terms of the sequence of activities before and after the adoption decision. For example, project needs and price check will be made before the decision. Training and productivity measures will be made after the decision. The novelty of the model is that it shows the relationship between "the adopter's activities after the adoption" and "other potential adopter's purchase decision". Figure 3 shows that 'operation commencement' is the first and the only activity that may occur after 'new technology purchase likelihood'. Then the figure shows a series of activities after the adoption which eventually affects the adoption process. For example, 'training', 'productivity', 'customer satisfaction' positively (i.e. +) affects the next purchase and may increase (i.e. +) the 'new technology purchase likelihood'.

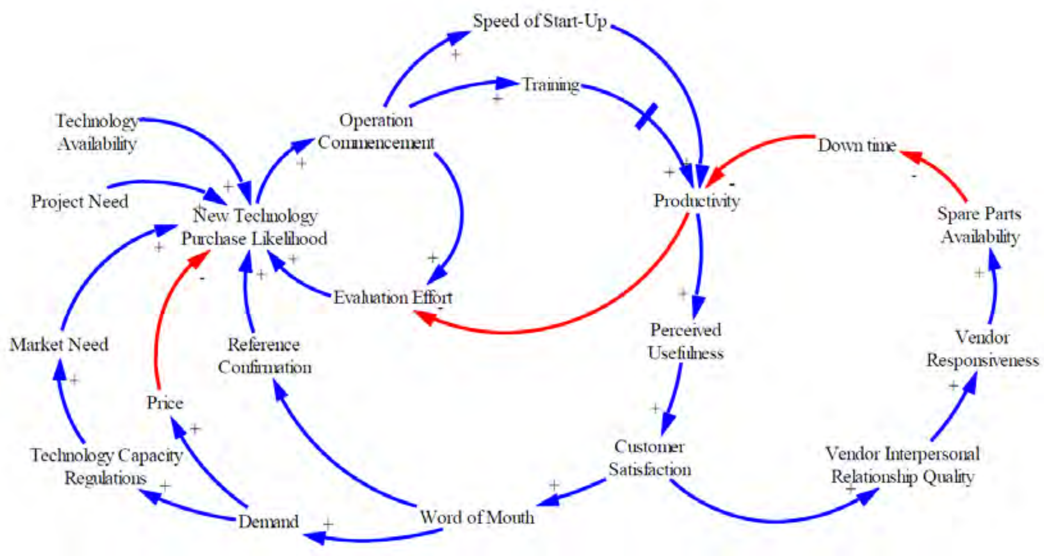


Figure 3. The conceptual dynamic adoption model

Figure 3 also shows that there are two groups of factors in terms of adoption and diffusion. The first group of factors is 'project need', 'technology availability', 'reference confirmation' and 'market need' which refers to pre-adoption process. The second group of factors will occur when the technology is purchased by a customer, and most likely will be the base of the next purchase decisions by the same customer or the customer's competitors. For example, 'productivity', 'downtime', and 'vendor interpersonal relationship quality' are some of factors which will occur after the adoption. Previous studies focused on the adoption within the organizations (Sepasgozar and Davis, 2015). Other studies focused on the influential factors outside the company in the industry level such as Kale and Arditi (2010). The advantage of DTAM is that it considers the outcome of the operation as the input of the decision, in terms of information feedback and word of mouth.

4.3 Contributing Factors

A qualitative system dynamics model can be validated by evaluations of model structure. Confidence in a system dynamics model is attained when the model passes more tests and some correspondence between the model and empirical reality are identified. In this investigation, test of model components, which examines structure and parameters directly, was employed in order to acquire confidence in the model.

In order to evaluate the importance of related factors in the larger context, participants were asked in their interviews to rate the importance of each factor in the decision. Answers were scored as high (3), medium (2) or low (1). Expert Choice is used as a specified program to calculate factors' rank based on their Local and Global weights. Local weight refers to the weight of each factor calculated in its category, and the global weighting refers to the weight of each factor calculated considering all factors. The factors that were ranked as ‘high’ most frequently (by above 70% of participants) are presented in Table 2. Table 2 also divides the factors into four main groups: 1) project, 2) technology, 3) company, and 4) vendors’ attributes.

Table 2. Key factors affecting the adoption process

Attribute (AHP rank)	Factor	% of times ranked high	Repeated by participants	AHP (L^1)	AHP (G^2)
1) Project (0.367)	Project objectives[3]	100	65	0.26	0.09
	Project obligations	82	45	0.13	0.05
2) Technology (0.353)	Reliability	91	52	0.23	0.08
	Performance quality	82	50	0.19	0.07
	Durability	88	49	0.15	0.05
	Features	82	39	0.04	0.01
3) Organization (0.160)	CBR	73	48	0.33	0.05
4) Vendor (0.120)	After sales support	73	46	0.12	0.01
	Vendor responsiveness	73	46	0.09	0.01

Note: [1] L refer to local weighting, [2]G refers to global weighting. [3]Refers to several items such as safety and quality, but in AHP separately considered in questionnaire (i.e. specifically refers to safety)

The number of references (repeated by participants) found in the coding analysis of transcriptions is also given. Participants were also asked to fill in the AHP questionnaire in order to evaluate the relative importance of each factor. The table also gives the AHP weighting for each factor. Overall inconsistency for the AHP analysis is 0.01 which is considered excellent (should be less than 0.1, see: Zeshui and Cuiping (1999) and Cao et al. (2008)). The data provided in Table 2 were normalized.

The analysis shows that most of the factors from technology attributes are important to customers. For example, reliability and performance quality are very important to customers, but they cannot exactly be measured for some advanced technologies such as concrete pumps until customers purchase and start using it on a specific site. Customers usually do not know whether the new concrete pump will deliver the expected functionality or its maintenance needs. For this reason, customers consequently are concerned about pump vendors’ attitudes such as vendors’ after sales support, to ensure they can get help when the technology breaks down or spare parts are needed.

The analysis shows that customers frequently discussed different variables related to vendors’ responsiveness and after sales support such as remote response over the phone, provision of spare parts, training, and sending technicians to the site. The results of ranking analysis and AHP are slightly different. However, since the data is normalized based only on the factors in the graph, this just indicates that these factors were rated lower than the other factors, not that they were completely unimportant.

From the above, causal links in the system dynamics model have been established and consequently verified in a number of ways, including direct observation, reliance on accepted theories, hypotheses, and statistical evidence. In this paper, causal relationships among the model variables were validated by AHP analysis. Table 2 shows the average value of relative importance of each factor influencing the adoption decision for construction equipment including advanced concrete pumps.

5. CONCLUSION

This paper aimed to explore Dynamics of Technology Adoption Model (DTAM) based on the concept of system dynamics incorporating time lags of each activity, operation feedback effects and causal links among identified factors. The main purpose of the model is to predict what factors may affect the adoption decision (purchase decision). The model also demonstrates the relationships between different attributes such as individual, financial and technological factors, in order to evaluate diffusion patterns of advanced concrete pumps and cranes. The findings show that vendor performance, parts availability and down time are three key factors which will affect user productivity and will consequently effect customer satisfaction. This will in turn impact on repeat purchase decisions. In addition, DTAM shows that purchase decisions are affected by needs (market and/or project) and productivity evaluations.

The model is verified using the results of a survey of 147 practitioners in the US and Australia. The novelty of the model is that it shows the relationship between “the adopter’s activities after the adoption” and “other potential adopter’s purchase decision”.

The original contribution of the paper lies in its careful collection and analysis of extensive empirical data to establish a scientifically sound understanding of technology dissemination and adoption processes. The novelty of the presented model is that it considers the dynamics of the process before the decision and during the implementation. The study is different to other studies as it considers customer and vendor dynamics and interactions whereas previous studies focus purely on the customer. In addition, findings apply to adopter organizations (i.e. technology adoption) rather than less relevant individual adopters (i.e. technology acceptance). The paper is the first step in explaining the dynamics of the adoption process and will help direct further study.

ACKNOWLEDGEMENT

The authors thank Jeff Scales for producing the figures.

REFERENCES

Abdelhameed, W. (2012) "Virtual Reality Applications in Project Management Scheduling", *Computer-Aided Design and Applications,* 9(1), 71-78.

Adriaanse, A., Voordijk, H. and Dewulf, G. (2010) "The Use of Interorganisational Ict in United States

Construction Projects", *Belconnen ACT, Australia,* 19(1), 73-83.

Arts, J. W., Frambach, R. T. and Bijmolt, T. H. (2011) "Generalizations on Consumer Innovation Adoption: A Meta-Analysis on Drivers of Intention and Behavior", *International Journal of Research in Marketing,* 28(2), 134-144.

Barlow, J. (2000) "Innovation and Learning in Complex Offshore Construction Projects", *Research Policy,* 29(7-8), 973-989.

BCA (2012) *Pipeline or Dream – Securing Australia's Investment Future*, Sydney: Business Council of Australia.

Cao, D., Leung, L. C. and Law, J. S. (2008) "Modifying Inconsistent Comparison Matrix in Analytic Hierarchy Process: A Heuristic Approach", *Decision Support Systems,* 44(4), 944-953.

Castro-Lacouture, D., Medaglia, A. L. and Skibniewski, M. (2007) "Supply Chain Optimization Tool for Purchasing Decisions in B2b Construction Marketplaces", *Automation in Construction,* 16(5), 569-575.

Davis, F. D., Bagozzi, R. P. and Warshaw, P. R. (1989) "User Acceptance of Computer Technology: A Comparison of Two Theoretical Models", *Management Science,* 35(8), 982-1003.

Dubois, A. and Gadde, L.-E. (2002) "The Construction Industry as a Loosely Coupled System: Implications for Productivity and Innovation", *Construction Management and Economics,* 20(7), 621-631.

Ganguly, I., Koebel, C. T. and Cantrell, R. A. (2010) "A Categorical Modeling Approach to Analyzing New Product Adoption and Usage in the Context of the Building-Materials Industry", *Technological Forecasting and Social Change,* 77(4), 662-677.

Goodrum, P. M., Zhai, D. and Yasin, M. F. (2009) "Relationship between Changes in Material Technology and Construction Productivity", *Journal of Construction Engineering and Management,* 135(4), 278-287.

Gourville, J. T. (2005) *The Curse of Innovation: A Theory of Why Innovative New Products Fail in the Marketplace*, Boston: Harvard Business School.

Hardie, M. (2010) "Influences on Innovation in Small Australian Construction Businesses", *Journal of Small Business and Enterprise Development,* 17(3), 387-402.

Hardie, M. and Newell, G. (2011) "Factors Influencing Technical Innovation in Construction Smes: An Australian Perspective", *Engineering, Construction and Architectural Management,* 18(6), 618-636.

Harty, C. (2008) "Implementing Innovation in Construction: Contexts, Relative Boundedness and Actor-Network Theory", *Construction Management and Economics,* 26(10), 1029 - 1041.

Heller, A. and Orthmann, C. (2014) "Wireless Technologies for the Construction Sector—Requirements, Energy and Cost Efficiencies", *Energy and Buildings,* 73(0), 212-216.

Hinkka, V. and Tätilä, J. (2013) "Rfid Tracking Implementation Model for the Technical Trade and Construction

Supply Chains", *Automation in Construction,* 35, 405-414.

IBM (2010) *Innovation Index of Australian Industry*, Melbourn Melbourn Institute of Appliad Economic and Social Research

Kale, S. and Arditi, D. (2005) "Diffusion of Computer Aided Design Technology in Architectural Design Practice", *Journal of Construction Engineering and Management,* 131(10), 1135-1141.

Kale, S. and Arditi, D. (2010) "Innovation Diffusion Modeling in the Construction Industry", *Journal of Construction Engineering and Management,* 136(3), 329-340.

Lee, S., Yu, J. and Jeong, D. (2013) "Bim Acceptance Model in Construction Organizations", *Journal of Management in Engineering*.

Loosemore, M. (2014) "Improving Construction Productivity: A Subcontractor's Perspective", *Engineering, Construction and Architectural Management,* 21(3), 245-260.

Loosemore, M. and Richard, J. (2015) "Valuing Innovation in Construction and Infrastructure", *Engineering, Construction and Architectural Management,* 22(1), 38-53.

Love, P. E., Matthews, J., Simpson, I., Hill, A. and Olatunji, O. A. (2014) "A Benefits Realization Management Building Information Modeling Framework for Asset Owners", *Automation in Construction,* 37, 1-10.

MacGauran, P. and Macfarlane, I. (2004) *Construction 2020 a Vision for Australias Property and Construction Industry*, Brisbane, Australia: CRC for Construction Innovation.

Manley, K. (2008) "Against the Odds: Small Firms in Australia Successfully Introducing New Technology on Construction Projects", *Research Policy,* 37(10), 1751-1764.

McCoy, A. P., Badinelli, R., Koebel, C. T. and Thabet, W. (2010) "Concurrent Commercialization and New-Product Adoption for Construction Products", *European Journal of Innovation Management,* 13(2), 222-243.

Milliou, C. and Petrakis, E. (2011) "Timing of Technology Adoption and Product Market Competition", *International Journal of Industrial Organization,* 29(5), 513-523.

Nikas, A., Poulymenakou, A. and Kriaris, P. (2007) "Investigating Antecedents and Drivers Affecting the Adoption of Collaboration Technologies in the Construction Industry", *Automation in Construction,* 16(5), 632-641.

Ozorhon, B., Abbott, C. and Aouad, G. (2013) "Integration and Leadership as Enablers of Innovation in Construction: A Case Study", *Journal of Management in Engineering*.

Park, Y., Son, H. and Kim, C. (2012) "Investigating the Determinants of Construction Professionals' Acceptance of Wb-Bsed Training: An Extension of the Technology Acceptance Model", *Automation in Construction,* 22, 377-386.

Robertson, T. S. and Gatignon, H. (1986) "Competitive Effects on Technology Diffusion", *Journal of Marketing,* 50(3).

Saaty, T. L. (1988) *What Is the Analytic Hierarchy Process?,* Berlin Heidelberg: Springer.

Sardroud, J. (2014) "Perceptions of Automated Data Collection Technology Use in the Construction Industry", *Journal of Civil Engineering and Management,* 21(1), 54-66.

Sepasgozar, S. M. and Davis, S. R. (2015) *A Decision Framework for Advanced Construction Technology Adoption,* translated by.

Son, H., Park, Y., Kim, C. and Chou, J.-S. (2012) "Toward an Understanding of Construction Professionals' Acceptance of Mobile Computing Devices in South Korea: An Extension of the Technology Acceptance Model", *Automation in Construction,* 28(0), 82-90.

Stewart, R. A., Mohamed, S. and Marosszeky, M. (2004) *An Empirical Investigation into the Link between Information Technology Implementation Barriers and Coping Strategies in the Australian Construction Industry* [Article], Sage Publications, Ltd.

Straub, E. T. (2009) "Understanding Technology Adoption: Theory and Future Directions for Informal Learning", *Review of Educational Research,* 79(2), 625-649.

Ulubeyli, S. and Kazaz, A. (2009) "A Multiple Criteria Decision Making Approach to the Selection of Concrete Pumps", *Journal of Civil Engineering and Management,* 15(4), 369.

Zeshui, X. and Cuiping, W. (1999) "A Consistency Improving Method in the Analytic Hierarchy Process", *European Journal of Operational Research,* 116(2), 443-449.

SURVEY OF THE RESEARCH OF ICT APPLICATIONS IN THE AEC INDUSTRY: A VIEW FROM TWO MAINSTREAM JOURNALS

Huaquan Ying & Sanghoon Lee

The University of Hong Kong, Hong Kong

ABSTRACT: *The application of information and communication technology (ICT) in the Architecture, Engineering and Construction (AEC) industry has attracted much attention by researchers in recent years. However, a comprehensive review is still missing from the existing literature. This paper aims to provide a comprehensive overview of the state-of-the-art research of ICT applications in the AEC industry. A total of 432 articles, published during 2011-2015 in two mainstream journals, namely Automation in Construction and Journal of Computing in Civil Engineering, are selected and analyzed. This review is conducted from three different views: 1) view of construction project lifecycle, aiming to investigate the distribution of research of ICT application in different stages; 2) view of ICT technologies, aiming to identify the popular ICTs in the AEC industry that researches focus on; and 3) view of ICT application areas, aiming to identify the areas in the AEC industry that ICTs are applied in. Throughout this review, the distribution of the research of ICT in four different stages (i.e., design stage, construction stage, operation & maintenance stage, and multistage) is firstly investigated. A total of 24 types of ICTs, categorized into 8 groups and 19 ICT application areas are then identified and analyzed. In additional, limitations of this review are also discussed.*

KEYWORDS: *Information and communication technology (ICT), Architecture, engineering, and construction (AEC) industry, literature review*

1. INTRODUCTION

The Architecture, Engineering and Construction (AEC) industry is an extremely information-intensive and knowledge-based industry where stakeholders create, consume and communicate a large amount of information throughout the project lifecycle (Dave and Koskela, 2009). Information and Communication Technology (ICT) has been widely recognized as a significant solution to improve the productivity and efficiency of information generating, transmitting, processing and managing in the whole construction process (Kang et al., 2013; Samuelson and Björk, 2014). Its applications in the AEC industry have attracted much attention by researchers since the last decades in the 20th century and a large number of relevant research have been conducted (Xue et al., 2012; Lu et al., 2014).

In the large body of existing research, many emerging ICTs have been explored and discussed to address specific issues in the whole life cycle of various AEC projects. To make a comprehensive and meaningful understanding of the research status of ICT applications in the AEC industry, an in-depth literature review is in need and important. A number of literature reviews have been conducted and they can be categorized in two groups: 1) reviews focusing on summarizing the research progress of one or several specific ICTs applied in the AEC industry, such as Augmented Reality (AR) (Chi et al., 2013), RFID (Lu et al., 2011), Building Information Modelling (BIM) (Volk et al., 2014), 3D/4D CAD (Park et al., 2011) and sensing technologies (Vähä et al., 2013); 2) reviews concentrating on ICT applications in specific domains of the AEC industry, such as review of digital design technologies used for construction safety (Zhou et al., 2012), IT applied for supporting collaborative work in construction projects (Xue et al., 2012), and digital ICTs used in procurement of construction projects (O. Ibem and Laryea, 2014). These studies provide ample specific views for understanding the research status of ICT uses in the AEC industry. However, a general and comprehensive view is still missing.

To fill this gap, this paper aims to provide a comprehensive overview of the state-of-the-art research on ICT applications in the AEC industry. More specifically, the objectives of this paper are: 1) to investigate the whole trend of the research on ICT applications in the AEC industry; 2) to identify key ICTs applied in the AEC industry and their key application areas; and 3) to brief the research trends of ICTs applications in the AEC industry. The rest parts of this paper are organized as follows: a clear scope definition of ICT discussed in this paper is given in Section 2; the research approach including qualified literature selection and review framework is described in Section 3; Section 4 presents detail study findings; and Section 5 concludes the paper.

2. ICT IN THE AEC INDUSTRY CONTEXT

A specific definition of the scope of ICT in the AEC industry context is required as a basis for this study. To achieve this goal, an attempt is made at reviewing the evolution of ICTs and different explanations in the literature. In a general context, Hamelink (1997) defined the ICTs as all those technologies that enable the handling of information and facilitate different forms of communication among human actors, between human beings and electronic systems, and among electronic systems. He explained that "digitization" is a common feature of ICTs. Hamelink (1997) further categorized ICTs into five groups: 1) capturing technologies for collecting and converting information into digital forms; 2) storage technologies for storing and retrieving information in digital forms; 3) processing technologies by creating systems and software applications that are required for the performance of digital ICTs; 4) communication technologies for transmitting information in digital forms; 5) display technologies for the display of digitized information.

In the AEC industry context, there is no specific and consistent definition of ICT. The explicit definition or scope of ICT is rarely discussed in relevant research even in some review studies. Based on a simple project process model, Froese (2005) discussed the roles of IT in construction projects. The main roles include: 1) individual tools or computer applications to implement project tasks; 2) communication technologies to convey the information; 3) IT systems to address systematic construction problems. Onyegiri et al. (2011) considered that ICT in construction can be "the interaction of meaning to reach a mutual understanding between a sender and a receiver via technology", which focuses on the communication function of ICT. Adriaanse et al. (2010) defined the inter-organizational ICT in the AEC industry context as "a digital coordination and collaboration tool used for communicating and sharing project information between participating organizations in a construction project". This definition emphasizes ICT's role of providing collaborative platforms or tools for construction management. Many researchers adopt this definition although it is not given explicitly. For example, Xue et al. (2012) conducted a review focusing on the IT supported collaborative work in the AEC projects by using "IT", "collaboration" and their relevant terms as the keywords to filter targeted papers.

Based on above studies, we believe that ICTs in the AEC industry context have the following characteristics: 1) the ICTs focus on handling construction information in digital forms; 2) the ICTs play various roles including capturing construction information in digital forms, and storing, processing, communicating and displaying these pieces of digital information; 3) the ICTs can be applied on different levels including individual task level and organizational task level. This paper focuses on all the ICTs that have these basic characteristics.

3. METHODOLOGY

3.1 Journal selection

To acquire the articles related to the research of ICT applications in the AEC industry, the source of these papers, namely the relevant journals, should be selected. Two criteria are adopted in this paper to select these journals: (1) the journal shall be a peer-reviewed scholarly journal; (2) the journal shall have a core focus on the research of ICT applications in the AEC industry.

A similar journal search was performed by Lu et al. (2014) and 12 peer-reviewed journals were picked out. According to the scope of ICT defined in this paper, there are a large number of researches on ICT applications in the AEC industry published on these journals. In this preliminary study, two representative journals, namely Automation in Construction (AIC) and Journal of Computing in Civil Engineering (CCE), are firstly selected and analyzed. Both two journals are peer-reviewed and accepted as prominent and high-quality journals in the research of ICT applications in the AEC industry (Xue et al., 2012; Lu et al., 2014). For example, Lu et al. (2014) adopted AIC and CCE as partial data source to present an in-depth review of mainstream studies of ICT-supported AEC organizations. In addition, unlike some journals such as *Journal of Construction Engineering and Management* that has relatively weak relevance, AIC and CCE are highly relevant. Therefore, to some degree, analyzing the distribution of articles in these two journals is helpful to investigate the status of ICT application research in the whole AEC academic community.

3.2 Article retrieval

After the selection of journals, qualified articles need to be retrieved from these two journals. Using ICT to address a range of operational and managerial issues in the AEC industry has been started in earnest in the last three decades of the 20th century by researchers (Lu et al., 2014). However, considering the goal of this study, which is to investigate the state-of-the-art research status of ICT applications in the AEC industry, and the huge number of relevant papers published in the past time, this study selects the recent five years, namely 2011-2015, as the review period. In addition, the number of selected articles reached at 432 (the selection process is described below) and we believe this quantity is appropriate to achieve our research goal. More details about the cover of the two journals can be found in Table 1.

Generally, keyword searching in specific databases such as Scopus, Web of Science and Google Scholar is a common and effective article retrieving method for literature research. However, this method requires that the keywords can be enumerated with a limited list of terms. In our case, the definition of ICT adopted in this paper has a rather broad scope. It is really difficult to list complete terms to form appropriate keywords for literature search. A general keyword search-based approach would easily cause remarkable omitting of qualified papers in this situation.

In this paper, we search target articles manually, more specifically, complying with the following steps:

Step 1: establish the inclusion and exclusion criteria

These criteria are set based on the research scope of this paper. Articles would be included if they focus on the research, review or survey of the applications of ICTs (defined in this paper) in the AEC industry. Articles would be excluded if they: (1) focus on the research of ICT applications in other industries such as the manufacturing industry (e.g. ICTs application in the manufacture of construction equipment); (2) focus on ICTs themselves instead of their applications in the AEC industry (e.g., pure theoretical or technological development of ICTs); (3) focus on the pure mathematical algorithms or simulation methods development.

Step 2: select articles from the selected journals

Qualified articles are selected by logically checking their titles, keywords, and abstracts to judge whether the articles comply with the established inclusion and exclusion criteria.

Following the two steps, a total of 432 articles have been retrieved from 1181 articles published in the two journals in the period of 2011-2015. The distribution of selected articles in different journals is shown in table 1. The percentages of selected articles in AIC and CCE are almost 40% and 30% respectively, which shows the two journals are highly relevant to the research of ICT applications in the AEC industry.

Table 1: Overview of journals and selected papers

Journal	Issue covered	Number of total articles	Number of selected articles	Percentage of selected articles
AIC	20(1), 2011 – 60, 2015	807	321	40%
CCE	25(1), 2011 – 29(6), 2015	374	111	30%
Total	-	1181	432	37%

3.3 Framework of review

An analysis framework is established to efficiently and effectively achieve the research objectives proposed above. In the framework, these selected articles are analyzed through three different views, namely view of ICT technology, view of ICT application area, and view of construction project lifecycle.

In the view of construction project lifecycle, all the selected articles are categorized into certain stages to investigate the research status of ICT applications in different construction stages. To make the classification simple and clear, in this paper, we set four groups to categorize these articles, including design stage, construction stage, operation and maintenance (O&M) stage, and multistage. The design stage covers the all the pre-construction activities such as planning, feasibility study and design. In addition to the on-site construction activities, off-site activities such as material procurement & transportation and component prefabrication also belong to construction stage. Other than operation and maintenance of facilities, the O&M stage also covers the demolition of facilities. Multistage applies to the situation in which the application of ICTs involves more than one single stage. The articles that cannot be classified into a certain stage also fall into this stage.

In the view of ICT technologies, all the articles are categorized based on the specific ICT technologies that the articles focus on. This view aims to investigate ICT technologies and their distributions in the state-of-the-art research in the AEC industry.

In the view of ICT application areas, the key application areas of ICTs are firstly identified from the articles. For each application area, the popular ICT technologies are further discussed.

4. FINDINGS AND DISCUSSION

4.1 Overview

The number of selected articles on ICT published annually in two journals is depicted in Table.2. From 2011 to 2015, the total number of articles published per year keeps a remarkable increase on the whole. Regarding to the two specific journals, the number of articles published annually in AIC shows the same trend with the total number, while the articles published annually in CCE keep a slow but stable growth from the year of 2011 to 2015. In addition, the articles published in AIC is much more than those published in CCE. As a whole, these trends show that the interests and effort on the research of ICT applications in the AEC industry keep at a high level in the recent 5 years.

Table 2: The number of articles published during 2011-2015

Journal	2011	2012	2013	2014	2015
AIC	48	63	82	57	71
CCE	13	22	23	22	31
Total	61	85	105	79	102

4.2 View of construction project lifecycle

In the view of construction project lifecycle, all the selected articles are categorized into 4 groups according to the certain stage that they focus on. The proportions of articles distributed in each stage are shown in Fig. 1. It is clear to find that the articles show a similar distribution in two journals: the articles focusing on construction stage account for the largest percentage (43% for AIC and 46% for CCE), the articles focusing on O&M stage and multistage come to the 2^{nd} and 3^{rd} place respectively, and the proportions of articles related to the design stage in two journals are lowest (only 11% for AIC and 4% for CCE).

Fig. 2 shows the trends of the annual percentages of all selected articles in different stages from 2011 to 2015. As a whole, the proportion of articles related to O&M stage increases significantly from 15% in 2011 to 35% in 2015. However, the figure related to construction stage falls remarkably from 50% in 2011 to 35% in 2015. To some degree, this two trends show that researchers give more attention to explore the application of ICTs in the O&M stage. Although there is some fluctuation during 2011-2015, the proportions of articles focusing on design stage and multistage remain stable at the value of 10% and 22% respectively.

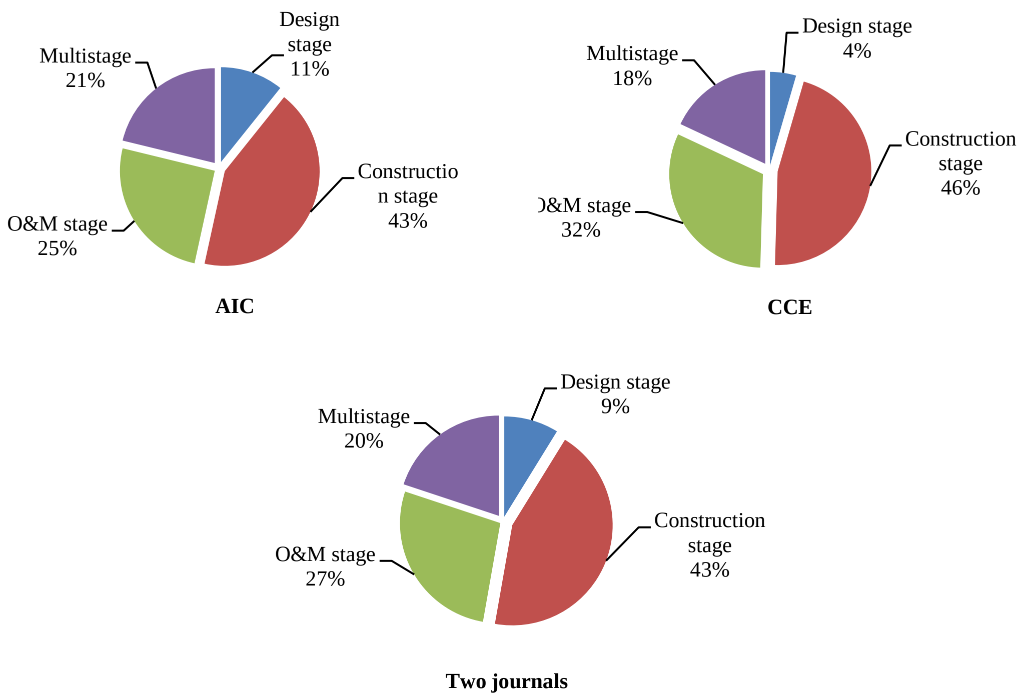


Fig. 1: The distribution of articles in different stages

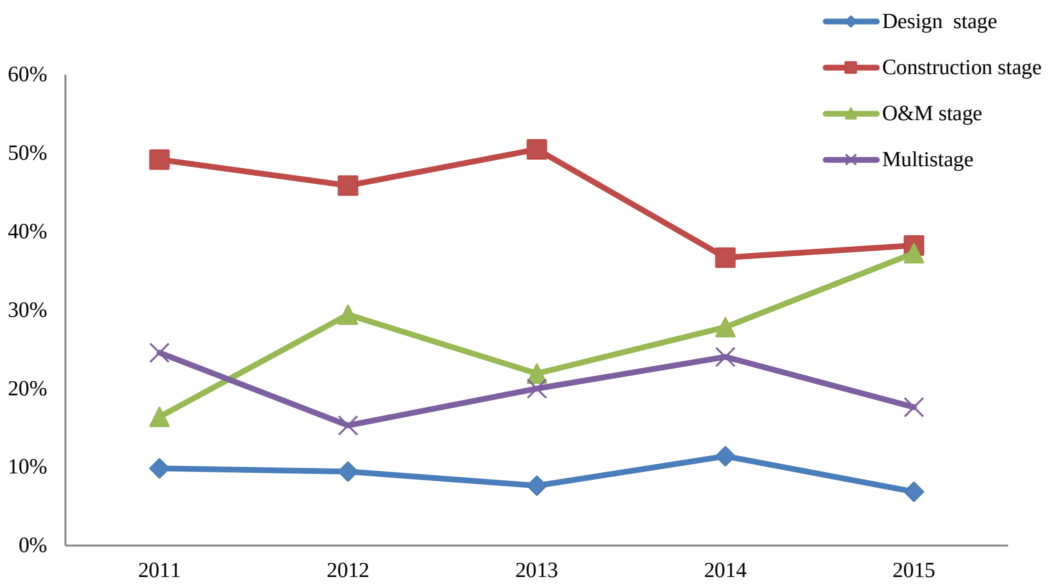


Fig. 2: The annual percentages of articles in different stages from 2011 to 2015

4.3 View of ICT technologies

According to the specific ICTs that the selected articles focus on, a total of 24 types of ICTs, categorized into 8 groups, are identified as shown in Table 3. In this paper, the type of ICT into which one article is classified depends on what ICT the article focuses on instead of what ICTs the article involves with. For example, the article "Real-time safety early warning system for cross passage construction in Yangtze Riverbed Metro Tunnel based on the internet of things" (Ding et al., 2013) focuses on the technology of Internet of Things (IoT) but also involves with other sensing technologies such as RFID and FBG sensor. This article is only counted as one paper in IoT. Also, it is worth to note that one article may equally focus on several ICTs. Then this article would be counted as one paper in all the relevant ICTs repeatedly. For example, in the article entitled "Extending BIM interoperability to preconstruction operations using geospatial analyses and semantic web services" (Karan etal., 2015), BIM, GIS and Semantic Web are the three core ICTs studied in this article. Therefore, this article would be categorized into the type of BIM, GIS and Semantic Web separately. In addition, articles that focus on complicated and integrated information system, or the survey or review of ICT applications in the AEC industry would fall into the group of "Integrated or general ICTs" in the Table.3.

Table.3 shows that, according to the statistics of two journals, sensing technologies and product modeling technologies are the two groups of ICTs in the AEC industry that researchers are most interested in. On the specific ICT level, BIM (121), image processing (53), laser scanning (42), Augmented Reality, or AR (27) and RFID (24) are the top five ICTs that existing studies focus on. As the most popular ICT in the AEC industry, BIM are applied or studied in almost all the application areas identified in this paper. As a whole, BIM based collaboration platforms (especially real-time or near real-time collaboration platforms), function extension and interoperability improvement with downstream applications, and more efficient and effective information processing (especially information extraction and visualization) mechanisms are the three major topics of BIM. In the areas of construction activities and progress monitoring, construction quality monitoring, defect detection and 3D reconstruction of as-built environment, image processing technologies receive increasing attention because of their low cost and flexibility of equipment. The images can be general photos, general videos and specific images such as 3D thermography. As a powerful non-contact data capturing technique, laser scanning (LiDAR/LADAR) has similar application areas with image processing in the AEC industry. Generally, this kind of technologies is more accurate but also more expensive than image processing technologies. AR, a state-of-the-art technology for superimposing information onto the real world object, has been studied to address many construction issues such as a lack of information for construction field operators and poor communications between project participants (Chi et al., 2013). The application of RFID in the AEC industry has been widely studied. Most of these studies related to RFID applications (16 out of 24) reviewed in this paper focus on construction stage, more specifically, the resource (e.g., construction materials and equipment) and workers' location tracking on construction site.

4.4 View of ICT application areas

A total of nineteen ICT application areas are identified and all the selected articles are categorized into these areas, as shown in Table.4. The number of articles distributed in the top ten application areas reaches at 376, which accounts for 87% of the total articles. The left nine application areas are discussed in only 58 articles in total. In the following parts of this section, we mainly focus on investigating the popular ICTs applied in the top ten application areas.

In the application area of safety monitoring and management, ICTs play an important role to achieve a real-time (or near real-time) and visual safety monitoring and risk warning. This area can be further divided into three sub areas, as follows: 1) construction safety monitoring, which focuses on the safety of workers, materials and construction activities; 2) construction equipment safety monitoring, which pays attention to the safety monitoring of construction equipment, especially heavy construction equipment such as cranes and excavators; and 3) disaster and emergency responding, which aims to put forward safer and more efficient approaches to respond natural disasters (e.g. earthquake) and emergencies (e.g. fire). Highly focused areas of the ICTs include BIM, sensing technologies (e.g., Sensor, RFID, GIS, GPS), networking and communicating technologies (e.g. WSN, UWB), and visualization technologies.

Table.3: The number of articles focusing on different ICT technologies

ICT technologies	Number of articles		
	AIC	CCE	Total
1. Product modeling			
(1) BIM (e.g., BIM, openBIM, BIM server, cloud BIM)	113	8	121
(2) CAD	13	4	17
(3) Others	10	1	11
2. Sensing and spatial technologies			
(1) Image processing	27	26	53
(2) Laser scanning	32	10	42
(3) RFID (Radio-Frequency Identification)	20	4	24
(4) Spatial analysis technologies			
GIS (Geographic Information System)	12	9	21
GPS (Global Positioning System) / GNS (Global Navigation Satellite)	7	1	8
(6) Ultrasound scanning	2		2
(7) Others	19	7	26
3. Networking and communicating technologies			
(1) Internet based Web (e.g., Email, e-business, agent system, P2P network, Social Networking Services (SNS))	20	3	23
(2) Wireless Local Area Network (e.g., ZigBee, UWB (Ultra-Wide band))	12	1	13
(3) Sensor Network (e.g., Wireless Sensor Network (WSN), Ubiquitous Sensor Networks (USN), IoT(Internet of Things))	6	2	8
4. Knowledge modelling			
(1) Ontology	1	4	5
(2) Semantic Web	18		18
5. Data management and analysis			
(1) Database	5	5	10
(2) Data warehouse	2	1	3
(3) Data mining	6	1	7
(4) Data fusion		3	3
6. Advanced computing (Cloud/Mobile/Distributed computing)	**9**	**2**	**11**
7. Visualization technologies			
(1) AR (Augmented Reality)	19	8	27

(2) VR (Virtual Reality)	10	5	15
(3) Others	12	3	15
8. Integrated or general ICTs	**23**	**5**	**28**

Table.4: The number of articles in different ICT application areas

ICT application areas	Number of articles		
	AIC	CCE	Total
Safety monitoring and management	52	18	70
Construction process monitoring	51	18	69
Sustainable construction	31	7	38
ICT adoption survey and assessment	33	2	35
Collaboration platforms and management systems	26	8	34
Construction quality monitoring and defect detection	22	12	34
As-built facility and environment modeling	21	8	29
Facility management and maintenance systems	15	8	23
Information retrieval and visualization	10	11	21
Construction planning and scheduling	14	5	19
Building design supporting	10	2	12
Construction cost management	9	2	11
Automated compliance checking	9	-	9
Worker training and student education	4	3	7
Construction data and document management	4	1	5
Construction activities simulation	2	2	4
Building space-use analysis	4	-	4
Construction product information searching	2	1	3
Construction component prefabrication supporting	1	1	2

In this paper, construction process monitoring consists of two sub areas: construction activity monitoring, and resource tracking and locating. In both areas, researchers focus on developing real-time, visual and automatic approaches or systems to monitor the construction activities or track resources for the various purposes such as recording construction progress, evaluating construction performance and conducting schedule management. In this area, a wide range of ICTs such as BIM, networking and communicating technologies (e.g., wireless network and sensor network), sensing technologies (e.g., laser scanning and image processing) are integrated. Similar with the area of construction process monitoring, other two areas, namely construction quality monitoring & defect detection, and as-built facility & environment modeling heavily rely on sensing technologies (e.g., laser scanning and image processing) to capture data.

The adverse impact of construction activities on environment and much carbon emission caused by building energy consumption have become a significant topic. Most of the relevant articles focus on the design, assessment, and operation monitoring of energy efficient buildings. Important ICTs involve BIM, sensing technologies and data mining.

In application areas of ICT adoption survey and assessment, the discussion of the benefits and hindrances of ICTs (especially BIM) adoption in the AEC industry has received an increasing attention. For example, a number of studies have been conducted to investigate the BIM implementation in a construction project lifecycle in different countries, to examine the driving factors of BIM adoption in design organizations, and analyze the cost and benefits of BIM adoption in construction projects.

Both in the application area of collaboration platforms and management systems, and facility management and maintenance systems, BIM, CAD, AR and VR are the most frequently mentioned ICTs used to develop specific collaborative work platforms and information management systems. A systematic and detailed review of ICT abled collaborative work in construction projects can be found in Lu et al. (2014).

In this paper, information retrieval and visualization refers to partial model information retrieval and 3D model visualization. Most of the research discussed in this paper focus on the BIM (especially IFC BIM) based partial building model information query. Regarding the model visualization, BIM, AR, VR and the integration of BIM with other visualization technologies are the major technologies. A number of articles focus on the automated generation of various types of construction plans and schedules as well as efficient visualization of this information. The involved ICTs include BIM, CAD, GIS and semantic web.

5. CONCLUSION

A total of 432 articles, published during 2011-2015 in two journals, namely Automation in Construction and Journal of Computing in Civil Engineering, have been selected and reviewed in this paper. This review aims to investigate the research of ICT applications in the AEC industry from three different perspectives: view of construction project lifecycle, view of ICT technologies and view of ICT application areas. The major findings from this review are summarized as follows:

- From the view of construction project lifecycle, construction stage and O&M stage are the top two stages that the research of ICT applications in the AEC industry focuses on. During 2011-2015, the proportion of the articles related to O&M stage increases significantly while the figure related to construction stage falls remarkably.
- From the view of ICT technologies, 24 types of ICTs categorized into 8 groups that researchers focus on are identified. BIM, image processing, laser scanning, AR and RFID are the top 5 ICTs that the selected articles

focus on. The main application areas of the five ICTs are analyzed.

- From the view of ICT application areas, 19 ICT application areas in the AEC industry that researchers focus on are identified. The top 10 application areas contains 87% of all the selected articles and the major ICTs involved in these application areas are analyzed.

We acknowledge that one major limitation of this paper is that the scope of this review is limited to the two journals, although a total of 432 articles are included. Therefore, the generality of the conclusion made in this paper need to be further validated. A number of other influential related journals, such as *Advanced Engineering Informatics*, *Journal of Information Technology in Construction* and *Journal of Construction Engineering and Management,* shall also be taken into consideration as future work for further data collection and more comprehensive data analysis. In addition, the current classification systems for ICT technologies and their application areas may be not structured, unambiguous and completed, we will continue to improve them in future after analyzing more data.

6. REFERENCES

Adriaanse A., Voordijk H., and Dewulf G. (2010). The use of interorganisational ICT in United States construction projects, *Automation in Construction*, Vol. 19, 73-83.

Chi H. L., Kang S. C., and Wang X. (2013). Research trends and opportunities of augmented reality applications in architecture, engineering, and construction, *Automation in Construction*, Vol. 33, 116-122.

Dave B., and Koskela L. (2009). Collaborative knowledge management - A construction case study, *Automation in Construction*, Vol. 18, 894-902.

Ding L. Y., Zhou C., and Deng Q. X. et al. (2013). Real-time safety early warning system for cross passage construction in Yangtze Riverbed Metro Tunnel based on the internet of things, *Automation in Construction*, Vol. 36, 25-37.

Froese, T. (2005). Information management for construction. *In 4th International Workshop on Construction Information Technology in Education*, Dresden, Germany.

Hamelink, C. J. (1997). New information and communication technologies, social development and cultural change, *United Nations Research Institute for Social Development (UNRISD) Discussion Paper No.86*. United Nations, Geneva, Switzerland.

Kang Y., O'Brien W. J., and Mulva S. P. (2013). Value of IT: Indirect impact of IT on construction project performance via Best Practices, *Automation in Construction*, Vol. 35, 383-396.

Karan E. P. and Irizarry J. (2015). Extending BIM interoperability to preconstruction operations using geospatial analyses and semantic web services, *Automation in Construction*, Vol. 53, 1-12.

Lu W. S., Huang G. Q., and Li H. (2011). Scenarios for applying RFID technology in construction project management, *Automation in Construction*, Vol. 20, No. 2, 101-106.

Lu Y. J., Li Y. K., and Skibniewski M. et al. (2014). Information and communication technology applications in architecture, engineering, and construction organizations: a 15-year review, *Journal of Management in Engineering*, Vol. 31, No. 1, A4014010.

O. Ibem E., and Laryea S. (2014). Survey of digital technologies in procurement of construction projects, *Automation in Construction*, Vol. 46: 11-21.

Onyegiri I., Nwachukwu C. C., and Jamike O. (2011). Information and communication technology in the construction industry, *American Journal of Scientific and Industrial Research*. Vol. 2, No. 3, 461-468.

Park J., Kim B., and Kim C. (2011). 3D/4D CAD applicability for life-cycle facility management, *Journal of Computing in Civil Engineering*, Vol. 25, No.2, 129-138.

Samuelson O., and Björk B.-C. (2014). A longitudinal study of the adoption of IT technology in the Swedish building sector, *Automation in Construction*, Vol.37: 182-190.

Vähä P., Heikkilä T., Kilpeläinen P. et al. (2013). Extending automation of building construction - survey on potential sensor technologies and robotic applications, *Automation in Construction*, Vol. 36, 168-178.

Volk R., Stengel J., and Schultmann F. (2014). Building Information Modeling (BIM) for existing buildings – Literature review and future needs, *Automation in Construction*, Vol. 38, 109-127.

Xue X. L., Shen Q. P., Fan H. Q. et al. (2012). IT supported collaborative work in A/E/C projects: A ten-year review. *Automation in Construction*, Vol.21, 1-9.

Zhou W., Whyte J., and Sacks R. (2012). Construction safety and digital design: a review, *Automation in Construction*, Vol. 22: 102-111.

INTELLIGENT EMERGENCY EXIT SIGNAGE GUIDANCE SYSTEM FRAMEWORK FOR REAL-TIME EMERGENCY EVACUATION

Jun Zhang, PhD Candidate

junzhangBIM@ufl.edu

Raymond. R. A. Issa, Holland Professor

raymond-issa@ufl.edu

Rinker School of Construction Management, University of Florida, USA

ABSTRACT: *Light-based single-function emergency exit signs may lead occupants to a fire-blocked route or a crowded exit resulting in a delayed evacuation and even more serious situation during an emergency evacuation. This paper will propose a real-time emergency evacuation sign guidance system which guides occupants to safe and fast evacuation routes considering fire source location and development trends, and human traffic flow trends in real time. The proposed system includes a fire detection sensor network system monitoring fire source and propagation, an occupant sensor network system evaluating the existing occupant traffic flow, and intelligent exit sign systems showing fire-free and crowd-free route directions. All fire detection sensor units communicate with each other to broadcast the danger location information. The occupant sensor network system detects the traffic flow coming in and going out for each direction, and detects and predicts crowd areas based on the traffic flow trends. The intelligent exit sign systems generate an evacuation strategy in response to the signals from the fire detection sensor network and occupant sensor network, and show the recommended directions to evacuate and the directions not suitable to evacuate. If crowded situation occurs, the exit sign systems also will show the directions to the fastest evacuation routes. The proposed system will generate first-hand evacuation sign guidance based on real-time emergency situations to achieve safe and fast evacuation. The installation of the proposed system will improve building evacuation performance and reduce injuries and fatalities.*

KEYWORDS: *Building emergency evacuation, exit signage guidance, fire emergency, shortest path, way-finding.*

1. INTRODUCTION

It is a key aspect of the design and operation of any building or facility to provide for life safety during fire emergency events. Although annual civilian deaths in structure fires has been dramatically reduced since 1997, statistics reports, in Figure 1, show little improvement from 2002 to 2013: about 3000 civilian deaths per year (Karter 2013). In addition, the enormous indirect costs associated with fires including temporary lodging, lost business, medical expenses, psychological damage, and others, are much higher. These statistics provide a stark illustration of the need to further improve fire escape even after the many fire protection and fire engineering measures have been implement in buildings from various aspects, e.g., materials, fire resistant structures, fire extinguisher facilities and so on.

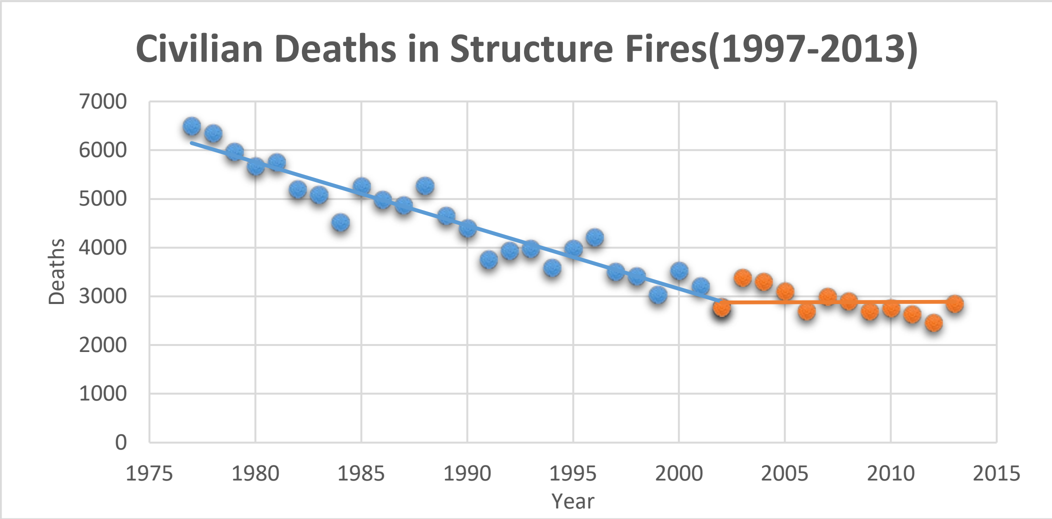


Figure 1. Civilian deaths annually in structure fires from 1997 -2013

Given the loss of lives and properties in fire disasters, the study of evacuation has become extremely necessary and important. Inefficient evacuation will result in a large number of casualties if fire occurs in a large place. Fire exit signs form one of the most important parts of any evacuation guidance system, they are traditionally designed to correctly mark the most efficient escape routes. Unambiguous guidance of the relevant fire exit signs will assist evacuation in times of emergency.

For example, for the evacuation of buildings typically floor-plans and escape signs attached to the walls show the nearest available building exits to be used when an emergency situation arises. After an incident occurs, the expectation is that the occupants look at the evacuation plan (or escape signs) and reach the nearest exit. However, the actual effectiveness of any pre-set evacuation plan can be limited by several issues: the impossibility for occasional visitors (e.g., customers) to know (or look at) the evacuation plan; the unpredictability of human behavior in panic conditions; the lack of information about the type of emergency, the occupant traffic congestion situation inside the building. Current evacuation signage guidance systems suffer from rigid guidance to the closest exits regardless of the existence of fire blockage or serious traffic congestion. Moreover, they may not respond to ad hoc hazard development. with large buildings and huge complexes. There is a need to improve the building signage guidance systems to direct people to the safest way to reach an exit. Prior state of the art systems typically suggested only the shortest escape path, which may actually get people closer to the most dangerous or hazardous locations in the populated area. However, the safest escape route can dynamically change according to people locations and hazard locations. Multiple parameters may influence the calculation of the safest exit path. Examples of such parameters are: location of hazards, number of people to evacuate and their travel speed, wayfinding strategy. For this purpose, sensors distributed in or around the building can help in gaining a better understanding of the real-time situation and allow intelligent evacuation.

2. RELATED WORK

In this section, related work of path way finding to guide occupants to exits during emergency evacuation is examined.

Many studies demonstrate how the use of efficient wayfinding systems could significantly decrease the occupants' egress time (Jensen 1998; Jeon and Hong 2009; Vilar et al., 2014, Occhialin et al. 2016). They represent the easiest and most effective way to assist occupants. The traditional exit signage systems guide occupants to the closest exits during the evacuation process especially in particular environmental conditions (e.g. darkness, smoke) or when people are not familiar with the building (Benthorn and Frantzich 1996). Wayfinding signs must provide an immediate identification of escape routes and exits and guarantee a quick comprehension of all that information they make available in different environmental situations. Following these guidelines, the needed time for the best evacuation paths choice should decrease and the evacuation process in terms of motion speeds should also accelerate (Wong and Lo 2007). Safe condition signs and exit signage systems include: reflective signs (BSI 2000), photo-luminescent (PLM) signs (DIN 2002; Tonikian et al., 2006; UNI 2004), electrically-illuminated signs (BSI 2000), interactive wayfinding systems (Ran el at. 2014), and acoustic wayfinding systems (Nilsson and Frantzich 2010). The related effectiveness is influenced by the pedestrians' perception in relation to the signs position and environmental conditions (Kobes et al. 2010a). The accurate design of evacuation facilities layout (including plan positions and elevation from the ground) cannot exclude investigations on their use by the pedestrians. Experiments about identification distance (Wong and Lo 2007; Tuomisaari 1997) and influence on motion in terms of total evacuation time and speed are performed so as to define the wayfinding systems effectiveness (Jeon et al.2011; Proulx and Bénichou 2010). In particular, when signs (mainly: low placed exit signs) are clearly visible (e.g. electrically illuminated, PLM) in smoke conditions, people statistically tend to follow their directional indications and to use the suggested shortest evacuation paths (Kobes et al. 2010b; Kobes et al. 2010c). Studies on evacuation behavior attempted to understand the wayfinding in virtual game environments (Zhang and Issa 2015). The most robust wayfinding systems is composed of PLM signs (Proulx and Bénichou 2010, Proulx et al. 2000; Kyle and Creek 1999) because of:

- no power supply (no interventions on building structure and layout),
- easy installation and uninstallation,
- low level of maintenance,
- high efficiency regardless of light conditions.

Requirements of PLM signs are also defined by regulations (DIN 2002; UNI 2004). Existing buildings scenarios have been tested and the results showed that PLM signs are able to guide the occupants towards the correct exit and to increase their evacuation speed in both corridors and stairs (Proulx and Bénichou 2010). Wayfinding systems are mainly divided in continuous (at least 1 directional sign per 5 m (~16 ft.) of path) and punctual (mainly placed at intersections and exits) applications (ISO 2004; Paulsen 1994). Applications on existing buildings are generally based on punctual systems. Tests with smoke conditions simulation are also performed (Jeon et al. 2011; Jeon and Hong 2009). Mainly, speeds sensibly increase (about +15% when using continuous PLM on the floor in respect to punctual guidance light) along the horizontal path, while the evacuation time decreases (up to about 65%) because people avoid wandering and more rapidly find the right direction (Jeon and Hong 2009). The positive effect on speed is more effective when directional arrows are closely placed (Jeon and Hong 2009). In staircase motion, despite high pedestrian densities, noticed speeds are higher than the predicted ones (up to about +15%) (Proulx et al. 2000). Finally, questionnaire responses qualitatively underlined that the evacuated people assessed a good environment visibility perception of the system in relation to lighting (70% of people defined as “acceptable” or “good” the PLM scenario without emergency lighting) (Proulx et al. 2000). Researchers has tempted to develop innovative emergency signage systems. Galea et al. (2016) developed an intelligent active dynamic signage system (IADSS) which could show the directions which are not shut down if needed. Instead of signage guidance systems, other researchers have attempted to develop indoor navigation systems using mobile devices (Inoue et al. 2008; Renaudin et al. 2007; Chittaro et al. 2008). Barnes et al. (2008) presented a distributed algorithm to direct occupants to exit using wireless sensor networks. However, intelligent emergency signage guidance system to clearly direct fast safe escape path has not been developed with consideration of real-time fire propagation and occupants’ traffic congestion information.

3. PROPOSED SYSTEM

The proposed system consists of exit signage panel, fire and smoke detection sensor, and human traffic monitor sensor which are integrated as one single node to build up a graph network. If there exists a path for two nodes, an edge exists between these two nodes. If any node detects a serious hazard (fire or smoke), or is damaged during the event, all its edges will be disconnected.

3.1 Exit Signage Unit description

The proposed intelligent exit signage system consists of exit signage units as nodes in a graph network. Each unit consists of an exit sign panel with direction arrows, fire and smoke detection sensor, and occupant traffic monitoring sensor as shown in Figure 2. Fire and smoke detection sensors detect the fire events and fire propagation and send warning information to the neighboring units. The occupant traffic monitoring sensors count the number of passing occupants and measure their speed. The sensing capability of each hazard sensor is not explored in this study. The operation of these devices is not discussed in this paper. To facilitate the operation of the algorithm, the data from the hazard and navigation graphs must be distributed throughout the network.

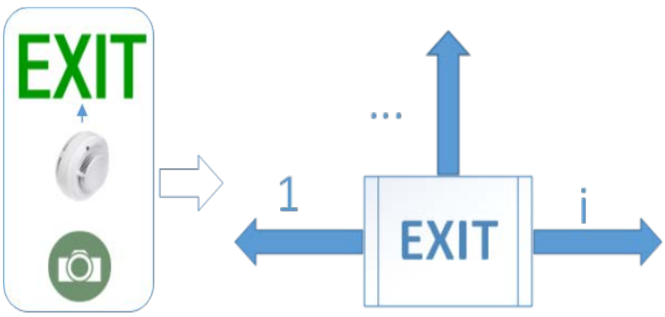


Figure 2. Node elements and Description

The direction arrows on the exit signage panels have three colors to show the evacuee different information according to real-time traffic information and hazard location. The idea of color signals in the proposed exit signage unit is inspired by the general traffic signal system as shown in Figure 3.

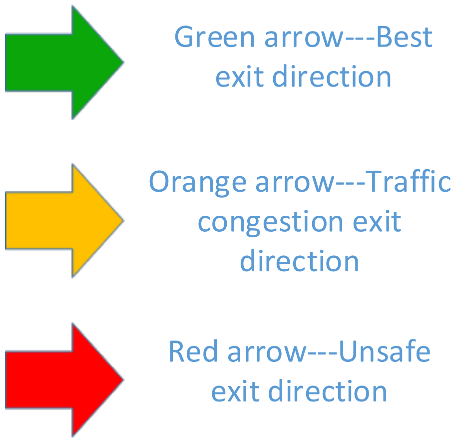


Figure 3. Direction arrow guidance with colors

3.2 Network Deployment

Exit signs panels integrated with hazard sensors and monitor sensors are to be deployed throughout a building to maximize coverage of hazard detection. Information communication between neighboring units is required to

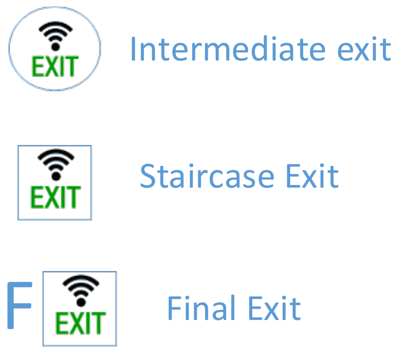


Figure 4. Node type in the graph network

form a real-time network. The neighboring units are defined as the units can be visually reached from each other without blocking building elements. The proposed framework uses the 3D building layout to construct a graph G in which different types of nodes indicate the location distribution difference, as illustrated in Figure 4. Final exits will be considered as the evacuation targets.

Each link between two neighbor nodes denotes the evacuation section from one exit signage position to another position in the building. We need consider evacuation time from node i to node j. Therefore, we need to consider:

a. Average travel/walk time, Tt(i,j)

$$Tt(i,j) = d(i,j)/v$$

d(i,j): the distance between two exit signage position;

v: occupant’s walking speed, obtained from the occupant traffic monitoring sensors, or use the historical data from previous observation.

b. Queuing time if any, Tq(i,j)

$Tq(i,j) = N(i,j)/F(i,j)$

$N(i,j)$: Number of occupants from i to j;

$F(i,j)$: traffic flow

c. Update of the queuing time to the graph network.

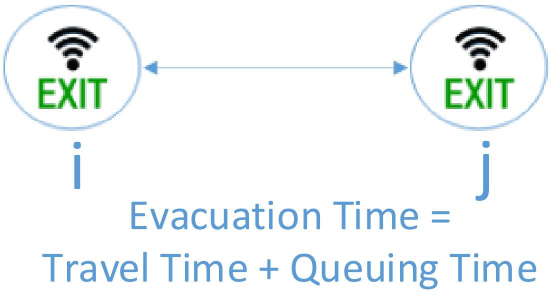


Figure 5. Evacuation time components

Since Tt(i,j) gives the total time to walk from node i to node j if there was no queuing, the additional of Tt(i,j) and Tq(i,j) would give a larger evacuation time than needed for the occupant to reach the exit. The network updates the Ad hoc queuing times, naming them "real time to queue" to consider the occupant traffic congestion, which may overwhelm time delay even it is on the shortest path.

```
FOR each node
  FOR each direction
   Send information
     IF it alarms
     Disconnect all its horizontal edges, show red arrows
     END IF
   Receive information
     IF this neighbor alarms
      Disconnect this edge, show red arrow to this direction.
     ELSE IF it's the best path
         Show green arrow to this neighbor
     ELSE
      Show orange arrow as warning of delay
```

```
    END IF
  END FOR
END FOR
```

Figure 6. Information Communication Algorithms

For each unit in the network, the algorithm to perform real-time information communication with its neighbors is shown in Figure 6.

3.3 Fastest (least cost) Path Finding

Instead of using the shortest path algorithm, the proposed framework uses the fastest path finding algorithms to consider the real-time traffic congestion and danger fire propagation locations. The framework starts to work from the fire emergency alarm, then a dynamic graph with exit signage units will be built up according to the unsafe fire locations. The information communication then starts from the final exits in the building, the initial evacuation times for all final exits are set to be 0, then the travel time and queuing time to the other nodes from bottom floors to top floors are updated. The staircase exit nodes only communicate with the neighboring staircases and the nodes on the same floor as illustrated in Figure 6. Each node will store the minimum evacuation time to the final exits, and show the corresponding directions to the best evacuation path, and show the warning signal if any direction is not safe to evacuate to or the evacuee has to delay their escape.

Figure 7 shows the floor of a building and the corresponding graph. The vertices of the graph correspond to locations where people can congregate (e.g. rooms, corridors, doorways or hallways). A link between two vertices of the graph represents a path that can be followed by the evacuees.

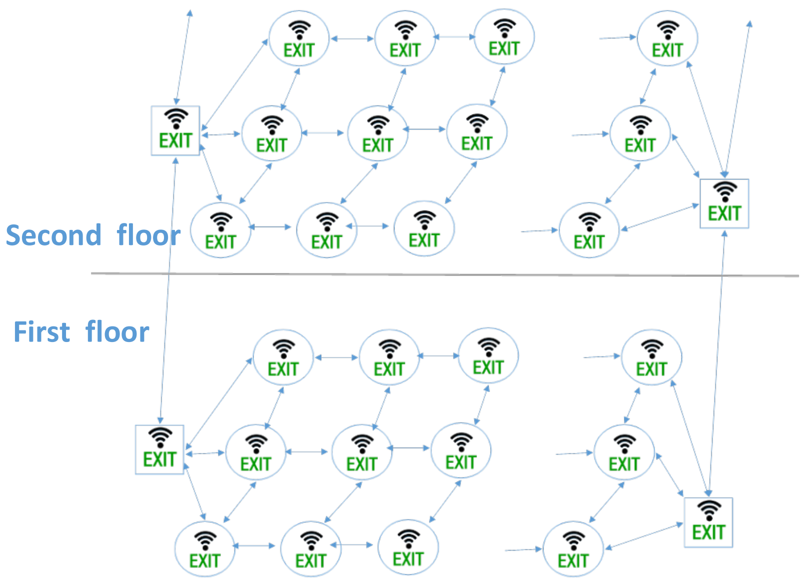


Figure 7. Exit Signage Network Framework

4. CONCLUSION AND FUTURE RESEARCH

The proposed exit signage guidance system that can be used during an emergency situation inside a building to support occupant decision-making to find the fast safe escape path. The system is able to function in real-time, adapt to the changes of the hazard situation and occupant traffic situations, and provide reliable suggestions to the evacuees regarding the direction of the best available exit.

By following the directions provided by the exit signage guidance system, occupants can evacuate the building using the best available paths while avoiding the hazardous areas and congested escape paths. Optimization of exit signage unit deployment in the building need further study to make it compliant with current building standards as well as to reduce the evacuation time. The current framework focus on normal human evacuation, Assistance for disabled occupants with reduced travel speed, or occupants with difficulties for color signal recognition should be considered in future research.

REFERENCES

Barnes, M., Leather, H. and Arvind, D.K., (2007), October. Emergency evacuation using wireless sensor networks. In *Local Computer Networks, 2007. LCN 2007. 32nd IEEE Conference on* (pp. 851-857). IEEE.

Benthorn, L. and Frantzich, H., (1996). Fire alarm in a public building: How do people evaluate information and choose evacuation exit?. *LUTVDG/TVBB--3082--SE*.

British Standards Institution, (2000). BS 5499-4:2000 - Safety signs, including fire safety signs Code of practice for escape route signing.

Chittaro, L. and Nadalutti, D., (2008), September. Presenting evacuation instructions on mobile devices by means of location-aware 3D virtual environments. In *Proceedings of the 10th international conference on Human computer interaction with mobile devices and services* (pp. 395-398). ACM.

DIN, DIN 67510, Photoluminescent pigments and products

D'Orazio, M., Longhi, S., Olivetti, P. and Bernardini, G., (2015). Design and experimental evaluation of an interactive system for pre-movement time reduction in case of fire. *Automation in Construction*, *52*, pp.16-28.

Fahy, R.F. and Proulx, G., (2001). Toward creating a database on delay times to start evacuation and walking speeds for use in evacuation modeling.

Galea, E. R., Xie, H., Lawrence, P., (2016). *Intelligent Active Dynamic Signage System: Bringing the Humble Emergency Exit Sign into the 21st Century,* SFPE EUROPE MAGAZINE--ISSUE 3.

Gwynne, S.M.V., (2007). Optimizing fire alarm notification for high risk groups research project. *The Fire Protection Research Foundation, NFPA, Quincy, MA*.

Inoue, Y., Sashima, A., Ikeda, T. and Kurumatani, K., (2008), December. Indoor emergency evacuation service on autonomous navigation system using mobile phone. In *Universal Communication, 2008. ISUC'08. Second International Symposium on* (pp. 79-85). IEEE.

ISO, (2004). ISO 16069 Graphical symbols - Safety signs - Safety way guidance systems (SWGS)

Jensen, G., (1998). Wayfinding in heavy smoke: decisive factors and safety products. Fire safety 98. *Fire Protection in Nuclear Installations, Mumbai, India*.

Jeon, G.Y. and Hong, W.H., (2009). An experimental study on how phosphorescent guidance equipment influences on evacuation in impaired visibility. *Journal of Loss Prevention in the Process Industries*, *22*(6), pp.934-942.

Jeon, G.Y., Kim, J.Y., Hong, W.H. and Augenbroe, G., （2011). Evacuation performance of individuals in different visibility conditions. *Building and Environment*, *46*(5), pp.1094-1103.

Kobes, M., Helsloot, I., De Vries, B. and Post, J.G., (2010). Building safety and human behaviour in fire: A literature review. *Fire Safety Journal*, *45*(1), pp.1-11.

Kobes, M., Helsloot, I., de Vries, B. and Post, J., (2010). Exit choice,(pre-) movement time and (pre-) evacuation behaviour in hotel fire evacuation—Behavioural analysis and validation of the use of serious gaming in experimental research. *Procedia Engineering, 3*, pp.37-51.

Kobes, M., Helsloot, I., de Vries, B., Post, J.G., Oberijé, N. and Groenewegen, K., (2010). Way finding during fire evacuation; an analysis of unannounced fire drills in a hotel at night. *Building and Environment*, *45*(3), pp.537-548.

Kyle, B. and Creak, J., (1999). *Assessment of photoluminescent material during office occupant evacuation*. Institute for Research in Construction.

Leslie, J (2001). *A behavioural solution to the learned irrelevance of emergency exit signage.* In: Human Behaviour in Fires: Proceedings of the 2nd International Symposium in Fire. Interscience Communications, London, pp. 23-33.

Nilsson, D. and Frantzich, H., (2010). Design of Voice Alarms—the Benefit of Mentioning Fire and the Use of a Synthetic Voice. In *Pedestrian and Evacuation Dynamics 2008* (pp. 135-144). Springer Berlin Heidelberg.

Occhialini, M., Bernardini, G., Ferracuti, F., Iarlori, S., D'Orazio, M. and Longhi, S., (2016). Fire exit signs: The use of neurological activity analysis for quantitative evaluations on their perceptiveness in a virtual environment. *Fire Safety Journal*, *82*, pp.63-75.

Paulsen, T.R.U.L.S., (1994). The Effect Of Escape Route Lnforemation On Mobility And Way Finding Under Smoke Logged Conditions. *Fire Safety Science*, *4*, pp.693-704.

Purser, D.A. and Bensilum, M., (2001). Quantification of behaviour for engineering design standards and escape time calculations. *Safety Science*,*38*(2), pp.157-182.

Proulx, G. and Bénichou, N., (2010). Photoluminescent stairway installation for evacuation in office buildings. *Fire technology*, *46*(3), pp.471-495.

Proulx, G. (2002) Movement of people: the evacuation timing SFPE Handbook of Fire Protection Engineering, pp. 342–366.

Proulx, G., Kyle, B. and Creak, J., (2000). Effectiveness of a photoluminescent wayguidance system. *Fire*

Technology, *36*(4), pp.236-248.

Ran, H., Sun, L. and Gao, X., (2014). Influences of intelligent evacuation guidance system on crowd evacuation in building fire. *Automation in Construction*, *41,* pp.78-82.

Italian Organization for Standardization (UNI), (2004) UNI 7543:2004 - Safety colours and safety signs.

Renaudin, V., Yalak, O., Tomé, P. and Merminod, B., (2007). Indoor navigation of emergency agents. *European Journal of Navigation*, *5*(3), pp.36-45.

Tonikian, R., Proulx, G., Bénichou, N. and Reid, I., (2006). Literature review on photoluminescent material used as a safety wayguidance system. *PLM V6-2*.

Tuomisaari, M., (1997). *Visibility of exit signs and low-location lighting in smoky conditions*. VTT, Technical Research Centre of Finland.

Vilar, E., Rebelo, F., Noriega, P., Duarte, E. and Mayhorn, C.B., (2014). Effects of competing environmental variables and signage on route-choices in simulated everyday and emergency wayfinding situations. *Ergonomics*, *57*(4), pp.511-524.

Wong, L.T. and Lo, K.C., (2007). Experimental study on visibility of exit signs in buildings. *Building and Environment*, *42*(4), pp.1836-1842.

Xie, H., Filippidis, L., Gwynne, S., Galea E.R., Blackshields, D., Lawrence, P.J., (2007). *Signage legibility distances as a function of observation angle,* Journal of Fire Protection Engineering, 17(1), pp.41-64.

Xudong, C., Heping, Z., Qiyuan, X., Yong, Z., Hongjiang, Z. and Chenjie, Z., (2009). Study of announced evacuation drill from a retail store. *Building and Environment*, *44*(5), pp.864-870.

Zhang, J., and Issa, R. R. (2015). “Collecting Fire Evacuation Performance Data using BIM-based Immersive Serious Games for Performance-based Fire Safety Design.” Proceedings of the 2015 International Workshop on Computing in Civil Engineering, ASCE, Austin TX.

Part VI: Computer Vision and UAV

USING A UAV FOR A DEBRIS FAN DIGITAL TERRAIN MODEL RECONSTRUCTION: A CASE STUDY OF THE PU-TUN-PU-NAS DEBRIS FAN

Cheng-Hsuan Yang, Er-Xuan Sung, Te-Chu Liu & Shih-Chung Kang

National Taiwan University, Taiwan

ABSTRACT: This paper presents a workflow for generating a digital terrain model (DTM) for a debris fan in a rugged and remote mountainous area. It successfully obtained models for roughly analyzing the dynamic terrain changes over two years. The workflow consists of four main phases: establishment of a ground control network, planning of flight routes, image acquisition, and DTM reconstruction. Each phase was defined by the properties of the debris fan. To verify that the workflow we developed was accessible and able to increase the efficacy of generating a DTM for a debris fan, we conducted a case study on the Pu-tun-pu-nas debris fan, which was the same experimental site for our previous research in 2014. The chosen debris fan lay near the Laonong River and the Pu-tun-pu-nas tributary in Kaohsiung, Taiwan. The result showed that, by following the workflow, the time required to collect data for a 0.86-km^2 debris fan could be reduced to 7.5 hours. It indicated that utilizing this workflow can reduce man-hours by 70% compared with our previous research. Furthermore, by comparing the DTMs generated in 2014 and 2016, the survey team could easily analyze the dynamic changes of the debris fan. The DTM with 3D terrain information can also be a very good reference for further hydraulics and topographical studies.

KEYWORDS: unmanned aerial vehicle, digital terrain model, debris fan

1. INTRODUCTION

1.1 Background

In our previous research (Wen *et al*., 2014), we presented an application of reconstructing a digital terrain model (DTM) using an unmanned aerial vehicle (UAV). Through an accessibility experiment on the Pu-tun-pu-nas debris fan in the south of Taiwan, we verified that employing a UAV for DTM reconstruction is possible. Moreover, the result showed that using a UAV can not only increase the efficiency and decrease the cost of the data collection process but also improve the accuracy of the model. In this research, we focus specifically on DTM reconstruction of a debris fan. We also compared results over two years to analysis and monitor the deposition of the target debris fan.

UAV systems were originally developed for military purposes, for example, the unmanned inspection and mapping of hostile areas (Liu *et al*., 2012). In recent years, the usage of UAV systems can be applied in different fields. One application is the study of geomorphic processes. Topographic data can be generated through either ground surveys or remote sensing and then be used for the study of geomorphic processes such as sediment budget assessment and detecting geomorphic changes (Ballow, 2016).

Using UAV systems in remote sensing and mapping has become common over the past four years. UAV systems allow people to collect data remotely from inaccessible areas and dangerous environments, such as forest fire and volcanoes, with a lower cost compared with piloted aerial vehicles (Everaerts, 2008). Subsequently, results such as DSM/DTM, contour lines, textured 3D models, and vector data can be produced by executing the photogrammetric process (Remondino *et al*., 2011).

Although using a UAV to reconstruct DTMs is convenient and flexible, there are still some issues to be resolved. For example, the occurrence of the "doming effect" will lead to systematic errors in the DEM (James *et al*., 2014). To address this issue, ground control points can be applied to eliminate the effect (Eltner *et al*., 2015) and a DEM with good quality can thus be produced (Hugenholtz *et al*., 2013).

A debris fan is formed when a stream's gradient decreases. Since a debris fan is typically located at a gentle section of a rapid stream, sediment deposition is a common issue in this kind of area. A serious sediment deposition problem may lead to damage to an existing bridge or highway and even cause hazards for people nearby. Therefore, it is worth developing an approach to assist in the monitoring of a debris fan.

2. Research Objective

Based on our previous research, this paper focuses on developing an integral procedure for constructing a DTM for a debris fan. Generating a DTM of a debris fan annually can help researchers to monitor the changes in the debris fan and determine an appropriate strategy for disaster-prone areas in advance. This research aims to achieve the following goals:

A. This research should define a workflow for using a UAV to reconstruct a DTM of a debris fan to accelerate creation of the model.

B. The DTM constructed in this research should be available to compare with the results of our previous research in 2014 for observing the states of sediment deposition during these two years.

3. DEFINITION OF WORKFLOW

This research defined a workflow for the use of a UAV system to reconstruct the DTM of a debris fan in a mountainous area, which was chosen as our case study. In general, image-based DTM reconstruction requires a UAV that is able to carry a camera to photograph landforms from the sky. This device can be either manipulated by a ground pilot for the entire duration of the flight or operated autonomously after a hand-launched take-off. In addition, ground control points (GCPs) must be deployed on the terrain surface to improve the accuracy of the model computation. The photography collected during flight operation will be processed to reconstruct the DTM. In this research, the workflow includes establishment of a ground control network, planning of a flight route, data acquisition, and DTM reconstruction (Fig. 1), which will be explained in the following subsections.

3.1 Establishment of a ground control network

A ground control network is a group of GCPs that provide geo-references for each image. Normally, GCPs will be distributed homogeneously over the study area. Markers have to be placed on pre-defined GCPs to make the point easily identifiable in the photos. Moreover, since the debris fan typically covers a large area over a deep mountainous landscape, the limited human resources and survey time should be considered when designing the GCP network.

3.2 Planning of flight routes

Flight routes should be well planned for evaluating the efficiency of the data-collection process. When planning the flight route, three key points should be considered: the maximum drone-control range, the established GCP network, and the overlap of each image. A debris fan is often too large for a UAV to collect images all at once, so it is necessary to divide the terrain into a series of sections. In order to merge these sections into one model in the DTM reconstruction phase, there should be at least three GCPs overlapped in each section. Furthermore, the overlap of each image should be at least 60%, as indicated by image modeling software, in order to generate a complete model.

3.3 Image acquisition

In image acquisition, only three people are required. One is the pilot who manipulates the UAV. Another should monitor the situation of the drone when it is in the air and reload batteries when the drone is landing. The other person should ensure that the actual flight route fits the planned route and check that the collected images have sufficient overlap. If the path is not correct or the overlap of each image is insufficient, the section should be executed again.

3.4 DTM reconstruction

For this phase, we chose the commercial software Argisoft Photoscan as the image modeling software. There are four steps to using Photoscan to generate the DTM. The first step is to remove blurred images manually. Second, the remaining images are imported into the software and aligned automatically. Third, we key in the GPS coordinates of the GCPs into the software and then generate a dense point cloud for each section. Finally, the dense cloud of each section will be merged to construct a complete DTM for the whole debris fan.

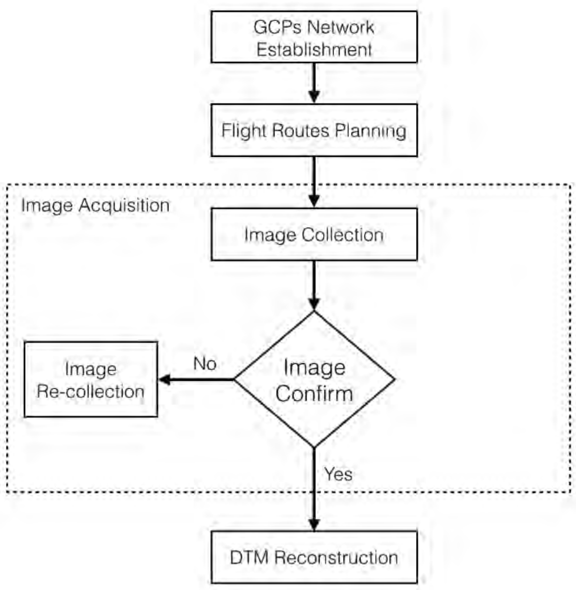


Fig 1. The developed workflow.

4. CASE STUDY

In order to verify that the workflow we defined can in fact increase the efficiency of using a UAV for DTM reconstruction of a debris fan, we conducted a case study. Furthermore, we chose the Pu-tun-pu-nas debris fan, the same debris fan used in our research in 2014, as the target area for comparing the results over two years.

4.1 Research Area

In this research, we chose a debris fan located in Kaohsiung, south of Taiwan, as our research area (Fig. 2). The debris fan is named Pu-tun-pu-nas because it is located in the intersection of the Pu-tun-pu-nas tributary and Laonong River. The Pu-tun-pu-nas debris fan has a serious sediment deposition issue since it is a relatively gentle section in a rapid river. According to our research in 2014, the level of the riverbed had been raised 36.5 m from 2009 to 2012 (Wen *et al*., 2014). This extremely serious sediment deposition problem has already caused damages to highways and bridges. Therefore, it is worth developing a good workflow to construct a DTM annually for monitoring of this area.

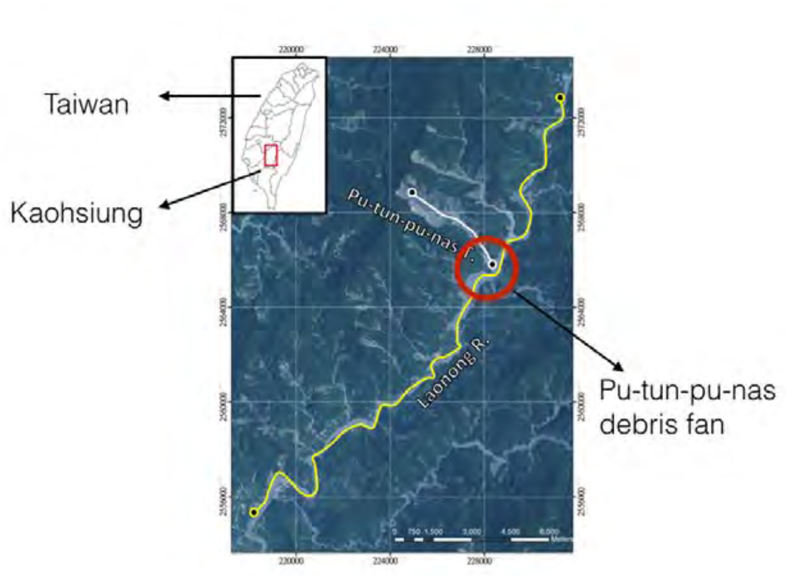


Fig 2. The location of the research area.

4.2 Hardware

A DJI Phantom 3 Professional (P3P), a commercial four-propeller drone, was utilized in this case study (Fig. 3). There were three reasons that we chose the DJI P3P as our research hardware. First, the DJI P3P can hover in the air for at least 20 minutes at a time, which was the same as the UAV we employed in 2014. The Pu-tun-pu-nas debris fan is approximately 1.26 km^2 large. According to our experience, the UAV used to collect the data over such a large area must have at least 20 minutes' hovering time or it might take too much time to take off, land, and reload the batteries. Second, data collection for a debris fan requires greater portability because the target area is typically located in a deep mountainous area. The DJI P3P (1280 g) weighs approximately five times less than the UAV (7000 g) we employed in our previous research. Finally, the DJI P3P can completely record a flight log. The real flight path may be mapped on a satellite image (Fig. 4) so we could immediately check if the flight path was consistent with the path we planned. This function can accelerate the data-checking process. Briefly, after specification, comparison, and function evaluation, the DJI P3P was suitable for use in data collection over the debris fan.

Fig 3 (left). The DJI Phantom 3 Professional employed in this case study.

Fig 4 (right). The real flight path may be mapped on a satellite image.

4.3 Data Collection

4.3.1 Establishment of the ground control network

A total of 44 markers were placed on the terrain (Fig. 5). To produce a high-accuracy DTM, we placed markers every 100 m. The markers were divided into four groups. Four groups of people were respectively assigned to place those markers and take charge of measuring the GPS coordinates of each marker. It took 80 man-hours to establish the ground control network.

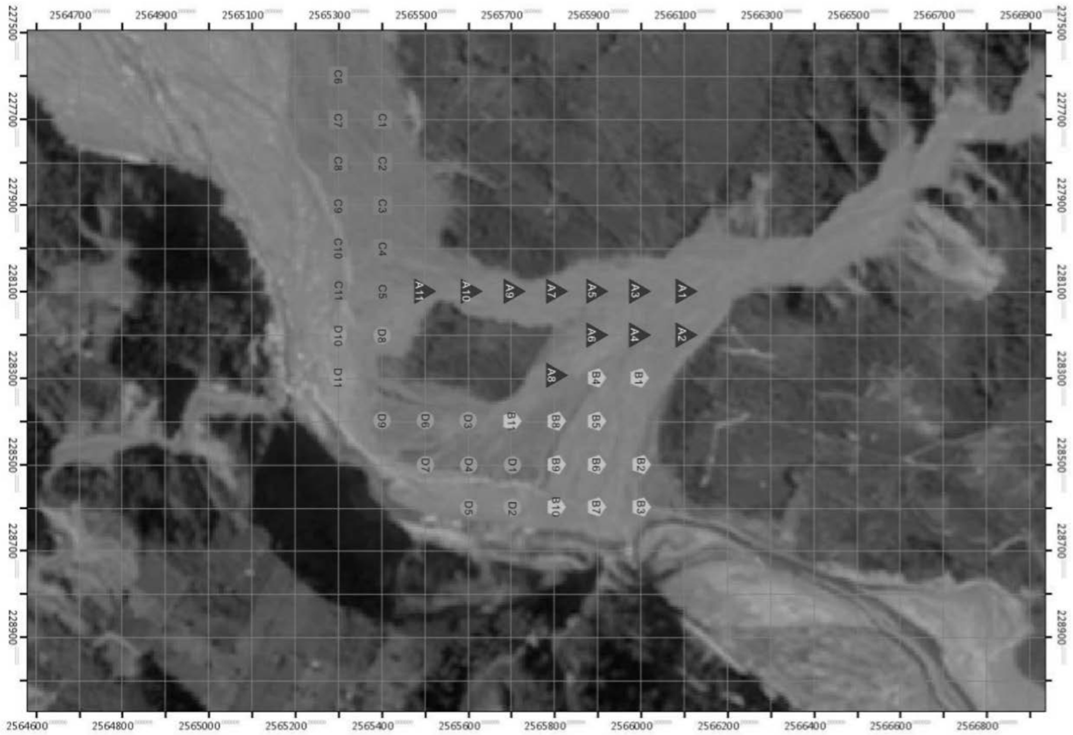


Fig 5. Establishment of a ground control network.

4.3.2 Flight route planning

The flight routes were planned based on the flying height, camera angle, established GCPs, and flying time limitations. The flying height was 200 m. The camera angle of the DJI P3P was 94°. The maximum safe flying time of the drone was 20 min. According to these conditions, we divided the Pu-tun-pu-nas debris fan into twelve sections, labelled as section A to section L, as shown in Fig. 6.

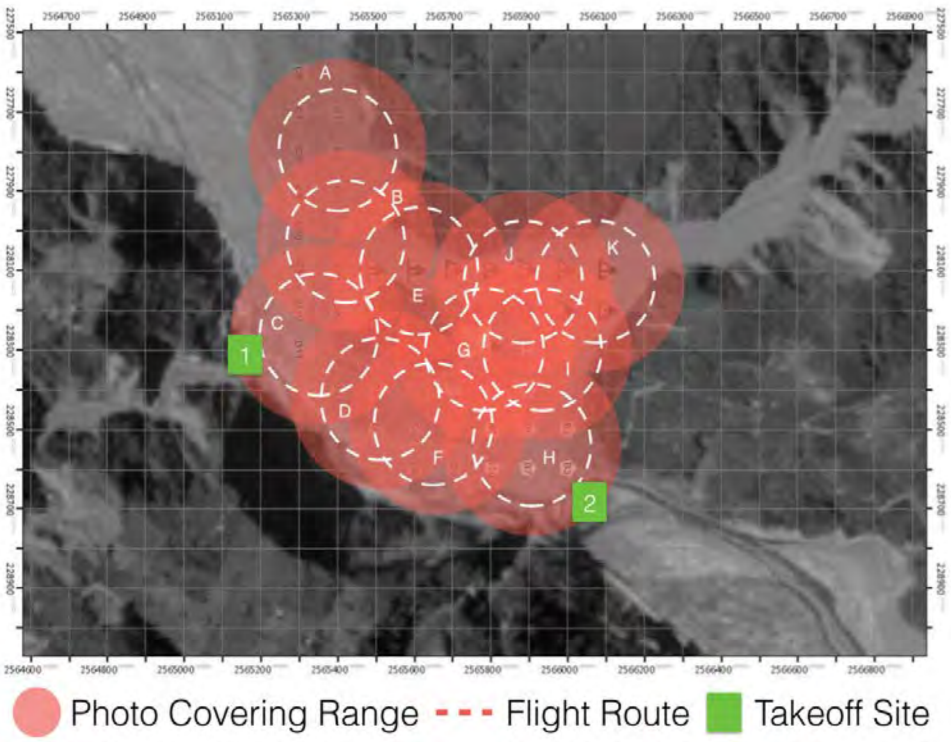


Fig 6. The planned flight route and takeoff sites.

4.3.3 Image acquisition

In this case study, we spent a total of 7.5 h and collected 1,668 photos. Figure 7 shows the actual flight routes of each section. Three people were involved in image acquisition. One was the pilot who was in charge of manipulating the drone to collect data. Another was needed to check the drone's situation when it was flying and reload the batteries when landed. The other was responsible for checking if the images covered enough markers and that the flight routes fitted the planned routes.

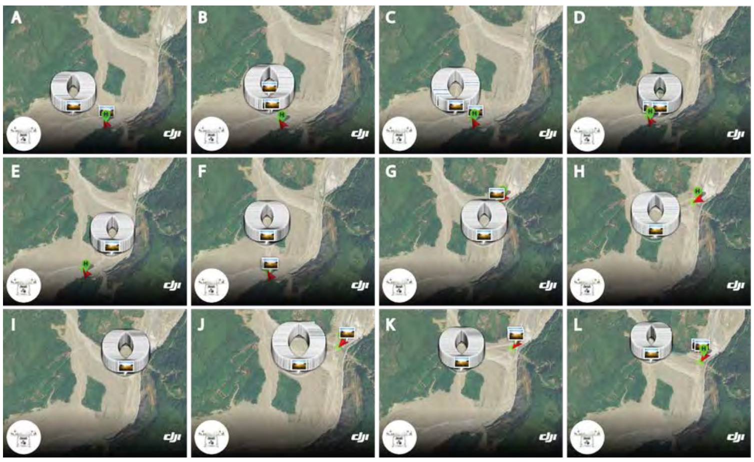


Fig 7. The real flight paths of each section.

4.4 Results

The results of this case study produced a DTM for the Pu-tun-pu-nas debris fan with errors estimated to be 0.29 m within 39 GCPs (Fig. 8). A total of 1,668 photos were collected in this experiment and 1,635 photos were used to construct the DTM. It took 7.5 h to collect all the data, including 3.9 h preparation time and 3.6 h flying time. The final DTM of the debris fan was composed from the results of the twelve sections. Table 1 shows the estimated errors of each section. Figure 9 shows the models for each section. The resolution of the complete model was 50.5 cm per pixel.

Table 1. The estimated errors of each section.

Section Name	Estimated Errors (m)	Number of GCPs
A	0.21	9
B	0.56	12
C	0.20	7
D	0.79	9
E	0.63	10
F	0.54	7
G	0.53	12
H	0.42	12
I	0.42	5
J	0.38	8
K	0.39	9
L	0.16	6
Final DTM	0.29	39

Fig 8. The complete DTM of the Pu-tun-pu-nas debris fan.

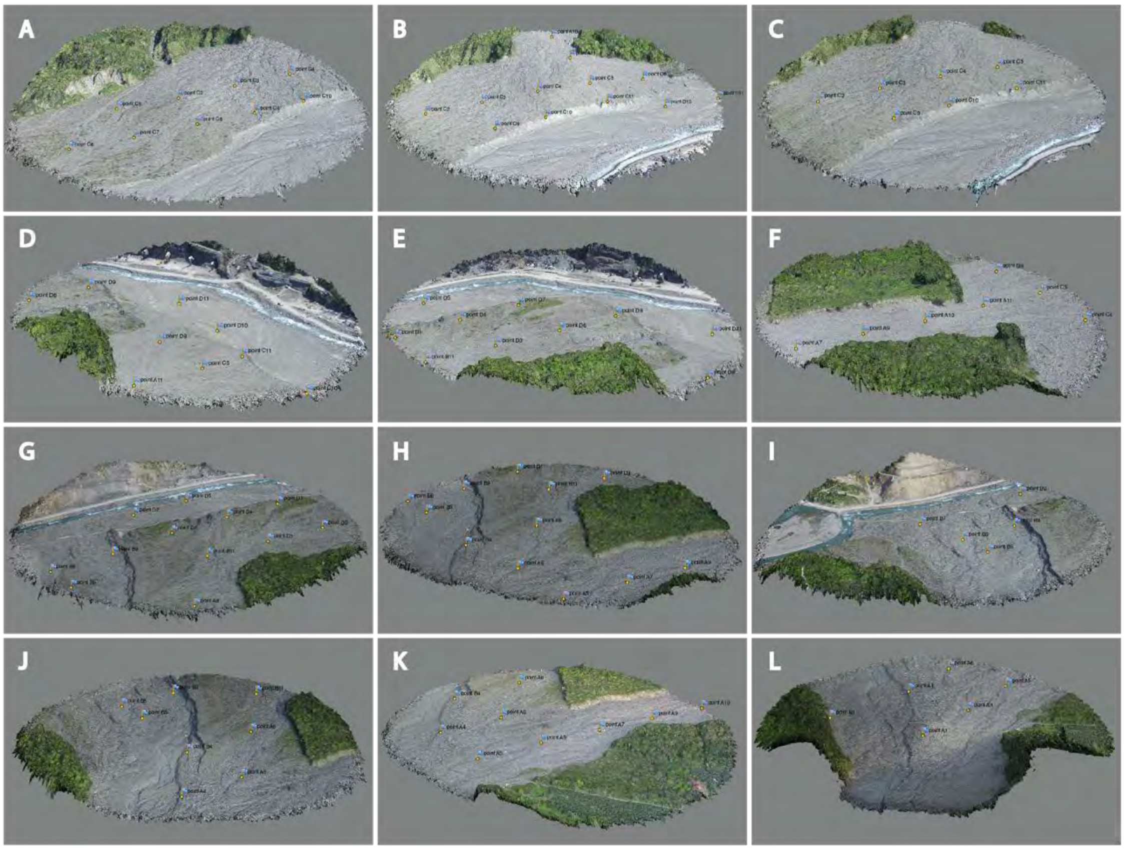


Fig 9. Models of each section.

5. DISCUSSION

This research improved the workflow of using a UAV to assist in DTM reconstruction of a debris fan. Moreover, the results of the research in two years can be used to analyze the changing terrain over these two years. This section compares the data-collection time for these two research efforts, discusses the changes in the terrain, and lists future work we should perform to further improve the technique.

5.1 Less Time Spent on Data Collection

By implementing the workflow we defined, the data-collection process was accelerated. Compared with our previous research, we reduced the man-hours required for the whole process by 33% and the man-hours for the data collection by 70%. In 2014, it took a total of 152 man-hours to collect the data. This included 80 man-hours to establish the GCP network and 72 man-hours to fly the UAV to collect imaging data. However, in this research, it took only 102.5 man-hours, including 80 man-hours for to establish the GCP network and 22.5 man-hours for image acquisition. This result demonstrated that the workflow we defined can in fact improve the efficiency of utilizing a UAV to construct a DTM for a debris fan.

5.2 Changes in the Terrain Between the Two Years

After generating DTMs for the two years, we overlapped these two models to observe the changes in the Pu-tun-pu-nas debris fan. Figure 9 shows the results of the overlapped models. The level of the riverbed upstream of the debris fan has obviously increased. However, the downstream of the debris fan has decreased. This indicates that, by reconstructing the DTM annually, we can effectively analyze and monitor the sediment deposition issues of a debris fan.

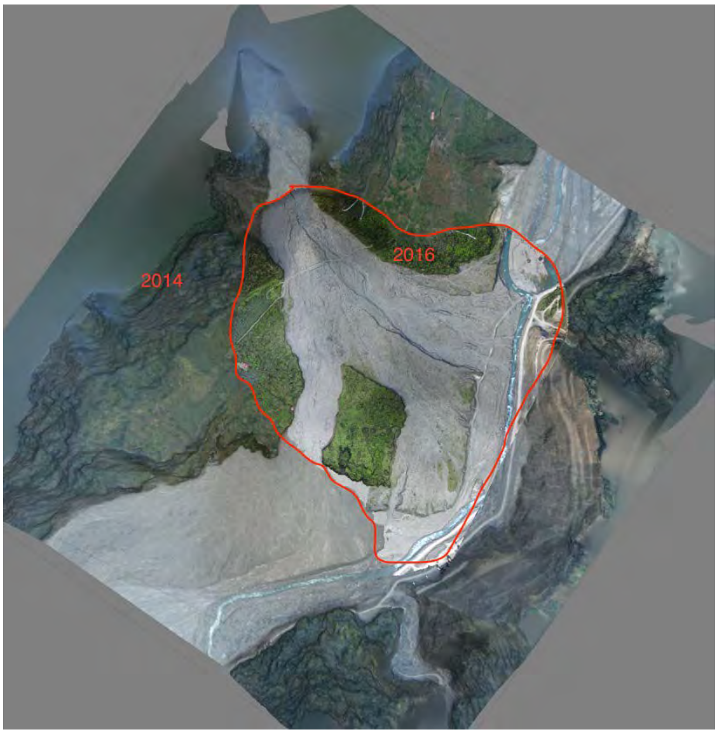


Fig 10. The result of overlapping the DTMs of the two years.

6. CONCLUSION

This paper proposed and validated a new workflow for using a UAV to perform DTM reconstruction of a debris fan. In this workflow, a GCP network was first established in order to give geo-references for the aerial photos that we planned to collect. Second, flight routes were selected to minimize flight duration. Subsequently, a flight plan was executed to acquire aerial photos of the landform. Lastly, a commercial application, PhotoScan, was used to process the DTM reconstruction. To validate the workflow, the DTM produced in our previous work in 2014 was compared with the one produced using the proposed workflow. The target debris fan, called Pu-tun-pu-nas, is located in Kaohsiung county, Taiwan. The results show that the improved workflow can successfully reduce the man-hours for the whole process by 33% and those for data collection by 70% when conducting field work. Further study will be focused on evaluating the changes in geomorphology along the surface of the debris fan.

7. REFERENCE

Anette E. and Danilo S. (2015). Analysis of Different Methods for 3D Reconstruction of Natural Surfaces from Parallel-Axes UAV Images, The Photogrammetric Record, Vol. 30, Issue 151, 279–299.

Ballow, W. (2016). The Evaluation of Measuring Stream Chanel Morphology Using Unmanned Aerial System Based Structure-from-Motion Photogrammetry, Georgia State University. [online] Available from: http://scholarworks.gsu.edu/geosciences_theses (Accessed 16 August 2016.)

Chris H. H., Ken W., Owen W. B., Thomas E. B., Brian J. M., Adam L., Kevin R., and Tayler H. (2013). Geomorphological mapping with a small unmanned aircraft system (sUAS): Feature detection and accuracy assessment of a photogrammetrically-derived digital terrain model, Geomorphology, Vol. 194, 16–24.

Everaerts J.(2008) The use of unmanned aerial vehicles (UAVs) for remote sensing and mapping, Remote Sensing and Spatial Information Sciences, Vol. XXXVII, Part B1.

Mike R. J. and Stuart R. (2014). Mitigating systematic error in topographic models derived from UAV and ground-based image networks, Earth Surface Processes and Landforms, Vol. 39, Issue 10, 1413–1420.

Remondino F., Barazzetti L., Nex F., Scaioni M., and Sarazzi D. (2011) UAV photogrammetry for mapping and 3D modeling- current status and future perspectives -, International Archives of the Photogrammetry, Vol. XXXVIII-1, C22.

Xiangfeng Liu, X., Peng Chen, P., Xiaohua Tong, X., Shuang Liu, S., Shijie Liu, S., Zhonghua Hong, Z., Lingyun Li, L. and Kuifeng Luan, K.: UAV-based low-altitude aerial photogrammetric application in mine areas measurement, in 2012 Second International Workshop on Earth Observation and Remote Sensing Applications, pp. 240–242, IEEE., 2012.

A VISION-BASED APPROACH FOR SCAFFOLDING MONITORING

Jian Chai, Changzhi Wu, Hung-Lin Chi, Jun Wang & Xiangyu Wang

Australasian Joint Research Centre for Building Information Modelling, Curtin University

Lei Hou

Griffith School of Engineering, Griffith University

ABSTRACT: *Scaffolding represents unavoidable and cost-consuming activities, and the wisely utilization of scaffolding is what the owner seriously concerns in mega construction projects. The efficient and effective monitoring of the scaffolding is important to proper management and safety of construction tasks. This paper illustrates a vision-based approach to promote monitoring of scaffolding during construction. The proposed system utilizes images captured on sites as raw data source and estimates the depth map of the scene. Based on depth differences between scaffolding and backgrounds, scaffolding is recognized and extracted via the segmentation of depth images. By analyzing patterns of scaffolding structures, a model between scaffolding volume and images is established to estimate the productivity of scaffolding tasks. A pilot study is conducted and results show that the proposed approach can efficiently and effectively recognize the scaffolding and it becomes possible to identify its daily progress in order to monitor the productivity.*

1. INTRODUCTION

Scaffolding, which serves as platforms for workers, is widely utilized in the construction industry. The efficient and effective monitoring of scaffolding is important to construction tasks including progress tracking, productivity control, safety management, .etc. In the past years, severe incidents ever happened related to collapse of scaffolding structures during construction (Service, 2015). An effective monitoring approach can be used to inspect scaffolding and detect visible defects, which possibly lead to structure failure. Besides, efficient monitoring can also to be used to track scaffolding erection progress, which is necessary for effective project control.

Recently, automated methods of monitoring construction project have been proposed by integrating innovative technologies, such as cyber-physical systems (CPS) and computer vision (Kopsida, Brilakis and Vela, 2015). RFID, laser scanning and cameras enables automatic data collection from a construction site. Those collected data contains rich information reflecting real status of a construction site. For example, RFID enables real time localization of onsite objects (Lee et al., 2013). Onsite images record objects' appearance, both geometrically and semantically. Information retrieval from raw data are conventionally manual processes which are inefficient and of high cost. Many novel information retrieval approaches are developed to improve efficiency of interpretation. Bosché (2010) proposed to monitor as-built dimension in construction by automated recognizing 3D models from laser scanned data when there exists an as-designed model. Han and Golparvar-Fard (2015) used images to recognize material classification of objects and to infer operation-level construction progress by integrating 4D BIM. There remains many challenges in retrieving information, which suffers from level of automation, high computation cost and insufficient semantic information.

Despite of large advancement in monitoring and interpreting as-built status of a construction project, those proposed methods are designed for specific objects or tasks and there are few works focusing on temporary structures as scaffolding. Chi et al. (2012) proposed to develop BIM models of scaffolding and to integrate relative regulations on safety compliance and productivity improvement. Cyber-physical systems were investigated to monitoring temporary structures and a simulated experiment was conducted on scaffolding structures (Yuan et al., 2016). This work demonstrated that CPS is promising in real time monitoring of temporary structures. Xu et al. (2015) investigated reconstruction scaffolding components in a building site with a photogrammetry method, which focused on reconstruction of geometric models and was designed for buildings. Jung (2014) developed an automated approach to detect failure of concrete shoring, which is similar to scaffolding. The approach firstly establishes edge history images from video surveillance, and then learns and predicts possible failure with a Hidden Markov Model (HMM). The results demonstrate that vision technology is promising in performing comprehensive site monitoring tasks.

In this paper, we propose a vision-based approach that monitors structure of scaffolding and estimates progress of scaffolding erection. The approach, which addresses issue of lacking monitoring methods for temporary structures, is developed simply using on-site captured photos and comes out with productivity estimations of scaffolding.

2. METHODOLOGY

2.1 OVERVIEW OF THE VISION-BASED APPROACH

In this section, the process of the developed approach is described. The vision-based approach is developed to automated monitor the as-is status of scaffolding structures by capturing onsite photos in construction or maintenance phases, which can provide efficient feedbacks to project managers and stakeholders on productivity and progress of scaffolding tasks. The process of the approach is displayed in Fig. 1.

The approach employs mobile cameras to collect images on construction sites. It is flexible and efficient to capture onsite photos with regular cameras, which can be handheld or mounted on mobile platforms like unmanned aerial vehicles (UAVs). Also, other equipment can be used is video surveillance cameras, which are commonly applied in current construction projects. Those images are required to be captured from multiple viewpoints and cover all areas of interests. The monitoring approach then recognizes scaffolding with image processing and recognition methods. A depth map of the scene is produced from images with the multi-view stereo technology (Strecha et al., 2006). Scaffolding is extracted from the depth map by thresholding segmentation, and Generalized Hough Transform (GHT) is used to estimate the structure and volume of scaffolding in images. Productivity of scaffolding is estimated according to prior knowledge of scaffolding modules and recognized those structures from images. The prior knowledge includes a library of scaffolding basic structures and scaffolding specifications for a project. The library serves as templates for GHT recognition, and specifications contain parameters used to estimate progress of scaffolding erection. The segmentation and recognition process will be discussed in detail in the following sections.

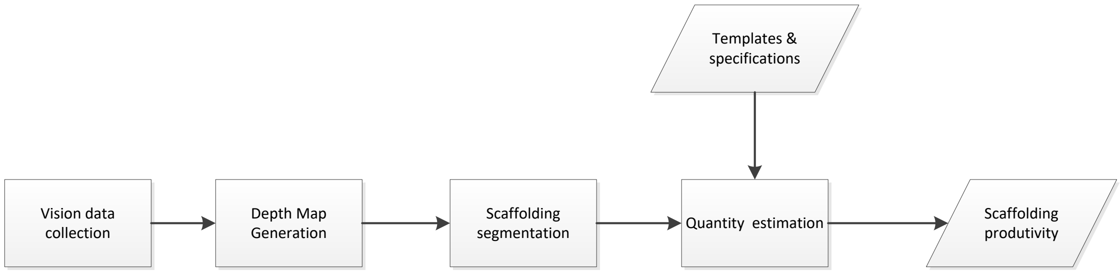


Fig. 1: Process of the developed scaffolding monitoring approach

2.2 SCAFFOLDING SEGMENTATION BASED ON DEPTH MAP

A key step of the vision-based monitoring approach is to effectively detect scaffolding from images. It is straightforward to employ image segmentation techniques based on features such as color and textures to segment scaffolding in raw images (Kaur et al., 2016). However, in cases where scaffolding and backgrounds have similar appearance, it is hardly possible to detect scaffolding with appearance-based segmentation (Dey et al., 2010). In the study, experiments are conducted to evaluate performance of various image segmentation methods for dividing scaffolding and backgrounds. Specifically, K-means (Yao et al., 2013), mean shift (Comaniciu and Meer, 2002) and graph cut (Boykov and Kolmogorov, 2004) segmentation approaches are exploit.

The K-mean clustering algorithm divides a whole image into k clusters, in which each pixel belongs to the cluster with the closest mean. During clustering, the distance of two pixels is measured by the Euclidean distance between their feature vectors. Instead of original RGB colour space, the clustering process is performed in the LAB colour space (Chen et al., 2008) as it can avoid the influence of illumination. The algorithm needs a user input parameter, which is the cluster numbers.

Mean shift is a feature-space analysis technique using nonparametric density gradient estimation, which can be applied to image segmentation problems. Image segmentation using Mean shift method is presented in detail by Comaniciu and Meer (2002). Segmentation is achieved by grouping and merging neighboring pixels that converged to the same spectral and spatial mode approximately. The mean shift is unsupervised clustering algorithm and needs the selection of only one parameter, which is the bandwidth of the kernel and controls resolution of segmentation. In our test, the bandwidth parameter is iteratively selected through experiments.

Graph-based image segmentation models an image as a graph. Each node in the graph represents a pixel and each edge represents connection between a pair of neighboring pixels. The weight of an edge measures dissimilarity between corresponding connected pixels. Image segmentation is interpreted as portioning nodes of a graph into disjoint subsets, which can be solved by the graph cut method. The graph cut method needs to measure the likelihood of a pixel belonging to a class, which is called the data energy term. In our test, the data energy term is estimated by Gaussian mixture models in spatial and color space. Graph-based image segmentation satisfies global properties and can partition an image into significative regions.

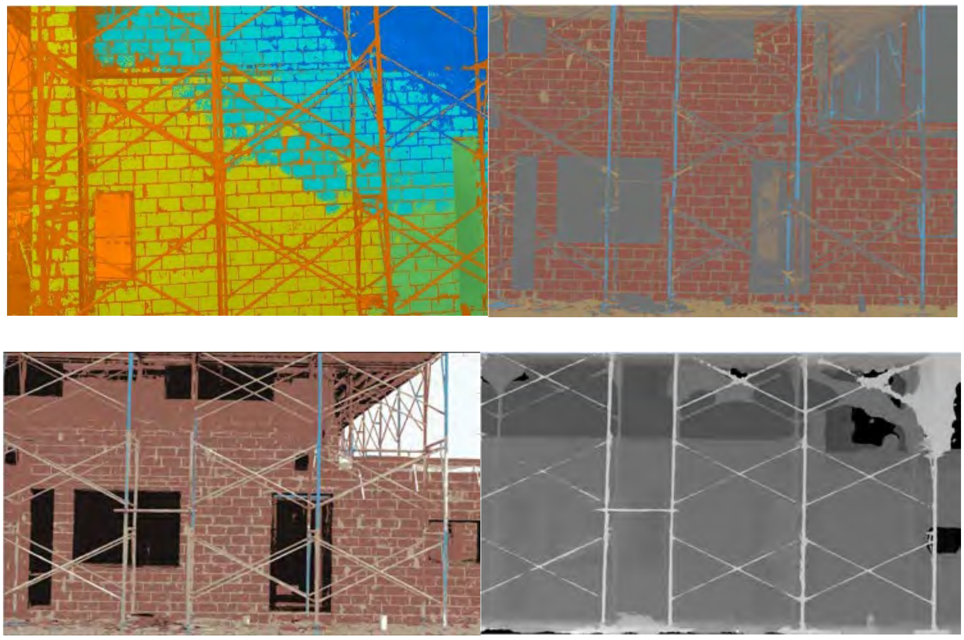


Fig. 2: Segmentation results with different methods: Graph cut (left above), Mean shift (right above), K-means (left below), and depth-based approach (right below)

The performances of different segmentation approaches are demonstrated in Fig. 2. Both the graph cut and mean shift algorithms suffer from under-segmentation by mixing scaffolding and objects belonging to backgrounds. In addition, mean shift also segments scaffolding with different appearances into different clusters.

To achieve an effective segmentation, a depth-based strategy is developed to recognize scaffolding from images. It is observed that scaffolding usually is erected to the surface of a facility. The distance of scaffolding to the surface will possibly produce local extrema in a depth map, which is an image that relates to distance of an object from a viewpoint. A depth map is essential to understanding the 3D geometry of a scene and can be estimated from stereo images or a single image. Fig. 2 shows the depth map corresponding to the same image as graph cut method. Given their depth differences, scaffolding and backgrounds thus can be segmented in a simple way. To be specific, we simply use a thresholding method, which is very efficient.

2.3 SCAFFOLDING STRUCTURE DETECTION

Scaffolding is typically a manual assembled structure which comprised of some fixed patterns. Based on this observation, it is possible that quantities of scaffolding can be estimated by counting numbers of those patterns. This transformed the problem to detect pre-defined patterns in a library from segmented images.

First, we establish a library of template shapes through investigating assembly rules and structures of scaffolding. In the library, each template shape corresponds to a scaffolding pattern and is represented with a binary image. One advantage of this is that the proposed approach is easily to be extended to different kinds of structures by adding new templates to the library. The proposed work utilizes Generalized Hough Transform (GHT) to detect scaffolding patterns from images (Ballard, 1981). GHT is a method for detecting an arbitrary non-analytic shape from an image. The GHT method takes a template of a shape and an image as inputs, and determines locations of objects matching the template in the image. Through iteratively detecting each template from a segmented scaffolding image, numbers of each shape in the library are estimated.

In industries, the quantities of scaffolding are usually measured by mass, typically by tons. So as to do this, a model between numbers of scaffolding shapes and respective mass is defined. The model between shapes and masses is related to materials of specifications of different scaffolding, which means it varies with different scaffolding manufactures and projects.

3. EXPERIMENTS

To evaluate feasibility of the proposed monitoring approach, we conducted an experiment in a building site, as displayed in Fig. 3. With photos of the building, the proposed approach generated a depth map of the building using multi-view stereo technologies. Then, the depth map was used to detect scaffolding with above-discussed methods.

Fig. 3: Overview of the experiment site

The depth map of the building is displayed in Fig. 4, where intensity of a pixel represents relative depth. It can be seen from the image that scaffolding is brighter than backgrounds, due to their depth variation. The intensities of pixels belonging to scaffolding and backgrounds show significant differences, which makes it easy to segments scaffolding from the image with a simple thresholding method. The binary image produced by thresholding is shown in Fig. 4, where white represents scaffolding. Even though there are some outliers and discontinuities, the thresholding produced clear skeleton of scaffolding.

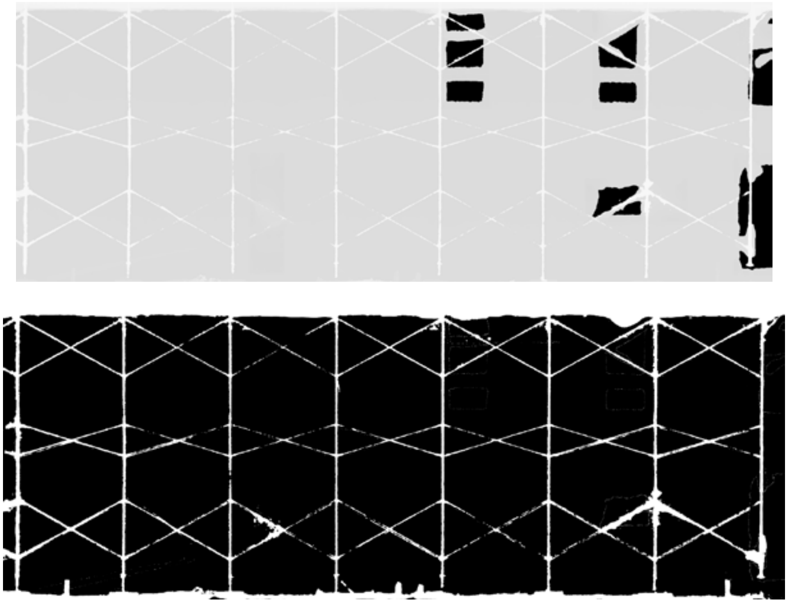


Fig. 4: Depth map (above) and binary image (below) from thresholding

As shown in Fig. 3, scaffolding in this scene is composed of one repetitive pattern. A template for this pattern is created and displayed as Fig. 5. To estimate occurrences and locations of this pattern template, we applied the GHT method to the segmented image as described in section 2.3. The results of GHT are displayed in Fig. 6, where detected templates are colored and overlaid on the original image, and numbers are used to label the order of detection. In this case, all 21 patterns are successfully detected.

Fig. 5: A template of scaffolding

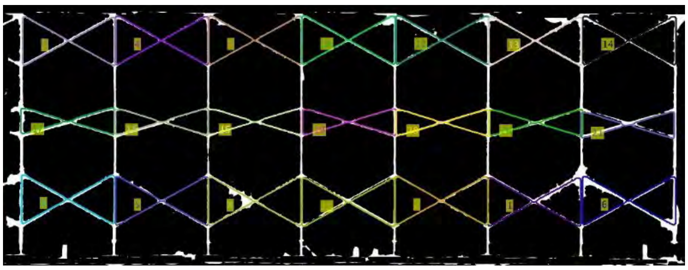


Fig. 6: Results of scaffolding structure detection with the GHT method

In our experiment, the proposed approach effectively segmented scaffolding from backgrounds and successfully detected all basic patterns of scaffolding. The performance in this case demonstrated that our proposed approach is feasible in monitoring scaffolding during construction.

4. SUMMARY

This paper illustrated a proposed vision-based approach for monitoring scaffolding in construction sites. The approach extracts scaffolding from depth maps and detects scaffolding structures by matching templates. The matched templates are then used to estimate quantities of scaffolding. We conducted a case study in a building site and the results demonstrated that the proposed approach is feasible, efficient and effective for monitoring productivity of scaffolding tasks.

In future, further studies will be conducted to validate the proposed approach in other complex construction sites including industrial plants. In addition to productivity analysis, it is also worthy extending the proposed vision-based approach to perform other tasks, such as monitoring the structure security of scaffolding and predicting possible structure failures.

5. REFERENCES

Ballard, D.H., 1981. Generalizing the Hough transform to detect arbitrary shapes. Pattern Recognition, 13(2), pp.111-122.

Bosché, F., 2010. Automated recognition of 3D CAD model objects in laser scans and calculation of as-built dimensions for dimensional compliance control in construction. Advanced Engineering Informatics, 24(1), pp.107-118.

Boykov, Y. and Kolmogorov, V., 2004. An experimental comparison of min-cut/max-flow algorithms for energy minimization in vision. IEEE Transactions on Pattern Analysis and Machine Intelligence, 26(9), pp.1124-1137.

Chen, T.W., Chen, Y.L. and Chien, S.Y., 2008, October. Fast image segmentation based on K-Means clustering with histograms in HSV color space. In Multimedia Signal Processing, 2008 IEEE 10th Workshop on (pp. 322-325). IEEE.

Chi, S., Hampson, K.D. and Biggs, H.C., 2012. Using BIM for smarter and safer scaffolding and formwork construction: a preliminary methodology. Modelling and Building Health and Safety.

Comaniciu, D. and Meer, P., 2002. Mean shift: A robust approach toward feature space analysis. IEEE Transactions on Pattern Analysis and Machine Intelligence, 24(5), pp.603-619.

Dey, V., Zhang, Y. and Zhong, M., 2010. A review on image segmentation techniques with remote sensing perspective. na.

Han, K.K. and Golparvar-Fard, M., 2015. Appearance-based material classification for monitoring of operation-level construction progress using 4D BIM and site photologs. Automation in Construction, 53, pp.44-57.

Jung, Y., 2014. An approach to automated detection of failure in temporary structures using image processing. Journal of Engineering and Architecture, 2(1), pp.49-61.

Kaur, G., Kaur, R. and Singh, M., 2016. Image Segmentation Methods and Techniques: A Review. International

Journal of Engineering Science, 6096.

Kopsida, M., Brilakis, I. and Vela, P.A., 2015. A Review of Automated Construction Progress Monitoring and Inspection Methods. CIB W78, pp.421-431.

Lee, J.H., Song, J.H., Oh, K.S. and Gu, N., 2013. Information lifecycle management with RFID for material control on construction sites. Advanced Engineering Informatics, 27(1), pp.108-119.

Service, C. (2015). 6 construction workers hurt after massive scaffolding collapse in Houston. [online] FOX6Now.com. Available at: http://fox6now.com/2015/10/16/scaffolding-collapses-outside-building-under-construction-in-houston/ [Accessed 28 Jun. 2016].

Strecha, C., Fransens, R. and Van Gool, L., 2006. Combined depth and outlier estimation in multi-view stereo. In 2006 IEEE Computer Society Conference on Computer Vision and Pattern Recognition (CVPR'06) (Vol. 2, pp. 2394-2401). IEEE.

Xu, Y., He, J., Tuttas, S. and Stilla, U., 2015. Reconstruction of Scaffolding Components from Photogrammetric Point Clouds of a Construction Site. ISPRS Annals of Photogrammetry, Remote Sensing and Spatial Information Sciences, 1, pp.401-408.

Yao, H., Duan, Q., Li, D. and Wang, J., 2013. An improved K-means clustering algorithm for fish image segmentation. Mathematical and Computer Modelling, 58(3), pp.790-798.

Yuan, X., Anumba, C.J. and Parfitt, M.K., 2016. Cyber-physical systems for temporary structure monitoring. Automation in Construction, 66, pp.1-14.

UNMANNED AERIAL VEHICLE PATH PLANNING FOR ALLUVIAL FAN DIGITAL TERRAIN MODEL RECONSTRUCTION

Cheng-Hsuan Yang, Ci-Jyun Liang & Shih-Chung Kang

National Taiwan University, Taiwan

ABSTRACT: *Alluvial fans typically cause serious damage to the surrounding environment during torrential rain and typhoon periods in Taiwan. Therefore, the survey and monitoring of alluvial fans are necessary for safety. Light detection and ranging (or LIDAR) or a total station are the traditional equipment and methods used to survey alluvial fans, but these are time consuming and labor intensive. In our previous study, we utilized unmanned aerial vehicles (UAVs) and survey data to reconstruct a alluvial fan model using a digital terrain model (DTM) technique. We found out that our method can improve the model precision from 1 m to 0.1 m and it is time efficient compared with the traditional methods. We also found that path planning for the UAV is the key factor in the survey time cost. In this study, we utilize two different types of flight path—fixed-height surrounding and fixed-height orthographic—for a UAV to collect image data to reconstruct a alluvial fan model with a DTM. We have conducted a field study of a alluvial fan at the Laonong River in Taiwan. We followed the steps of the previous field study. First, six to eight ground control points were marked on the alluvial fan. Second, the UAV collected image data with the two different types of flight path at a height of 200 m. Finally, the image data were processed and the DTM was constructed using PhotoScan software. The result shows that the fixed-height orthographic flight path reduces the time by 75% compared with the fixed-height surrounding path. The accuracy of the fixed-height surrounding path is similar to that of the fixed-height orthographic path except in some small overlapped areas which the accuracy decreased.*

KEYWORDS: *digital terrain model, unmanned aerial vehicle, path planning, alluvial fan*

1. INTRODUCTION

Rivers in Taiwan have multiple tributaries and high flow speeds, which cause sediment deposition in tributary mouths and form alluvial fans. The over-deposition of a alluvial fan will cause debris flow and in turn cause serious damage to the surrounding environment and downstream area during torrential rain and typhoon periods (Chou *et al*., 2016). Therefore, monitoring and survey of alluvial fans are necessary to prevent hazards from occurring. Digital terrain model (DTM) reconstruction is one of the most commonly used survey methods to reconstruct a alluvial fan model for monitoring variation (Cavalli and Marchi, 2008). The DTM is constructed from large amounts of survey data, which are collected by different instruments and approaches. For instance, Fritsch and Stallmann (2000) utilized high-resolution optical satellite imagery to reconstruct the DTM of an area of land in Germany. This method improved the efficiency of the survey process but had only a 10-m model precision. Light detection and ranging (LIDAR) and laser scanners are other types of survey method that can be utilized to reconstruct a DTM (Luo and Gavrilova, 2006). Petschko *et al*. (2015) analyzed a DTM constructed from LIDAR data to map a landslide inventory. Corsini *et al*. (2013) integrated a laser scanner and a total station to construct DTM and monitor a rock slide.

The unmanned aerial vehicle (UAV) has recently become widely used in civil engineering (Liu *et al*., 2014). The UAV is low cost and possesses high mobility, which are advantageous for large-area land surveys. Vallet *et al*. (2011) utilized a fixed-wing UVA to collect image data and reconstruct a DTM. Siebert and Teizer (2014) surveyed an earthwork project with a UAV and DTM method.

In our previous research (Wen *et al*., 2014), we utilized a UAV to collect image data of a alluvial fan located at the intersection of the Pun-tun-pu-nas tributary and Laonong River in Kaohsiung, south of Taiwan. We then used the image data to construct a DTM of the alluvial fan (Wen *et al*., 2014) and compared the results with traditional total station survey results. We found out that the combined UAV and DTM method can yield 0.1-m precision and is less time consuming than the traditional survey method (three days for the DTM method compared with five days for the traditional survey method). We also found out that the UAV flight path is the key factor in the survey time. We divided the area into seven sections and utilized a fixed-height surrounding path to perform collection. A suitable path planning is required since it will influence the survey precision and efficiency.

In this study, we use two different types of flight path—fixed-height surrounding and fixed-height orthographic—to collect image data of the alluvial fan at the intersection of the Pun-tun-pu-nas tributary and Laonong River in Kaohsiung. Following the field survey, DTMs are reconstructed using the image data. We compare the DTMs from the different types of flight path with the traditional survey method to verify the precision and survey time.

2. FIELD STUDY

A field study was carried out at the alluvial fan located at the intersection of the Pun-tun-pu-nas tributary and Laonong River in Kaohsiung. We followed the steps of the previous field study. First, we marked the ground control points on the alluvial fan at 100-m intervals. A total of 44 ground control points were marked on the alluvial fan. A total station and a GPS sensor were utilized to measure the relative and absolute positions of each ground control point. Second, the UAV collected imaging data with the two different types of flight path at a height of 200 m. Finally, the imaging data were processed and the DTM was constructed using PhotoScan software.

3. FLIGHT PATH TYPE

Fixed-height surrounding and fixed-height orthographic types of flight path were utilized to plan the survey path. We followed three requirements to generate the UAV flight path. First, the imaging data should have 80% overlap. Second, the flying height was fixed at 200 m. Third, the angle of view of the camera was 94 degrees. The following section will introduce each type of path.

3.1 Fixed-Height Surrounding Type Path

The fixed-height surrounding type of path is a circular-shaped path. The key feature of the fixed-height surrounding path is that the camera will point at the center throughout the surrounding period. The UAV will follow a circular path to survey the whole alluvial fan. Therefore, we have to determine the diameter of the circular path to ensure that the UAV can cover the whole alluvial fan. Figure 1 shows the mathematical model for the UAV camera and the diameter of the circular path. From the mathematical model, we can calculate the camera range L:

$$L = h\left[tan\left(\frac{\phi}{2}+\beta\right)+tan\left(\frac{\phi}{2}-\beta\right)\right]$$

$$\text{Let } Overlap = X$$

$$L_0 = L \cdot X = hX \cdot \left[tan\left(\frac{\phi}{2}+\beta\right)+tan\left(\frac{\phi}{2}-\beta\right)\right]$$

$$D = 2h\,tan\left(\frac{\phi}{2}+\beta\right) - Xh\,tan\left(\frac{\phi}{2}+\beta\right) - Xh\,tan\left(\frac{\phi}{2}-\beta\right)$$

$X = \frac{2h\,tan\left(\frac{\phi}{2}+\beta\right)-D}{h\cdot\left[tan\left(\frac{\phi}{2}+\beta\right)+tan\left(\frac{\phi}{2}-\beta\right)\right]} \geq 80\%$ (*i.e.*, overlap should be larger than 80%).

With the camera having an angle of view of $\phi = 94°$, a tilt angle of $\beta = 20°$, and a flying height of $h = 200$, we can determine the circular path's diameter as $D \leq 484.8$ m. Therefore, we select a diameter of 300 m. Based on the previous calculation, we divided the alluvial fan into eleven sections. Each section represents a circular path with a diameter of 300 m, as shown in Fig. 2. The green areas 1 and 2 are the landing areas.

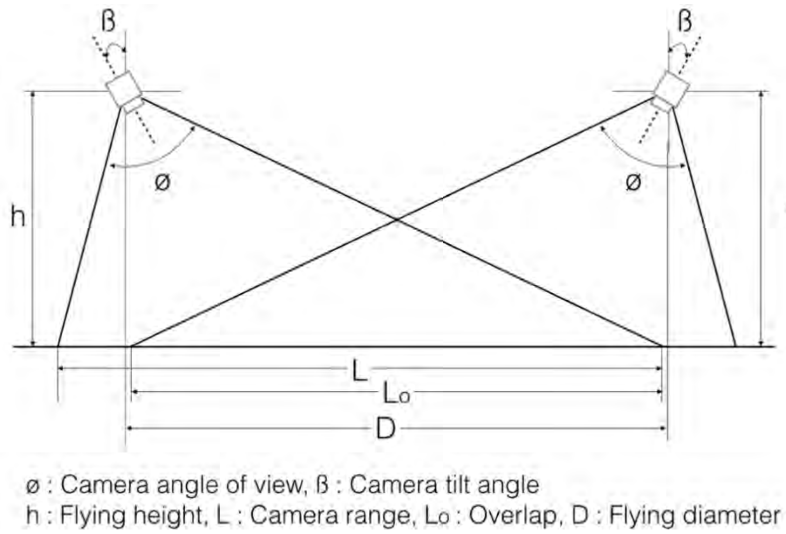


Fig. 1: The mathematical model for the camera and the diameter of the path.

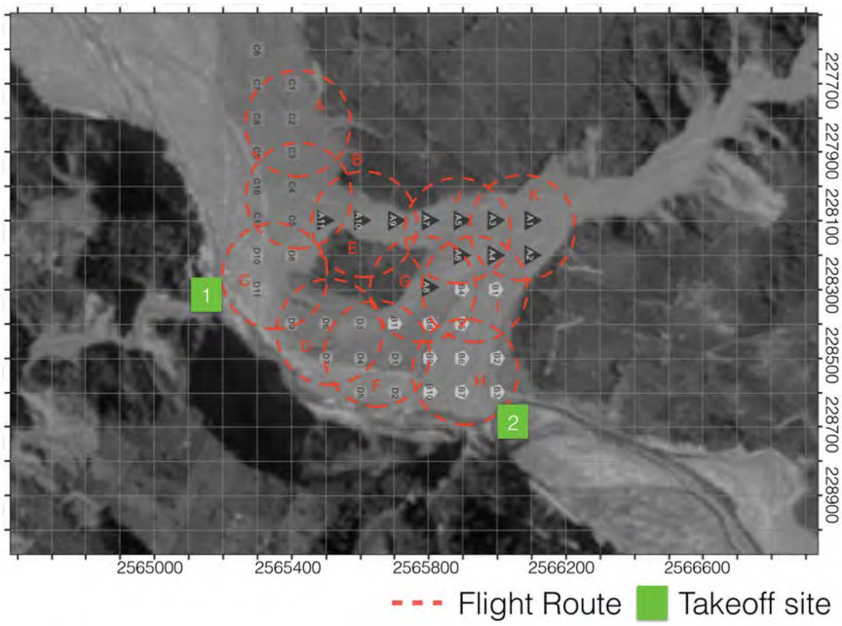


Fig. 2: Fixed-height surrounding path planning.

3.2 Fixed-Height Orthographic Type Path

The fixed-height orthographic type of path is a linear back-and-forth path. The key feature of the fixed-height orthographic path is that the camera will be orthogonal to the ground throughout the survey period. The UAV follows the back-and-forth path to survey the whole alluvial fan similar to the fixed-height surrounding path. We divided the survey area into three sections, as shown in Fig. 3. Path a, Path b, and Path c are the planning paths of the three chunks.

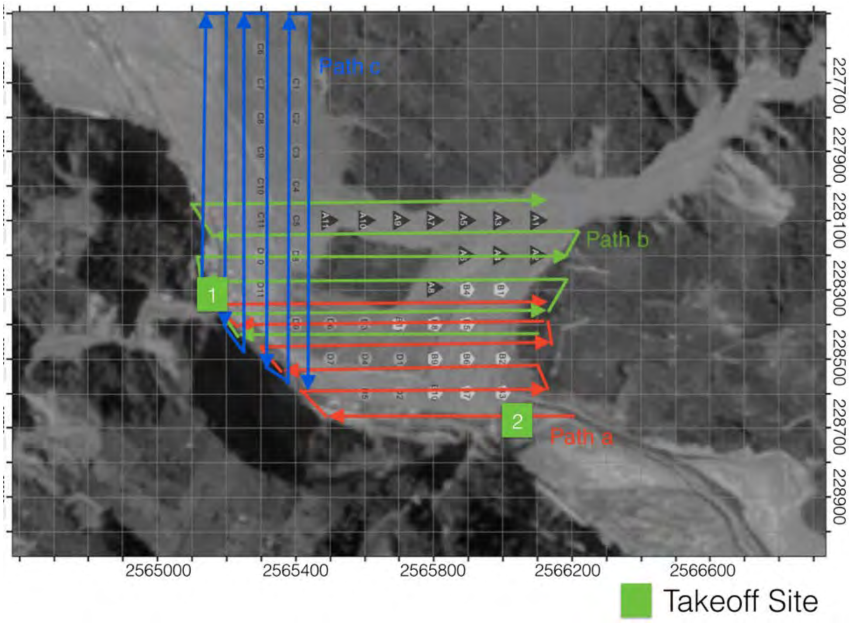


Fig. 3: Fixed-height orthographic path planning.

4. RESULTS AND DISCUSSION

After the field study, post-processing was performed in the lab. We imported the imaging data into the commercial software PhotoScan and marked the ground control points in the imaging data. PhotoScan then computed and reconstructed the DTM. The total image taken from the fixed-height surrounding path comprised 1,668 images. The flight time was 214 min and the survey time was 117.9 min. On the other hand, the total image taken from the fixed-height orthographic path comprised 1,819 images. The flight time was 55 min and the survey time was 38.3 min. The fixed-height orthographic path required 75% less time than the fixed-height surrounding path since the orthographic type had more linear paths than the surrounding type. The time costs for both types were less than for the traditional survey method, which takes four days to complete the survey.

We compared the results of the DTM with the results of the traditional survey after post-processing. We divided the alluvial fan into six areas: right edge, upper edge, left edge, ancient river terrace, tributary 1, and tributary 2 to calculate errors in the Z-coordinate, as shown in Fig. 4. Table 1 shows the results and the errors. We can see that the errors between the DTM and survey are less than 0.5 m, which means that the UAV DTM method can significantly reduce survey time and yield high-accuracy results. The results also show that the two types of path can produce similar accuracy, except for the upper edge area because the fixed-height surrounding path has more overlap in this area.

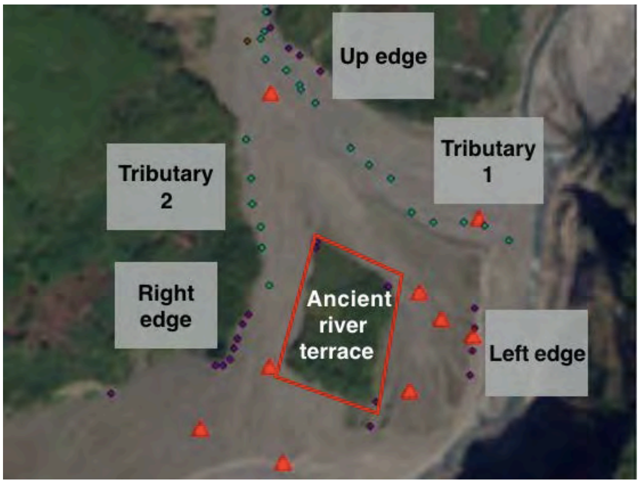


Fig. 4: Six selected areas of the alluvial fan.

Table 1: Errors of the DTM and survey (m).

Area	Error (fixed-height surrounding)	Error (fixed-height orthographic)
Right edge	0.0633	0.0687
Upper edge	0.4861	0.1784
Left edge	0.0914	0.1472
Ancient river terrace	0.1917	0.1513
Tributary 1	0.1849	0.1954
Tributary 2	0.1206	0.1441
Average	**0.3362**	**0.1475**

5. CONCLUSION

In this study, we aimed to compare two different types of flight path—fixed-height surrounding and fixed-height orthographic—for UAV DTM reconstruction. The surrounding type was a circular-shaped path and the orthographic type was a linear back-and-forth path. The UAV followed these two types of flight path during the survey. We conducted a field study at a alluvial fan at Pu-tun-pu-nas to compare these two paths. The results showed that the orthographic type reduces the survey time by 75% compared with the surrounding type and produces a model of similar accuracy.

6. REFERENCES

Cavalli, M. and Marchi, L. (2008). Characterisation of the surface morphology of an alpine alluvial fan using airborne LiDAR. *Natural Hazards and Earth System Sciences,* Vol. 8, No. 2, 323-333.

Chou, H.-T., Lee, C.-F. and Lo, C.-M. (2016). The formation and evolution of a coastal alluvial fan in eastern Taiwan caused by rainfall-induced landslides. *Landslides*, In Press.

Corsini, A., Castagnetti, C., Bertacchini, E., Rivola, R., Ronchetti, F. and Capra, A. (2013). Integrating airborne and multi-temporal long-range terrestrial laser scanning with total station measurements for mapping and monitoring a compound slow moving rock slide. *Earth Surface Processes and Landforms,* Vol. 38, No. 11, 1330-1338.

Fritsch, D. and Stallmann, D. 2000. *Rigorous photogrammetric processing of high resolution satellite imagery*, Universität Stuttgart, Fakultät Bauingenieur-und Vermessungswesen, Institut für Photogrammetrie.

Liu, P., Chen, A. Y., Huang, Y.-N., Han, J.-Y., Lai, J.-S., Kang, S.-C., Wu, T.-H., Wen, M.-C. and Tsai, M.-H. (2014). A review of rotorcraft unmanned aerial vehicle (UAV) developments and applications in civil engineering. *Smart Structures and Systems,* Vol. 13, No. 6, 1065-1094.

Luo, Y. and Gavrilova, M. L. 3D Building Reconstruction from LIDAR Data. *In:* GAVRILOVA, M., GERVASI, O., KUMAR, V., TAN, C. J. K., TANIAR, D., LAGANÁ, A., MUN, Y. & CHOO, H., eds. *Computational Science and Its Applications*, May 8-11 2006 Glasgow, UK. Springer Berlin Heidelberg, 431-439.

Petschko, H., Bell, R. and Glade, T. (2015). Effectiveness of visually analyzing LiDAR DTM derivatives for earth and debris slide inventory mapping for statistical susceptibility modeling. *Landslides*, In Press.

Siebert, S. and Teizer, J. (2014). Mobile 3D mapping for surveying earthwork projects using an Unmanned Aerial Vehicle (UAV) system. *Automation in Construction,* Vol. 41, 1-14.

Vallet, J., Panissod, F., Strecha, C. and Tracol, M. Photogrammetric performance of an ultra light weight swinglet UAV. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, 2011. 253-258.

Wen, M.-C., Yang, C.-H., Sung, E., Wu, T.-H. and Kang, S.-C. Optimized Integration of UAVs, Surveys, and Image-based Modelling Strategies for Digital Terrain Model Reconstruction. *Proceedings of 14th International Conference on Construction Applications of Virtual Reality*, Nov. 16-18 2014 Sharjah, UAE.

A UAV-BASED IMAGE PROCESSING SYSTEM FOR IDENTIFYING AND VISUALIZING CONSTRUCTION HAZARDOUS AREAS

Bahaa Eddine O. Mneymneh, Mohamad F. Abbas & Hiam M. Khoury

(American University of Beirut, Lebanon)

ABSTRACT: *Construction safety management processes primarily entail implementing health and safety regulations to maintain a safe environment. Yet a major component of these processes comprises identifying potentially hazardous areas, and consequently taking remedial actions. If left undetected, such areas would be a primary factor to create injuries and cause fatalities. Having said that, traditional practices have been relying on either the workers' capabilities in identifying hazardous zones, or safety officers circulating and recognizing on-site hazards and notifying workers of unsafe conditions. However, the former practice is considered to be incompetent and not very reliable, while the latter practice of relaying information is considered manual, tedious, and time-consuming. In order to address the aforementioned limitations, this paper presents work that is aimed at efficiently and conveniently identifying on-site hazardous areas using Unmanned Aerial Vehicles (UAVs) or what is commonly known as drones. These are aerial camera-equipped robots capable of rapidly navigating spacious environments and capturing their dynamics. More specifically, the purpose behind this study is two-fold: (1) collecting real-time videos from a construction site using a UAV system, and (2) analyzing the constituent elements of a perilous site and identifying potentially hazardous areas using digital image processing techniques. The components of the proposed system were created. The preliminary results highlighted the potential of using camera-equipped UAVs coupled with image analysis and visualization techniques to conveniently identify and visualize on-site hazardous areas in construction environments.*

KEYWORDS: *Construction, Safety, Hazard, Automation, UAV, Image Processing.*

1. INTRODUCTION

Construction is undoubtedly one of the riskiest industries. According to the Health and Safety Executive (HSE), 65,000 non-fatal workspace injuries have been self-reported in the U.K. in 2014/15, of which 45% were associated with the presence of hazardous areas on construction sites. This was reinforced by Carter and Smith (2006) who presented an investigation indicating the efficiency rate in identifying hazardous areas within the U.K. construction industry. On the other hand, Kim *et al.* (2016) worked on identifying hazardous areas.by developing a system that detects the obstacles onsite through the comparison of the actual laborer's movement path versus the optimal route or the shortest path. In other words, when moving on a construction site, the laborer tends to move on an optimal path, and any deviation tracked on their actual movement path can be considered as an obstacle.

Nonetheless, a comprehensive safety monitoring of the whole construction site is deemed necessary. Therefore, various research efforts have recently focused on adopting drones or UAVs in the construction industry. Drones are aerial camera-equipped robots capable of rapidly visualizing spacious environments. For instance, Ham *et al.* (2016) reviewed the works related to the use of drones in visual monitoring of civil infrastructure systems. The most relevant applications were considered progress monitoring, site monitoring, building inspection, building measurement, surveying and safety inspection. Irizarry *et al.* (2012) evaluated the potential of using UAVs in improving safety on construction sites. In their work, videos captured from construction sites using drones were provided to safety inspectors to manually count the number of helmets. However, similar to other construction applications, information extracted from real-time videos captured by the UAVs can be better analyzed using digital image processing techniques rather than manually. Among many related research efforts, Yang *et al.* (2010) tested and demonstrated the possibility of tracking multiple workers on construction sites by analyzing videos from moving cameras. Seo *et al.* (2015) reviewed previous efforts that applied computer vision in construction applications and highlighted the possibility of using such techniques in safety and health monitoring. Furthermore, Shrestha *et al.* (2015) developed a system that uses image processing techniques, in particular edge detection, in order to recognize whether workers are wearing hard hats. However, none of the latter safety research efforts captured images using drones.

Therefore, the overarching objective of this paper is to enhance construction safety inspections by developing an automated and comprehensive hazardous area detection system. The system aims at (1) capturing real-time videos of the construction site using drones or UAVs, and (2) analyzing the videos using image processing techniques to detect and identify hazardous areas.

2. METHODOLOGY

In order to achieve the aforementioned objectives, the paper tackles three task areas: (1) Survey, (2) Hardware, (3) Software and Algorithms.

2.1 Survey: Pre-defined Hazardous Areas

Prior to developing the automated hazardous areas detection system, a survey was conducted to determine the most dangerous hazardous areas or on-site operations. In this survey, construction workers, foremen and engineers were asked to rate the different unsafe areas or activities. Results showed that the situations ordered from most hazardous to least were considered: (1) shaft opening, (2) steel welding, (3) fire, and (4) steel grinding.

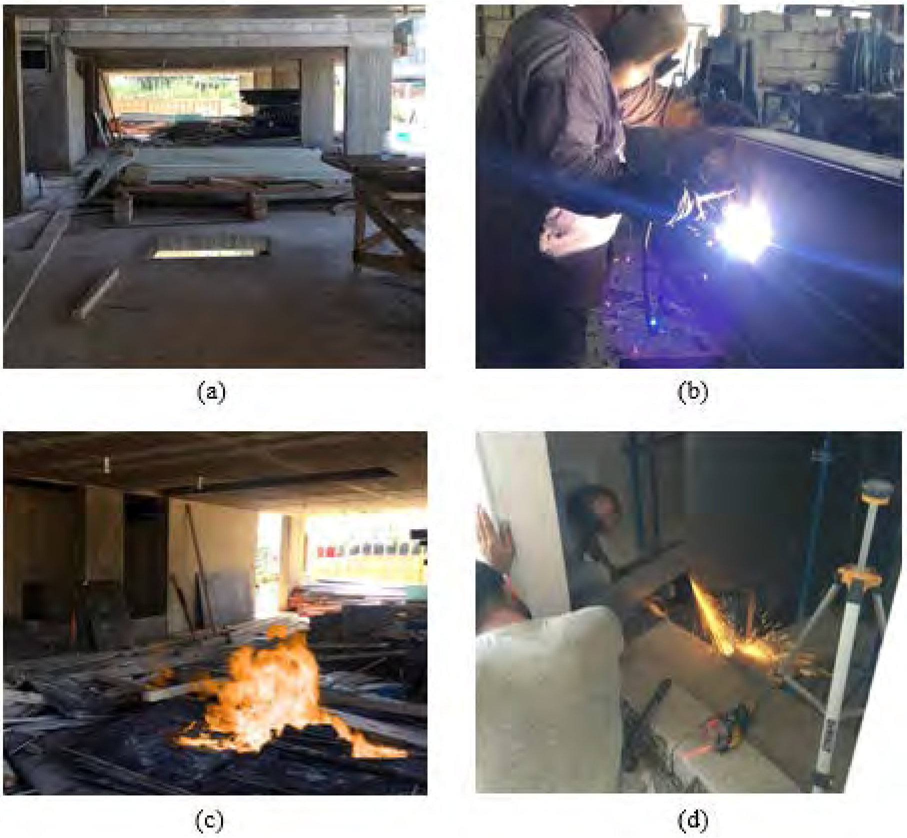


Fig. 13: (a) Shaft opening, (b) Steel welding, (c) Fire, and (d) Steel grinding

2.2 System Hardware: UAV Selection and Specifications

The UAV used is a Merlin's Quadcopter UAV equipped by a high-quality camera. It can be operated within a 30 meter range using the controller or a smartphone. The six-axis gyroscope makes it easy to control the drone and permits stable flights. The two main advantages of this drone are: (1) it streams live videos to the mobile device due to its 2.4 GHz Wi-Fi network, and (2) it flies over the construction site without compromising the ongoing construction activities or causing any derailment to workers.

Fig. 14: Merlin Quad Copter UAV

2.3 System Software and Algorithms

Image processing algorithms were used to analyze the real-time videos captured by the UAV. In this case, three main algorithms can be used for object detection, namely: (1) Feature detection, extraction and matching, (2) Template matching, and (3) Cascade object detector.

Feature detection, extraction and matching algorithm detects objects by finding features correspondences between the reference image and the target one (Oueiss *et al.* 2012, Khoury *et al.* 2015). Therefore, this technique works best for object containing non-repeating patterns and textures. On the other hand, template matching (Kour 2015) is a computer vision technique that inspects the presence of a given object in an image using a reference image of the object (i.e. template image). The algorithm inspects the presence of the template by calculating the similarity between the pixels of the two images at every possible position of the template, using cross-correlation. A cross-correlation of 1 implies a perfect match while a value of 0 implies zero matches. While advanced template matching algorithms are able to identify objects rotated and scaled differently than those of the template image, these techniques still have two major drawbacks: (1) they are not likely to work well on objects whose forms and shapes may vary, and (2) they are time consuming and not suitable for a real-time application. Another pertinent computer vision technique is the cascade object detector used to detect objects having an appearance that does not change significantly (Alionte and Lazar 2015). This technique involves training the detector by creating a large database containing images of relevant objects from several angles and views. The detector then uses a cascade classifier to decide whether the window sliding over a certain image contains the object of interest. This classifier is composed of a defined number of stages. Each stage may have two possible results: (1) positive (object found) or (2) negative (object not found). When the result is positive, the classifier moves to the next stage. The object is considered detected when the result of all stages is positive. Reducing the number of false detections can be done either by increasing the number of stages or by decreasing the false alarm rate.

Since hazardous areas have repeating patterns, and given that the drone captures real-time images from different angles and views of the construction site, it was decided, among the aforementioned techniques, that the cascade object detector suits best for detecting hazardous areas in real-time. More specifically, based on the survey results (Section 2.1), the detector was used to identify the most hazardous areas due to welding, fire and grinding. As for the shaft opening case, the exact location is typically known in any construction project and can be obtained from the as-planned drawings. The following subsections discuss, using Matlab, how the cascade object detector is trained in the case of welding specifically and then tested.

2.3.1 Training a Cascade Object Detector for Welding

A database that consists of 56 pictures of welding was collected from different angles and views and from several construction sites as depicted in Fig. 3.

In every picture of the welding database, the region of interest (ROI) was selected using ‘Training Image Labeler’ by Matlab (Fig. 4).

Fig. 15: Welding pictures database

The output is a 1x56 structure array named ‘PositiveWelding’ with 2 fields: (1) the image file name and (2) the ROI bounding box. It is worth mentioning that the training process requires a set of pictures not containing welding or what is called negative images. These were stored in a folder for which the path was stored in a variable called ‘NegativeWelding’ as follows:

```
NegativeWelding = fullfile('C:\NegativeFolder')
```

The function *trainCascadeObjectDetector* was then used to train the welding detector and the resulting output is an XML file named ‘WeldingDetector.xml’ . The false alarm rate, the true positive rate and the number of cascade stages were respectively set to 0.1, 0.995 (default value) and 7 as shown below:

```
trainCascadeObjectDetector('WeldingDetector.xml',PositiveWelding,NegativeWe
lding,'FalseAlarmRate',0.1,'NumCascadeStages',7)
```

2.3.2 Testing the Trained Cascade Object Detector

In order to test the trained detector, a function called *CountWelders* was created. This function uses the generated XML file from training, takes as input captured images and visualizes and highlights with a rectangle identified welding activities. This is depicted in the code snippet below and Figure 5. The same procedure applies to other hazardous scenarios (fire and grinding).

```
function welders=CountWelders(I)
weldingDet = vision.CascadeObjectDetector('C:\ WeldingDetector.xml');
```

```
detection = step(weldingDet,I)
if (welders>1)
welders=size(detection,1)
LabeledI = insertObjectAnnotation(I, 'rectangle', detection, 'Welding');
figure, imshow(LabeledI), title('Detected Welding activities');
end
```

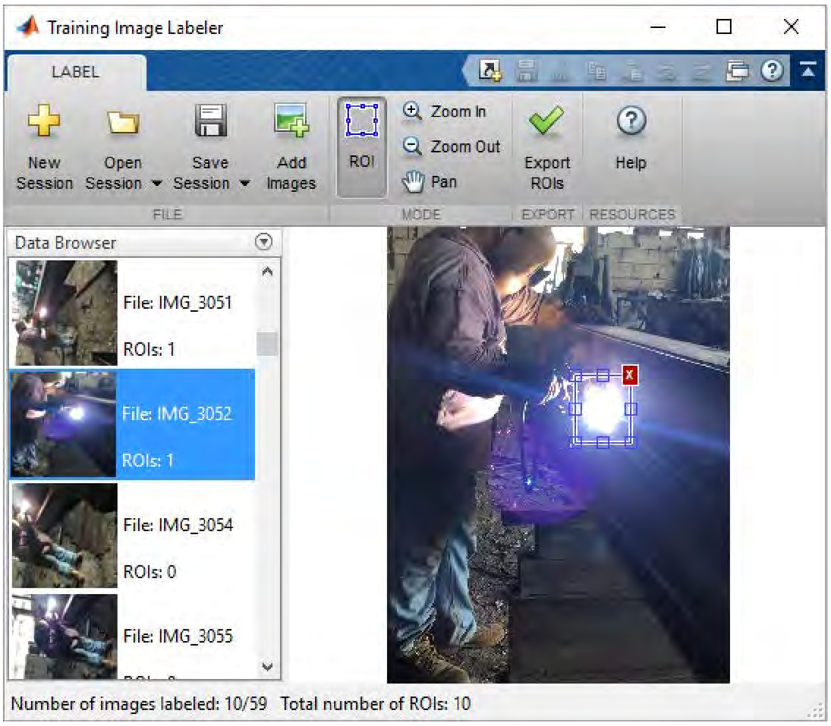


Fig. 16: Region of interest selection

One last step consists of refining the algorithm so that hazardous areas can be conveniently and rapidly identified from large sets of captured images. . In this case, a function was created as follows that takes the images as input and returns an array containing the number of detected welders.

```
function a=weldingDetector(folder)
filePattern = fullfile(folder, '*.jpg');
jpegFiles=dir(filePattern);
a=ones(1,length(jpegFiles));
for i=1:length(jpegFiles)
filename=jpegFiles(i).name;
fullfilename=fullfile(folder,filename);
im=imread(fullfilename);
a(i)=CountWelders(im);
end
```

3. EXPERIMENTS AND RESULTS

In order to confirm the practicality of the proposed method and in particular test the ability of the algorithm in detecting actual welding activities, several experiments were carried out on a construction site using the UAV (Fig. 6).

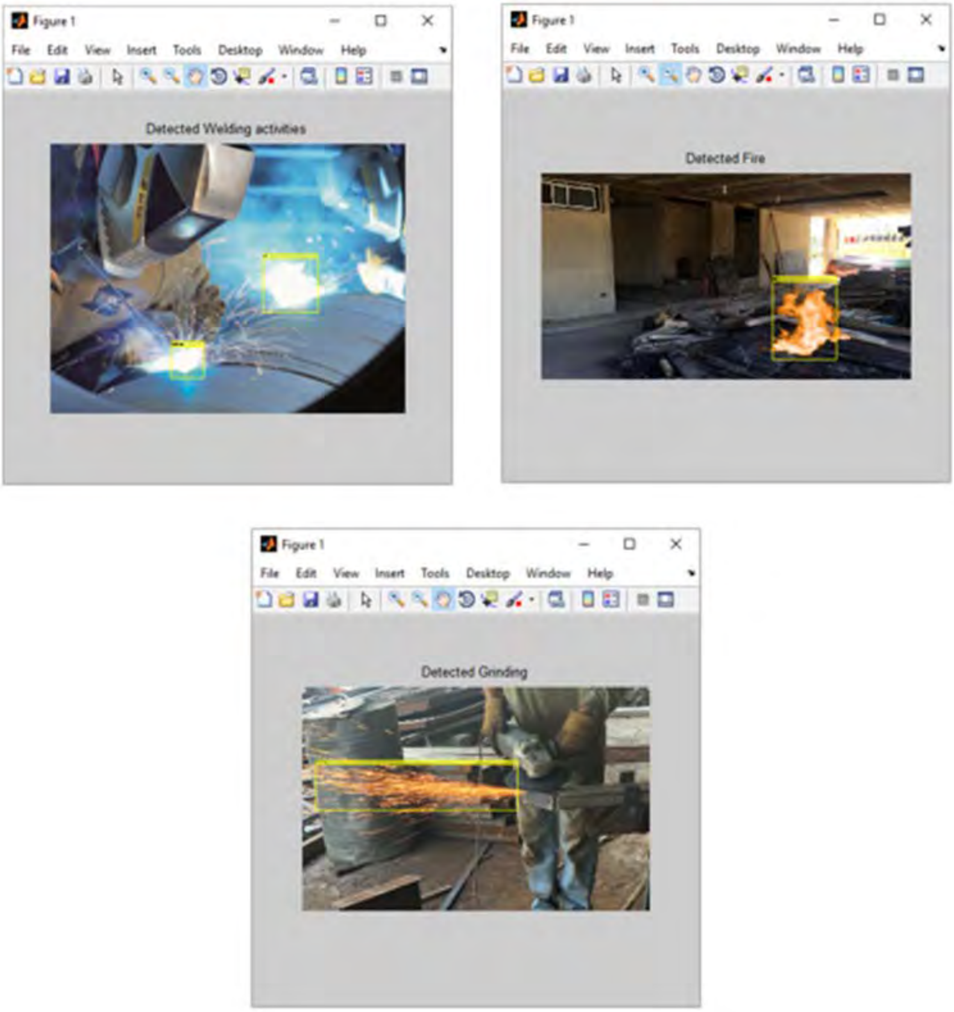


Fig. 17: Preliminary testing results

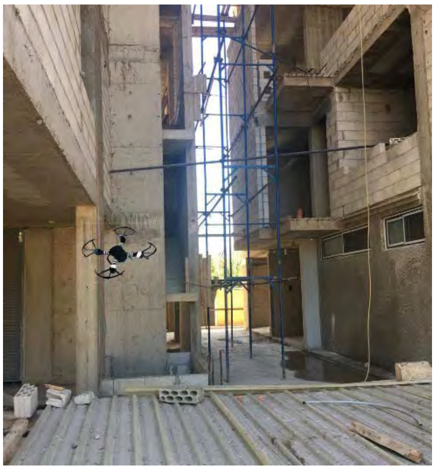


Fig. 18: Drone hovering over the construction

More specifically, two sets of 68 images were used whereby the first set contains one welding activity per image (i.e. positive images), while the other contains no welding activities (i.e. negative images).

3.1 Tests on Images with Welding Activities

In the first experiment performed on the images containing welding activities, the number of stages was set to 7 while the ‘False Alarm Rate’ had three different values of 0.05, 0.1 and 0.15. The number of false detections expectedly increased with the increase of the false alarm rate (Table 1).

Table 1: Variation of the number of detected welding activities in function of the false alarm rate for a number of stages equal to 7 – Welding Images

	Number of Detected Welding Activities											
False Alarm Rate	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**>10**
0.05	29	36	3	0	0	0	0	0	0	0	0	0
0.1	10	47	9	0	2	0	0	0	0	0	0	0
0.15	1	19	12	7	9	5	3	4	1	1	3	3

Three possible outcomes can possibly occur as shown in Table 2: (1) under prediction, when the algorithm fails to detect an existing welding activity, (2) correct prediction, when it detects the existing welding activity, and (3) false alarm, when it detects more than one welding activity .

Table 2: Results Summary (%)

False Alarm Rate	**0.05**	**0.1**	**0.15**
Under Prediction	42.65	14.71	1.47
Correct Prediction	52.94	69.12	27.94
False Alarm	4.41	16.18	70.59

In the second experiment, the 'False Alarm Rate' was set to 0.1 while the number of stages had three different values of 5, 7 and 9. In this case, the number of false detections decreased with the increase of the number of stages (Table 3).

Table 3: Variation of the number of detected welding activities in function of the number of stages for a false alarm rate equal to 0.1 – Welding Images

	Number of Detected Welding Activities											
Number of stages	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**>10**
5	0	20	17	12	5	5	2	1	0	0	2	4
7	10	47	9	0	2	0	0	0	0	0	0	0
9	30	36	2	0	0	0	0	0	0	0	0	0

3.2 Test on Images with no Welding Activities

The same procedure was repeated for the images not containing welding activities and the results of the first set of experiments are summarized in Table 4.

Table 4: Variation of the number of detected welding activities in function of the false alarm rate for a number of stages equal to 7 – Negative Images

	Number of Detected Welding Activities											
False Alarm Rate	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**>10**
0.05	61	6	1	0	0	0	0	0	0	0	0	0
0.1	45	10	4	5	3	1	0	0	0	0	0	0

0.15	11	18	13	7	4	2	3	4	1	1	2	2

The results of the second experiment are summarized in Table 5.

Table 5: Variation of the number of detected welding activities in function of the number of stages for a false alarm rate equal to 0.1 – Negative Images

	Number of Detected Welding Activities											
Number of Stages	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**>10**
5	7	20	14	12	5	5	2	1	0	0	1	1
7	45	10	4	5	3	1	0	0	0	0	0	0
9	65	2	1	0	0	0	0	0	0	0	0	0

4. CONCLUSION

In this paper, the detection of pre-defined hazardous areas was achieved using computer vision, in particular the Cascade object detector technique. The results, obtained from several experiments conducted on an actual construction site, highlighted the potential applicability of drones and computer vision techniques in automating safety inspections on construction sites.

Experimenting with the parameters of the algorithm showed a presence of a trade-off between improving the percentage of correct decisions and increasing the percentage of false alarms. Additionally, the proposed algorithm, in its current form, might occasionally confuse object sunlight reflection with a welding activity. Hence, future efforts necessitate the use of a larger training sample and improvements to the algorithm and its implementation to address the aforementioned limitations. Further research aims at fully automating the proposed system and will be achieved by (1) adopting an autonomous stable drone capable of safely circulating the jobsite along pre-defined paths, and (2) rapidly locating workers and alerting them of a nearby hazardous area.

5. REFERENCES

Alionte E. and Lazar C. (2015). A Practical Implementation of Face Detection by Using Matlab Cascade Object Detector. *Conference on System Theory, Control and Computing*, Cheile Gradistei, Romania, 785-790.

Carter G. and Smith D. S. (2006). Safety hazard identification on construction projects, *Journal of construction engineering and management*, 132(2), 197-205.

Ham Y., Han K. K., Lin J. J. and Golparvar-Fard M. (2016). Visual monitoring of civil infrastructure systems via camera-equipped Unmanned Aerial Vehicles (UAVs): a review of related works. *Visualization in Engineering*.

Health and Safety Executive, about HSE, Statistics, Industries, Construction, http://www.hse.gov.uk/statistics/industry/construction/#p1.

Irizarry J., Gheisari M. and Walker N. B. (2012). Usability assessment of drone technology as safety inspection tools. *Journal of information technology in construction*, 17, 194-212.

Kim H., Lee H., Park M., Chung B. and Hwang S. (2016). Automated hazardous area identification using laborer's actual and optimal routes. *Automation in construction*, 65, Elsevier Science, New York, 21-32.

Khoury, H. M., Chdid, D., Oueis, R., Elhajj, I., and Asmar, D. (2015). Infrastructureless approach for ubiquitous user location tracking in construction environments", *Automation in Construction*, 56, Elsevier Science, New York, NY, 47-66.

Kour A. (2015). Face Recognition using Template Matching. *International Journal of Computer Applications*, 115(8), 10-13.

Merlin website, QuadCopter UAV, http://merlin-digital.com/quadcopter-uav.html

Oueiss, R., Chdid, D., Khoury, H.M., Asmar, D, and Elhajj, I. (2012). Infrastructureless Inspection Process Automation in Construction, *Gerontechnology*, 11(2), International Society for Gerontechnology, Eindhoven, Netherlands, 92-98.

Seo J., Han S., Lee S. and Kim H. (2015). Computer vision techniques for construction safety and health monitoring, *Journal of Advanced Engineering Informatics*, 29(2), 239-251.

Shrestha K., Shrestha P. P., Bajracharya D. and Yfantis E. A. (2015). Hard-Hat Detection for Construction Safety Visualization, *Journal of Construction Engineering*, Volume 2015, Article ID 721380, 8 pages.

Yang J., Arif O., Vela P. A., Teizer J., and Shi Z. (2010). Tracking multiple workers on construction sites using video cameras. *Advanced Engineering Informatics*, 24 (4), 428-434.

THE TRAFFIC WARNING SYSTEM FOR CROSSROADS ON CONSTRUCTION SITE BASED ON COMPUTER VISION

Lingjing Liu, Xiaorong Zhang, Tongtong Li, Sheng Xu, Jun Wang, Dianchen Zhu, Hongyang Li & Yichuan Deng

South China University of Technology, Guangzhou, China

ABSTRACT: *Many studies have been done for improving the safety of construction industry. However, few focus on the safety of crossroads on construction sites. Due to the unreliable manual management, information lag, as well as continuously changing and complex working conditions, accidents happened frequently at the crossroads on the construction site. In order to address the aforementioned limitations, this paper presents a computer vision based traffic warning system designed specifically for the crossroads on construction sites. The main facilities of the system include a panoramic camera, a close-up camera, a central computer and a forewarning signal lamp device. The prototype developed uses the crossroad monitoring data to capture movement of vehicles. This study consists of seven modules and sets up the experimental platform through VS2013 and open CV. The study also utilizes the image processing and computer visual library in the open source of open CV to realize the algorithm of each module. With the algorithms we developed, the system is able to detect on-site vehicles, estimate speed, gather vehicle statistical information, and predict vehicle driving routes. According to the corresponding traffic rules of traffic crossroads on the construction sites, the system can identify unsafe situations to make forewarnings. Compared to other methods such as GPS and UWB, this computer vision-based system can provide traffic participants with information to support real time monitoring at complex crossroads. Test results showed that the evaluation of moving objects detection, tracking and simple classification can reach the accuracy of 90%. As it proves, the prototype system offers a potential approach to identify traffic risks of crossroads on the construction site and achieve safer and more effective traffic management on sites.*

KEYWORDS: *Construction Safety, Crossroads of Construction, Computer Vision, Forewarning*

1. BACKGROUND

There is no doubt that construction is one of the riskiest industries. As accidents of construction usually cause much loss, the safety of onsite crossroads arouses our attention. It was reported that there were 665 fatal traffic accidents in Anhui province, China, in the past two years, which took up 81% of the major accidents. Wenxing Zhang (2010) pointed out that the main problems of crossroads are the dynamic and complexity of construction sites, unreliable manual management and information lag. It is noteworthy that there are numerous accidents caused by the blind spots of the crossroads and differences of radius between inner wheels of large vehicles. However, the current observational methods are costly and time-consuming, which shows an immediate need to reduce the risks at crossroads in a timely manner.

Therefore, the objective of this paper is to realize real-time monitoring of different kinds of traffic participants at complex crossroads by computer vision. According to the existing traffic rules, the computer vision-based system can identify unsafe conditions and act to make forewarnings immediately, which reminds workers to keep away from the risks nearby. It’s worth mentioning that the system relies on existing facilities, which reduces the set-up cost and makes it easy to deploy.

2. RELATED WORK

2.1 The study on safety of crossroads on construction site

It is hard to identify the potential safety hazard in time due to the limitation of manual observation, especially in construction projects. Thus, the study on the construction vehicle monitoring system has drawn more and more attention. In order to monitor the motion of large vehicle timely and remotely, Cheu et al.(2004) designed a system to monitor container vehicles. Through GPS and sensors, the system can collect data and monitor the vehicles. Qiao et al. (2014) proposed a system for monitoring concrete transportation and heavy residue in carrier, which is helpful for controlling the vehicles on construction sites. Yunbo Liu et al. (2015) presented a method for monitoring vehicles on construction sites which can be used for identifying pedestrian, vehicles and the scale of vehicles. Liu et al. (2015) presented a method for warning the over-speeded. To avoid accidents at crossing, Ranjitkar et al. (2014) developed a device (RTK GPS) to monitor the location and speed of vehicle on real time, which can obtain the result quickly. Yan (2007) proposed a method for identifying overloaded vehicles without stopping the vehicles. Notably, previous works show that many studies have been done for pedestrian or vehicles themselves, while few focus on the crossroads. Compared with other places, the crossroads on construction sites have many domain-specific issues in safety monitoring such as continuously changing and complex environments and limited visibility of pedestrian.

2.2 The study on traffic warning system for construction sites

Traffic accidents occur frequently at the crossroad because of the blind spots and limitation of supervision of human. Hence it is necessary to use the traffic warning system to provide warnings to drivers and pedestrians. Many automatic alarming devices have been designed according to our literature study. Wang (2016) invented an automatic traffic alarming device for the pedestrian crossing without signal light, which provides a two-way warning method. Zhang (2015) invented a traffic reminder device which is based on Internet of things. This device does not rely on city electricity, and it solves the complex line connecting problems. Cao (2015) invented a device for avoiding the vehicles collision so as to solve the collision problems at the crossroads. This device not only provides collision warning, but also provides the drivers the methods for dealing with the collision. Toyota Motor Corporation (2014) invented a new device to satisfy the need of driving assistant. Han (2015) use ARM to provide a driving forewarning method for fatigue driving. Comparatively speaking, computer vision based system can provide a richer set of information about construction sites. With such information, workers can fully understand the scene to identify the unsafe acts and conditions nearby.

2.3 The application of computer vision technology in the construction

Nowadays computer vision technologies have been widely used in construction management such as productivity analysis and progress monitoring. Gong (2009) established a computer vision based video interpretation model for automated productivity analysis of construction operations. To improve the timeliness of supervision, Lin et al. (2013) used mobile RFID system to perform supervision. Yang et al. (2015) made use of still images, time-lapse photos, and video streams to monitor construction performance. Brilakis et al. (2011) developed an automatic image recognition technique to track the engineering entity objects, which can be used to analyze the efficiency and detect path conflict. In order to improve the detection accuracy and reduce the human error, Park (2012) introduced construction worker detection in video frames for initializing vision trackers, which can reduce the error caused by human subjectivity. Gong (2014) introduced an intelligent video computer method for automated productivity analysis of cyclic construction operations, which offers a new way of gathering data for improving on-site operations. Liu (2013) applied embedded video and image recognition technology in overhead transmission line surveillance. It is possible for the operation personnel to determine the security level of the transmission line in real time and adjust the inspection strategy. Obviously, the method is objective and efficient. It provides a real-time monitoring with higher accuracy and less cost. It can also address the limitations of human manual observation.

2.4 Research gaps

According to our literature study, we summarized the following research gaps:

1. At present, there are comprehensive researches on drivers, pedestrians and traffic vehicles. However, they did not take the crossroad on construction sites into consideration. Because of the continuously changing working environments, workers have to face potential safety risks frequently in the construction process. Combined with these unique conditions, the situations at crossroads become more complex.

2. The existing technology still depends on the drivers' own judgment. It is an essential reason for the low efficiency of management. For example, previously, workers should understand scenes using their own perceptual capability and evaluate the information with rules, guidelines or their experiences to identify unsafe unique situations. Therefore, a more intelligent system according to the onsite situation should be developed. Computer vision approaches has the ability of extracting perceptual information and classifying unsafe conditions immediately.

3. Most existing methods require a complicated terminal, so we propose a new way to simplify the system by using computer vision technology and existing facilities such as cameras and personal computers.

3. RESEARCH METHODOLOGY

3.1 Overview

The crossroads onsite are unique and dynamic, which increases the risks on construction sites. These complex conditions call on workers' perceptual and cognitive capabilities. Hence the purpose of our system is to make sure that forewarnings are effective and timely. The system is developed based on the technology of image processing and computer vision, which can regulate vehicular traffic at the crossroads on construction sites. Through our algorithm, the system can achieve the goal of real-time vehicles detection, tracking, speed monitoring, vehicle information gathering, and vehicles driving direction judgment. According to the corresponding traffic rules of traffic crossroads on the construction site, the system can identify potential risks conditions and act to issue forewarnings.

3.2 Basic Process

This system consists of seven modules and uses monitor to capture the video of moving vehicle at the crossroads. This study sets up the experimental platform through VS 2013 and open CV. The study also utilizes the image processing and computer visual library in the open source of open CV to realize each module's algorithm. The system framework is shown in figure 1:

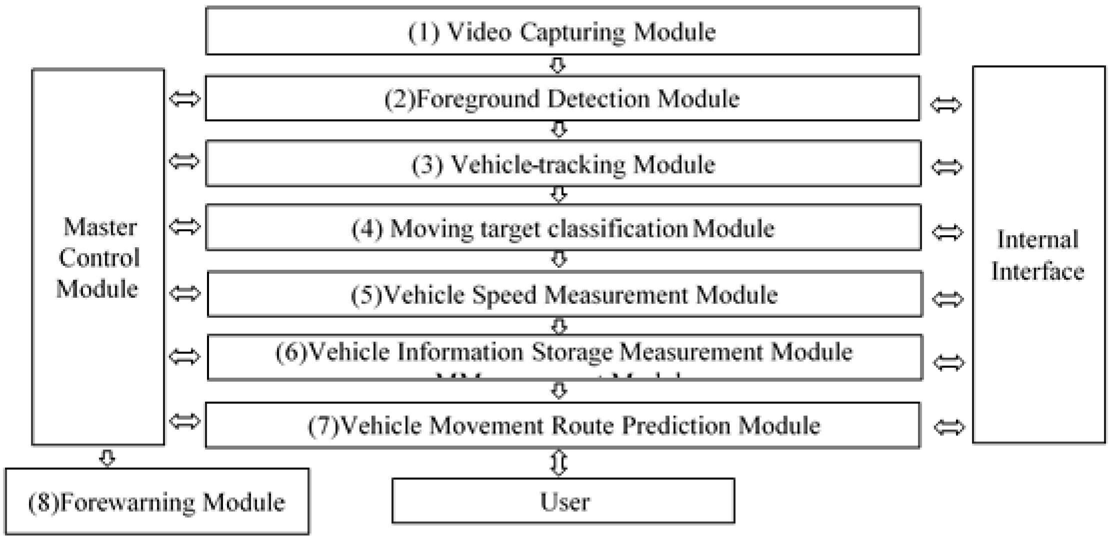


Fig. 1: Component modules of system

1. Video capturing module: this module uses real-time monitoring to collect the scene information of crossroads. In construction, video cameras are usually used for observing on-site activities to provide alive image for management. There is a high-definition network camera above the major crossroads to collect video information of vehicle. Panoramic camera is used to capture video images and send them to foreground detection module. The system can obtain 2D imagery data from these cameras. However, Joonoh Seo et al. (2015) proposed that the range of 2D cameras varies depending on lens disparity and adjusted exposure values. In addition, the system needs to consider mobility and portability of devices because of changing working environments. The cameras could not cover all scenes. Thus, a close-up camera is used for snapshot.

2. Foreground detection module: as the figure 2 shows, this module utilizes Gaussian mixture model to extract the foreground image of vehicles. The motion target will be detected through the video sequence images.

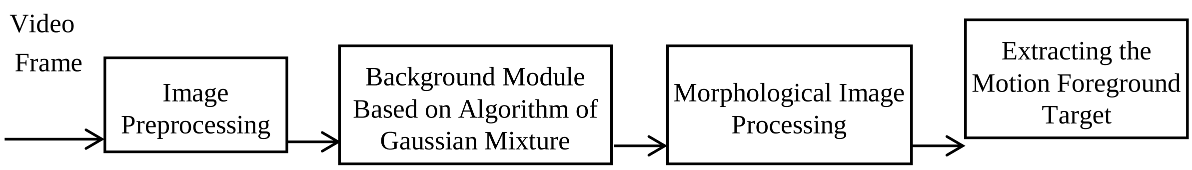


Fig. 2: Foreground detection module of system

3. Vehicle-tracking module: the main function is to distill and track moving objects in real-time through the video and calculate the trajectory of the moving object to provide data for the next target recognition and motion analysis. A tracking method based on region and feature and the mass of the vehicle is used to form a tracking area. In this area, the centroid of the external rectangle is used as the tracking feature to realize the tracking of multi targets in the surveillance video.

4. Moving target classification module: the main function is to collect the images of moving targets (pedestrians, engineering vehicles and private cars) to establish the sample library. Machine learning algorithm is adopted for supervised learning, and the moving target classification module is developed. As the figure 3 shows, the support vector machine (SVM) and the histogram of oriented gradients (HOG) classifiers are used to classify the moving targets by extracting the color features as well as direction gradient histogram. The SVM is a supervised learning model. It is widely used for classification and regression analysis. This system uses SVMs to perform classifying images. As Vapnik suggested that SVMs achieve higher accuracy than traditional query refinement schemes after just three to four rounds of relevance feedback (2014). This is also true of image segmentation systems, including those using a modified version SVM that uses the privileged approach. (2015) The HOG is a feature descriptor used in computer vision for the purpose of object detection. At the IEEE, Qiang Zhu, Shai Avidan, Mei-Chen Yeh, and Kwang-Ting Cheng presented an algorithm to significantly speed up human detection using HOG descriptor methods. (2006)Their method uses HOG descriptors in combination with the cascading classifiers algorithm normally applied with great success to face detection.

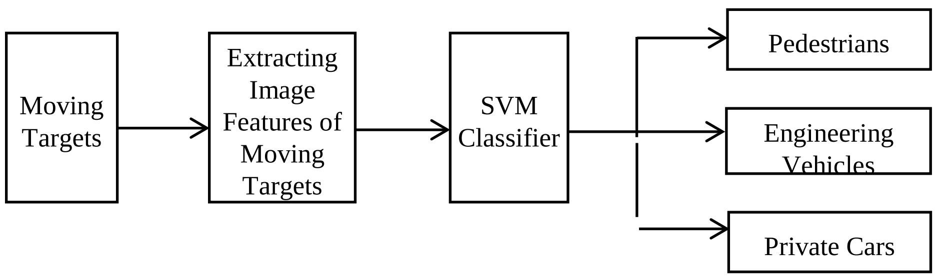


Fig. 3: Classification module of system

5. Vehicle speed measurement module: the main function of the module is to estimate the speed of vehicles. It utilizes frame rate of video and the displacement of the vehicles' center point to calculate the driving speed. There are two detection lines to establish a detection area. When the vehicle passes the detection area, the system is able to use the length of the area, the time of vehicle passing through the area and the video frame rate to calculate the average speed. When the speed is higher than the reference value we set, it will transfer the information to the warning module.

6. Vehicle information storage measurement module: this module establishes a database to storage the information of the vehicle and identifies the vehicles and the license plates to allow workers to manage the vehicles that pass through the construction. It analyzes the image, judges the vehicles according to its size and

discrete degree of shape, and saves the vehicle information into the database.

7. Vehicle movement route prediction module: this module utilizes Kalman filter to predict the driving direction of vehicles which enter the crossroad and to provide information for the vehicle driving forewarning module. By the centroid coordinates of the moving target and the running speed, the Kalman filter algorithm is used to predict the position of a 0.5 second gap for the moving target, so as to achieve the goal of predicting moving direction of moving objects. Remarkably, Kalman filter is an algorithm widely used in various fields, including robot navigation, radar systems, and missile tracking. In the field of computer vision, this filter is used to predict to the various states of moving targets. The algorithm works in a two-step process. In the prediction step, the Kalman filter produces estimates of the current state variables, along with their uncertainties. Once the outcome of the next measurement is observed, these estimates are updated using a weighted average. The algorithm is recursive and can run in real time. Henry Medeiros et al. used a cluster-based Kalman filter to track object in wireless camera networks. They employed a cluster-based Kalman filter to aggregate information, which is able to achieve tracking accuracy comparable to the centralized tracking method. (2008) Erik Cuevas et al. also proposed the usage of Kalman filter in the vision tracking. They considered the capacity of the Kalman filter to allow small occlusions and also the use of the extended Kalman filter to complex movements of objects. (2005)As it proves, Kalman filter has the potential to make the localization method more efficient.

3.3 System hardware

The main facilities of the system include a panoramic camera, a close-up camera, a central computer and a forewarning signal lamp device. There is a high-definition network camera above the major crossroads to collect video information of vehicle. Panoramic camera is used to capture video images and send them to foreground detection module. Close-up camera is used for snapshot. The prototype developed uses the crossroad monitoring data to capture movement of vehicles. The hardware of system is shown in figure 4.

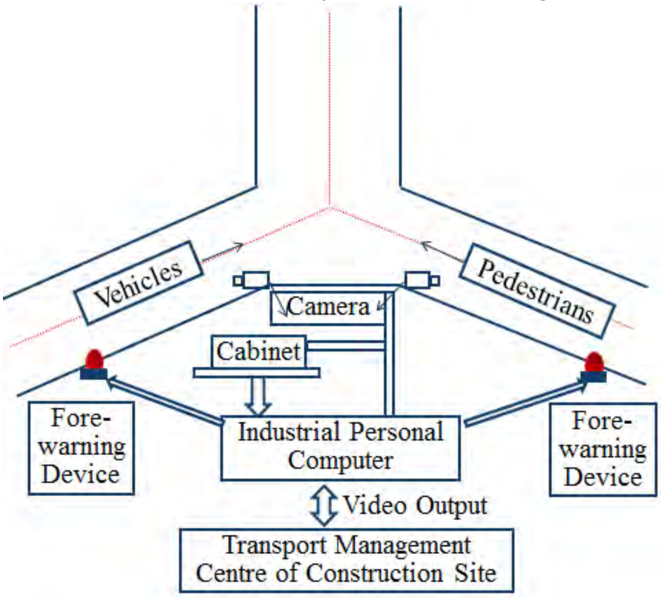


Fig. 4: The hardware of system

As the figure 5 shows, the detection of vehicle is captured by high-definition color camera. Through the video capture card, the analog signal is digitally conversed into a digital image. The processing object is the sequences of real images from the video capturing card input.

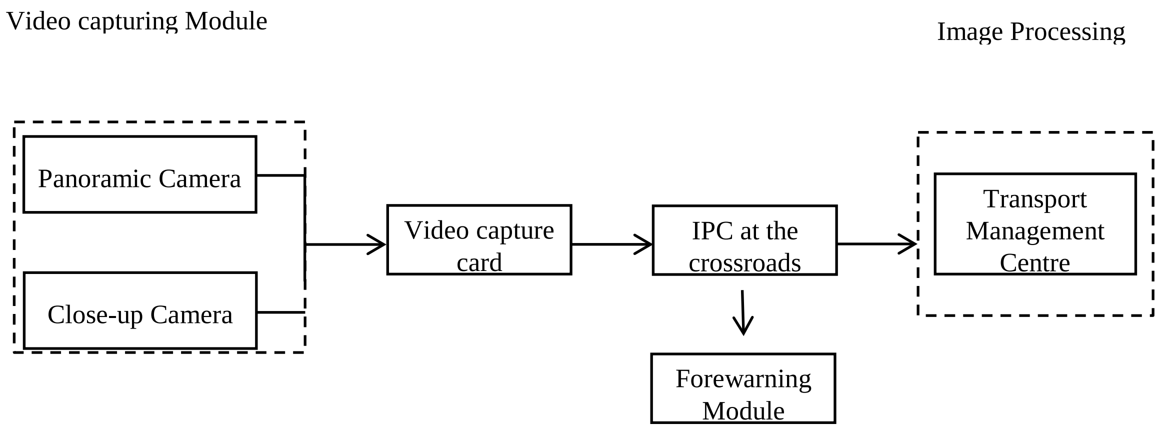


Fig. 5: The hardware design

4. RESULTS

Firstly, when vehicles or pedestrians go through the crossroads of construction sites, the camera will capture video images and send them to foreground detection module. And then, the foreground detection module utilizes Gaussian mixture model to extract the foreground image of vehicles is shown in figure 6.

(a) Original image (b) Processed image

Fig. 6: Foreground image

Secondly, after extracting the foreground images, the system will detect moving targets. According to the characteristics of the construction vehicles set in the image recognition, unauthorized vehicles can be found. As shown in figure 7

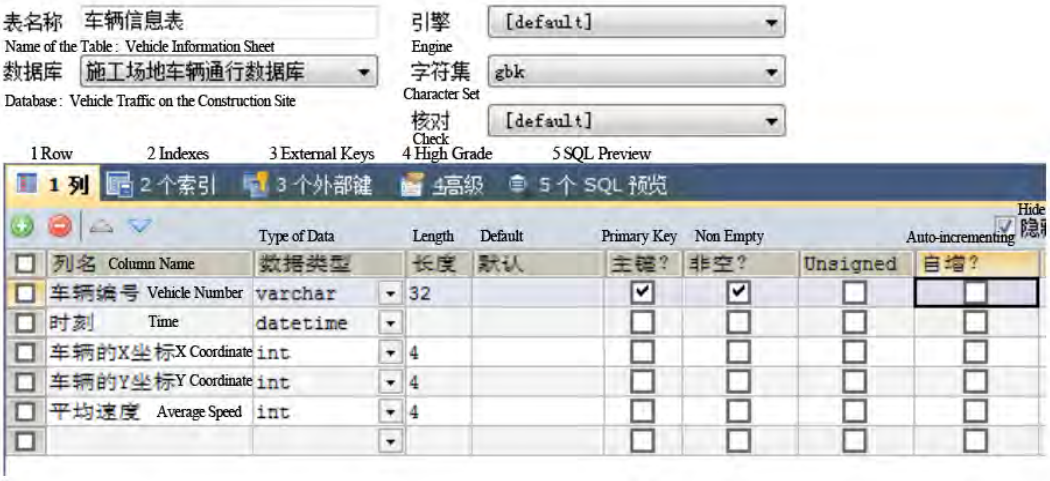
(a) Engineering vehicles *(b) Private cars* *(c) Pedestrians*

Fig. 7: Targets identification

When the speed is higher than the reference value we set, it will transfer the information to the warning module. The vehicle identification and velocity measurement are shown in figure 8.

Fig. 8: Velocity measurement

Thirdly, we build a database shown in figure 9 to collect the vehicle information through the storage module. This module carries out the information management of construction transport vehicles to achieve the intelligent control of the vehicle. The system applies HOG descriptors to describe the interest points on images of moving targets and the SVM classifier uses a set of spatio-temporal patterns of descriptors to classify actions. Thus, the system only



needs to regard objects of interest as the points, and the record points information to build the database.

Fig.9: Vehicle information storage interface

After detection, the vehicle movement route prediction module starts working. As the figure 10 shows, the blue point represents the centroid of the target, red point represents the predicted location in 0.5 second and the white line shows the predicted path. The Kalman filter is a recursive estimator. Therefore, only the estimated state from the previous time step and the current measurement are needed to computer the estimate for the current state.

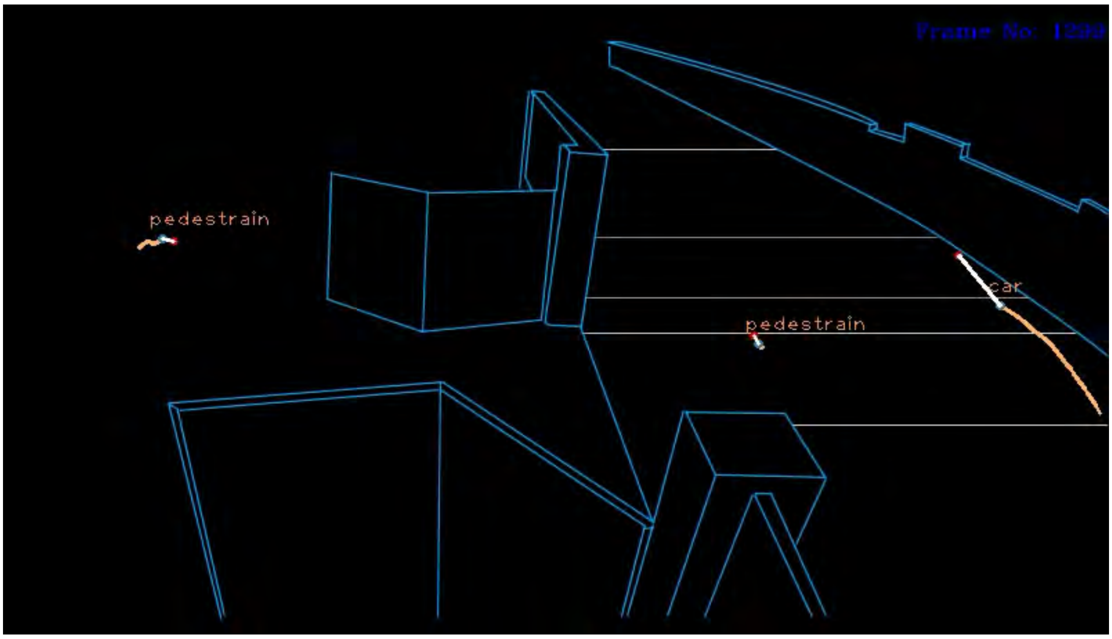


Fig. 10: Path discrimination renderings

Finally, combined with the modules mentioned above, our system can issue forewarning for the following functions: 1) Over speeding. 2) Irrelevant targets passing through the specific part of road. 3) Targets entering or about to enter a prohibited area. 4) Traffic accident occurs nearby. The results are shown in figure 11. As shown in figure a, when the workers stand at the crossroads, they cannot see the engineering vehicles nearby. At the same time, the system is able to identify the risks and make forewarnings. As shown in figure b, irrelevant (private car) target that is over-speed passing through the crossroads triggers the forewarnings.

(a) Blind areas warning (b) Over speed warning

Fig. 11: Warning for dangerous situation

5. DISCUSSIONS AND FUTURE WORK

Most existing methods of construction vehicles monitoring require a complicated terminal. Therefore, the development of a simple device to monitor the construction vehicles attracts a lot of attention. In this paper, our system introduces the collision warning method and takes full advantage of surveillance cameras on construction sites. The system makes an image analysis on imaging objects of video, which can be regarded as the innovation and deepening of image identification. It increases the intelligent degree of the management at the crossroad on construction sites. According to the forewarning system developed in this paper, the following main functions can be achieved:

1. Real-time tracking and classification of pedestrians and vehicles.

The system interface is shown in figure 12. Window 1 shows the original surveillance video. Window 2 shows the tracking targets. Window three shows the foreground image. Window four shows the prediction of vehicle movement route. According to the window 2, the system achieves many goals including vehicle detection, tracking, velocity measurement and classification. This function solves the problem of inefficient regulation, which requires less manpower expense and makes management more efficiency.

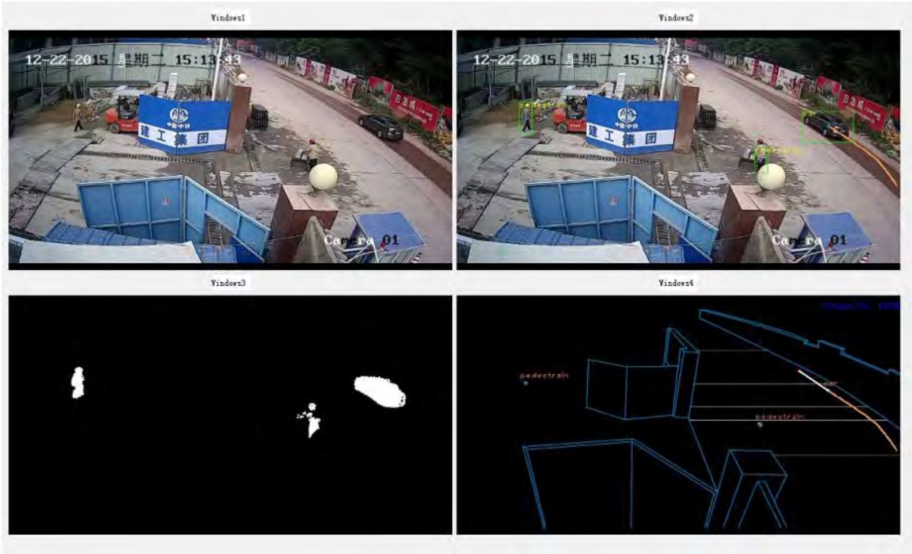


Fig. 12: System interface

2. Classification of engineering vehicles and private cars.

Through the image sequence in the video, the moving targets are detected based on the foreground detection module and moving target classification module. According to the characteristics of the engineering vehicles, the system is able to determine whether it is a unauthorized vehicle.. The function relieves the chaos caused by unauthorized vehicles effectively. It also can remind the pedestrians of the dangers on construction sites.

3. Velocity measurement

This function achieves the goal of velocity measurement. When the speed is higher than the reference value we set, it will transfer the information to the forewarning module. This module will give warning to drivers, which can reduce the probability of accidents.

4. Vehicle information statistics

This function establishes a database to storage the information. It makes use of digital image processing and pattern recognition technology to detect vehicle models, license plate and other related information. Carrying out the information management on construction sites will make control of the vehicle more intelligent.

5. Vehicle driving direction prediction and forewarning

Given that on-site conditions, the aforementioned modules are used to achieve the function of vehicle driving direction prediction. Through this function, the system is able to detect the potential unsafe situations and make forewarnings. It reduces the probability of accidents caused by difference of radius between inner wheels or blind areas.

As it proves, the system offers a potential approach to identify traffic risks of crossroads the construction sites and achieve safer and more effective on-site management. However, there remain some limitations to be settled. First of all, the system cannot recognize the extreme cases like shelter problems and bad weather. Secondly, there are no commonly acceptable rules available for identification. Thirdly, there are no comprehensive datasets for studies in construction. For some parts of the challenges, adding some supplementary devices like radar can improve the accuracy of the system. Nevertheless, others indicate there is a need for further research in these areas.

6. CONCLUSIONS

This system is developed based on the technology of image processing and computer vision. By collecting the video data of vehicles and using stationary algorithm, the system achieve many goals including vehicle detection, tracking, velocity measurement, vehicle information statistics and vehicle driving direction prediction. The system utilizes the existing monitoring devices, hence provides less input of assets for site managers. The system provides accurate data for the vehicle movement route prediction module and forewarning module. We have tested the system on 90 video footage from construction sites, and test results show that the evaluation of moving objects detection, tracking and simple classification can reach the accuracy of 90%. We summarize following conclusions:

1. Utilizing the digital image processing and pattern recognition technology, the system can identify the vehicle, license plate and the speed. Through video monitor, the system can identify unsafe conditions and warn traffic participants to make forewarnings in real time.

2. The system improves the efficiency of manual management, which makes the crossroads management of construction site more intelligent. Firstly, it relieves the chaos caused by non-construction vehicles effectively. Secondly, it can remind people of the dangers of the construction vehicles.

3. The system is reliable, timely and efficient, which results in a desired warning effect. The computer vision-based techniques the system use are regarded as effective solutions complementary to time-consuming. Accordingly, the accident caused by the blind area and people's poor awareness of security can be avoided to achieve a satisfactory effect of forewarning.

4. The system is environmentally-friendly and economic. The system utilizes the existing monitoring devices, which provides less input of assets for the contractors.

Generally speaking, this paper provides a potential approach and fresh opportunities to practitioners in adopting advanced knowledge to manage on-site construction.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the support by the China Postdoctoral Science Foundation, Grant No. 2016M592498, and the support by National Natural Science Foundation of China, Grant No. 71501074.

REFERENCES

Zhang, W. X. (2010). Tentative discussion on safety management problems existing in architectural construction site and countermeasures. Shanxi Architecture.

BaoJie Yan,& J Xie. (2007). Study on Management of the Overload Transportation without Car Stopping. *International Conference on Transportation Engineering*,3785-3790.

Brilakis I, Park M W,&Jog G. (2011). Automated vision tracking of project related entities. *Advanced Engineering Informatics*,25(4):713-724.

Changxuan Cao. (2015). Preventing device and method about Vehicle collision. CN104325931A[P].

Cheu R L, Wang H, Lee D H, et al. (2004). Incorporating Telemetry and Car-Following Data for Real-time Monitoring of Container Trucks[C] *Applications of Advanced Technologies in Transportation Engineering. Eighth International Conference.*

Gao Liu,& Yihui Zeng. (2013). Embedded Video and Technology of Image Recognition in the Intelligent Monitoring of Overhead Transmission Lines. *Application of computer system*, (11):58-61.

Gong, J., & Caldas, C. H. (2009). Computer vision-based video interpretation model for automated productivity analysis of construction operations. *Journal of Computing in Civil Engineering*, 24(3), 252-263.

Gong, J., & Caldas, C. H. (2014). An Intelligent Video Computing Method for Automated Productivity Analysis of Cyclic Construction Operations. *International Workshop on Computing in Civil Engineering* (pp.64-73).

Hai-chuan Han,& San-peng Deng. (2015). Research on Driver Fatigue Early Warning Method Based on ARM. *International Journal of Plant Engineering and Management*, 20(4):250-254.

Jiaqi Wang. (2016). Automatic traffic warning device for pedestrian crossing of non-signal lamp. CN105225475A[P].

Lin, Y. C., Su, Y. C., Lo, N. H., & Chen, W. F. C. A. (2013). Application of mobile rfid-based safety inspection management at construction jobsite. *Radio Frequency Identification from System to Applications.*

Lingya Zhang. (2015). Traffic crossed prompting device based on Internet of things. CN204856904U[P].

Maowei Qiao, Yongbin Wei,& GUO Kaifeng. (2014). Operation monitoring system for construction vehicle. CN203786549U[P].

Park, M. W., & Brilakis, I. (2012). Construction worker detection in video frames for initializing vision trackers. *Automation in Construction*, 28(15), 15-25.

Ranjitkar P, Nakatsuji T, Gurusinghe G S, et al. (2014). Car-Following Experiments Using RTK GPS and Stability Characteristics of Followers in Platoon. *PLOS Negl Trop Dis*, 10(4):470-1.

Toyota Motor Corporation. (2014). Driving auxiliary device. CN104221066A[P].

Wenxing Zhang. (2010). Tentative discussion on safety management problems existing in architectural construction site and countermeasures. *Shanxi Architecture*,36(35):196-197.

Yang, J., Park, M. W., Vela, P. A., & Golparvar-Fard, M. (2015). Construction performance monitoring via still images, time-lapse photos, and video streams: now, tomorrow, and the future. Advanced Engineering Informatics, 29(2), 211-224.

Yunbo Liu, Quanzhen Xu& Jun Ma. (2015). Vehicle monitoring method in construction site. CN104463905A[P].

Seo, J. O., Han, S. U., Lee, S. H., & Kim, H. (2015). Computer vision techniques for construction safety and health monitoring . Advanced Engineering Informatics, 29(2), 239-251.

Vapnik, V. (2014) Invited Speaker. IPMU Information Processing and Management
Barghout, Lauren. (2015) .Spatial-Taxon Information Granules as Used in Iterative Fuzzy-Decision-Making for Image Segmentation. Granular Computing and Decision-
Making. Springer International Publishing. 285-318.

Zhu, Q., Yeh, M. C., Cheng, K. T., & Avidan, S. (2006). Fast Human Detection Using a Cascade of Histograms of Oriented Gradients. (Vol.2, pp.1491-1498).

Medeiros, H., Park, J., & Kak, A. C. (2008). Distributed object tracking using a cluster-based Kalman filter in wireless camera networks.Selected Topics in Signal Processing IEEE Journal of, 2(4), 448-463.

Cuevas, E., Zaldivar, D., & Rojas, R. (2005). Kalman filter for vision tracking.

NOVEL OCCUPANCY SENSING IN LIVING SPACES – EVALUATION OF APPROACHES USING HUMAN MOTION ANALYSIS TECHNIQUES AND THEIR EXTENSIONS

Arun Rajagopalan & Ivan Mutis

Illinois Institute of Technology, Chicago

ABSTRACT: *This paper proposes a novel occupancy sensing system based on human motion analysis and evaluates several motion analysis techniques which use vision sensors to collect data on humans in living spaces. Most automated occupancy sensing systems that are prevalent today analyze either the environmental conditions, like room temperature and pressure, or data from entities in the room, such as states of computers and routers, to make human occupancy predictions. The assorted environmental sensors used in conventional occupancy sensing systems are difficult to calibrate and may output unreliable data due to sensor drifts and inadequate or incorrect commissioning. The distributed nature of these systems, which fuse data from myriad scattered sensors to assess occupancy, hardens and complicates the maintenance process. Also, since little emphasis is placed on observing humans directly, the estimations of customary sensing systems are often inaccurate. Erroneous occupancy estimation leads to poor control of building resources such as HVAC (Heating, Ventilation and Air-conditioning) and lighting systems. To address the aforementioned issues, this paper puts forth a lean, vision based system that estimates number of occupants and recognizes their activities using segmented stacked history of human movements over transient intervals. Thus the system described in this paper provides more meaningful, insightful information about the state of living spaces than existing sensing systems, by extracting activity contexts alongside occupancy numbers, which can be used to build occupancy management solutions of better sophistication. Currently, our system achieves nearly 83% accuracy while recognizing fewer activities although improvement is needed in cases involving multiple activities.*

KEYWORDS: *Motion Analysis, Occupancy Sensing, Pose Estimation*

1. INTRODUCTION

Detecting and tracking human occupants for the purpose of automated control of services offered in buildings is called Occupancy Sensing. Studies show that nearly 20% of all the energy generated in the world is used to comfort living spaces in buildings, with the help of HVAC (Heating, Ventilation and Air-Conditioning) and illumination systems (Pérez-Lombard, Ortiz and Pout, 2008). But not all of that energy is spent usefully. Conditioning the air present in unoccupied living spaces has made almost 40% of US domestic building energy go waste, claims another study (Meyers, Williams and Matthews, 2010). An accurate occupancy sensing system would obviate such energy wastage and thus help reduce the cost incurred in the maintenance of buildings by large. For instance, if the sensing system estimates zero occupancy in a room with good confidence, it can proceed to update the central cooling or lighting system of the building, advising to stop serving the room. But the performance and capabilities of occupancy sensing systems that have been in use till date are limited.

1.1 Overview of existing systems

Early HVAC control systems installed in commercial buildings function based on time of the day, assuming peak occupancy in pre-defined office hours and nil occupancy in non-office hours and weekends. Due to differential usage of office space (For example, meeting spaces may not be used as regularly as cubicles) and flexible work timings, these primitive systems do not provide best energy savings possible (Ekwevugbe *et al.*, 2013). Other customary control systems use only temperature, pressure and humidity sensors for sensing, which often leads to incorrect decisions since data from these sensors are not accurately descriptive of human activity. Some vision based and wearable sensor based occupancy estimation setups monitor humans directly but they are plagued by privacy and weak adoption issues respectively. Latest HVAC control systems use sensor fusion based approach to occupancy sensing, where inputs from many types of sensors, ranging from normal environmental sensors to wearable sensors are weighed in to make occupancy estimation. While these fusion based systems offer good improvement in energy savings, they are not so facile to install and maintain. Moreover, none of these systems address the needs of advanced living space management solutions such as precise oxygen level moderation in buildings to help prevent ‘sick building syndrome’, where people experience health and comfort effects proportional to time spent in buildings.

1.2 Overview of proposed system

The proposed occupancy sensing technique is based on Human Motion Analysis (HMA), which primarily aims to identify the activities of building occupants. Human Motion Analysis, also termed Human Activity Recognition, has been an active research area for years. It has several pragmatic applications including but not limited to intelligent occupancy analysis, human-computer interaction, surveillance of indoor and outdoor spaces, gaming, telepresence, health care, content based video retrieval and so on (Zhu *et al.*, 2009; Li, Zhang and Liu, 2010; Aggarwal and Ryoo, 2011; Masood *et al.*, 2011; Yang and Tian, 2012; Paul, Haque and Chakraborty, 2013; Shotton *et al.*, 2013). This area of computer vision research is particularly challenging and the results achieved thus far are not very appealing due to the narrow capabilities and affordability of the tools that were available for research. Now with the advent of advanced tools that are affordable, like cheap vision sensors and open-sourced Machine Learning libraries, we can witness increased interest and more stable solutions being introduced for solving the problem of human motion analysis.

To recognize activities, our system uses a special kind of spatio-temporal representation called Motion History where only the changes happening in the scene over a specified short period of time are stacked together and highlighted, with their intensity inversely proportional to the time elapsed since their occurrence. This Motion History is completely anonymized and the only characteristics that are used for activity recognition are the height, width and the pose of the human body under observation, thereby addressing privacy concerns. Once the Motion History is recorded, it is segmented to extract regions of interest (ROI) that have high possibility of containing a single Human Motion Map (Motion histories of individual human figures are called Human Motion Maps). The number of individual Human Motion Maps (HMMs) give us the occupant count estimate. Finally, these HMMs are input to a series of Computer Vision techniques that identify the activity being performed in each of the maps.

Our technique is thus able to estimate not only the count of occupants, but also the activities that are going on in the area under study. Since our system has the most comprehensive occupancy data, it has the capability to surpass all the current systems in terms of energy efficiency and can also address exquisite use-cases such as oxygen/aerosol level moderations in buildings based on current activity types and frequencies for utmost comfort.

2. LITERATURE SURVEY

2.1 Survey on existing occupancy sensing systems

Traditional occupancy detection systems have significant drawbacks due to their operating style and components involved. A majoring of them perform sparse sensing which is sensing using room conditions that are determined by few or more specialized sensors with limited capabilities. Sparse sensing, albeit being quick, is not very effective in near-precise estimation of human occupancy. (Ekwevugbe *et al.*, 2013) gives a great summary of such traditional systems in existence. Detailed survey of several prominent approaches towards occupancy sensing is as follows.

2.1.1 Systems using states of existing IT equipment or power consumption patterns

Melfi (2011) proposed calculating the number of active IT equipment in the room, using their MAC and IP addresses to estimate the occupancy status. Their method also observed strokes from keyboard and mouse events among other inputs. The system was able to attain only 40% accuracy at floor level and 80% accuracy at building level. This is because the system failed to detect people who were not using computers and more than one IT resource could have been used by every occupant. An alternative method proposed by (Brown *et al.*, 2012) recorded the power utilization patterns of room equipment including computers and employed it for occupancy detection. They attached portable temperature sensors to the periphery of computers and periodically monitored the computer status to detect its duty cycles with a precision of up to 97%. This system was also incapable of accounting for transient occupants who were sans computers.

2.1.2 Systems using passive infrared (PIR) sensors or its combinations

Most of the commercial operational occupancy sensing systems use PIR sensors for controlling illumination in buildings, owing to their affordability and simplicity. Detection of moving targets in the living space is easy with the usage of PIR sensors since they constantly monitor heat energy emitted by objects in the room and report changes of magnitude greater than a specified threshold, but these sensors cannot identify stationary targets. Also it is tough to estimate occupancy numbers with PIR sensors since differentiating humans from other targets is not straightforward. Hence the possibility of false-offs (turning off services during non-zero occupancy) is high in PIR sensor based systems (Delaney, O’Hare and Ruzzelli, 2009).

For improving the accuracy, PIR sensors are often used in conjunction with other sensors. Telephone sensors were coupled with 3 PIR sensors to build a Bayesian belief network where occupancy in rooms was modelled with a

Markov chain. The system was only able to detect occupants with an accuracy of 76%, not count them. To estimate occupancy numbers with good confidence, especially in open-plan offices, (Khee Poh Lam *et al.*, 2009; Khee Poo Lam *et al.*, 2009; Dong *et al.*, 2010) put forth systems that harnessed carbon-di-oxide and acoustic sensors alongside PIR sensors. Their approaches used Information theory for feature selection and three machine learning algorithms namely support vector machines, artificial neural networks and hidden Markov model for feature fusion where the hidden Markov model gave the best accuracy at 73%.

2.1.3 Systems using vision and wearable sensors

Several systems (Tomastik, Lin and Banaszuk, 2008; Benezeth *et al.*, 2011) proposed sensing using vision sensors, but their approaches could face privacy concerns from occupants, since they use unprocessed video streams to get data for occupancy estimation. Also the aim of their systems was to detect only the occupancy numbers and not the activities being performed. Other novel systems like the one featured (Korhonen, Pärkkä and Van Gils, 2003) uses wearable sensors for occupancy sensing, but the success of such systems depend mainly on the inclination of occupants to adopt the usage of sensors.

2.2 Survey on existing Human Motion Analysis techniques

2.2.1 Volume based methods

Traditional RGB cameras have been mostly used for HMA research in the past, where test inputs are usually videos which are sequences of 2D frames with RGB channels in chronological order. Volume based methods involving space and time have been extensively used for identifying actions in these videos, by calculating semblance between separate activity volumes. Various techniques have been proposed to measure this semblance, differing in their detection and representation of spatio-temporal volumes (Dollár *et al.*, 2005; Laptev, 2005, 2008). Also, some methods model human activities as trajectories where the actions are construed by the movement patterns of a set of cardinal joints of human physique (Sun *et al.*, 2009). But all these approaches suffer from the fact that rapid detection and reliable tracking of joints in a physique are not so facile.

2.2.2 Challenges associated with Human Motion Analysis

The common challenges associated with human pose estimation and detection from monocular RGB streams range from forward-backward ambiguities, self-occlusion, general unconstrained motions, kinematic singularities (uncertainty on reachable points) among others, described with great detail in (Sminchisescu, 2006). Several researchers claim that trying to recognize human activity from single camera RGB videos is an arduous problem due to the considerable loss of information, mainly depth details, in these traditional videos (Sminchisescu, 2006; Aggarwal and Xia, 2014). Hence, many recent systems use stereo or depth camera setup for observing human motion.

2.2.3 Depth sensing based methods

Recording and mapping depth information allows for easy identification of differences between the variety of actions (Kim *et al.*, 2014) that humans perform, which would have been difficult to observe from a traditional single camera output. Owing to this feature of depth maps, computer vision researchers show a lot of interest lately on human motion analysis using depth information (Li, Zhang and Liu, 2010; Jiang *et al.*, 2012; Wang *et al.*, 2012; Aggarwal and Xia, 2014; Cai, 2015; Xu, Lee and Lee, 2015). Out of all the literature that feature depth maps, one of the few that we consider to display good potential is (Li, Zhang and Liu, 2010), which employs a 3D silhouettes or Bag-of-points in 3D method to depict human poses from several three dimensional points of depth maps. To recognize human activities, the study uses an action graph to model the sampled points and it claims that results from their experiments using depth map 3D silhouettes are far better than that achieved with 2D silhouettes. Other commendable research works are featured in (Yang, Zhang and Tian, 2012) which uses depth motion maps (DMM) and (Kim *et al.*, 2014) which utilizes descriptors called depth motion appearance (DMA) and depth map history (DMH) to aid the motion analysis. (Dai, Zheng and Li, 2007; Gavrila and Munder, 2007) improve the conventional pre-processing step of pedestrian detection to a more robust one, using multiple inputs based on shape, texture and depth. But these systems overlook the fact that depth streams usually have significant range limitations. Depth sensors that offer a decent range of more than 20 meters are several times costlier than its RGB counterparts and hence sensing large living spaces using depth sensors may not be affordable for everyone. Also it is noteworthy that many of the challenges linked with RGB stream based analysis are either irrelevant for human motion analysis or have already been addressed by the recent advancements in the field of Deep Learning.

3. IMPLEMENTATION DETAILS

Our system architecture has 3 major modules namely History Acquisition, Actor Segmentation and Activity Prediction. The system's control flow follows the same order - starting from History Acquisition, passing on to Actor Segmentation and finally ending with Activity Prediction. The modules are coupled loosely to facilitate easy extension or modification of the system workflow in the future. Fig. 1 shows the architecture diagram of our proposed system. The implementation details of each module along with information on their associated components are as follows.

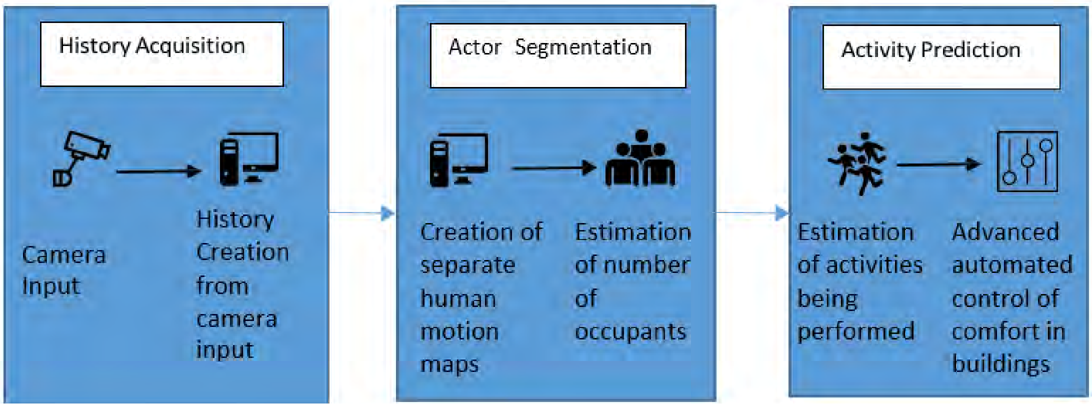


Fig. 19 Architecture diagram of the system

3.1 History Acquisition

This module is responsible for generating motion history from video streams. As evident from the survey of existing systems, two types of video streams that are commonly used for history generation are traditional RGB streams from monocular cameras and depth streams from Infrared or stereo cameras. Both types have their own merits and demerits – Monocular or conventional cameras cost lesser and the RGB streams that they generate have better range when compared to depth cameras and their streams respectively. Depth streams provide lot more information, a whole new dimension of distance from the camera to be exact, than RGB streams. Yet they suffer from poor range, especially when the relatively affordable Infrared cameras are employed. Stereo depth cameras use two RGB sensors that target the same scene and are separated by a small distance, instead of using Infrared rays. These cameras estimate depth by the process of triangulation, with matching points in both RGB images captured by the sensors. Stereo cameras have higher depth range than Infrared cameras, but they are further costlier. We initially used Orbbec Astra Pro infrared depth camera for the implementation of this module, but since our testing environment was moderately large with 30ft X 30ft dimensions, the output depth streams had significant noise. Also the OpenNI library used to interact with the depth sensor was not flexible with programming language requirements and the functionalities that it offers. Hence we decided to employ a conventional RGB camera for living space data collection.

On startup, the module initializes itself with the current state of the living space using first frame captured by the RGB camera. All state changes that are detected in the subsequent frames post initialization are represented by change masks which have non-zero values only at pixel positions where recent changes have occurred. A change mask is created by subtracting the current frame from previous frame and hence we will have change masks for

$$\text{history\_record}(x,y) = \begin{cases} \text{current\_timestamp}, & \text{if change\_mask}(x,y) \mathrel{!=} 0 \\ \text{zero}, & \text{if change\_mask}(x,y) = 0 \text{ (or)} \\ & \quad \text{current\_timestamp} - \text{history\_record}(x,y) > n+d \\ \text{history\_record}(x,y), & \text{otherwise} \end{cases}$$

all frames except the first, each of which will have same dimensions as the camera frames. Using the change masks, we create or update a two-dimensional array that we call the history record, using the following function.

Here n denotes the maximum duration for which each activity is tracked and d denotes the extended duration after n for which activity history should be maintained. While existing motion history based systems use only n, this paper introduces the new constant d, which enables the system to combine several human activities together and represent human behaviors using extended motion histories. The history record will thus be constantly updated using every change mask and at any given instant, the history record will have the current timestamp at recent change locations, older timestamps at previous change locations and zeros at locations where no change has occurred during the past n+d seconds. We chose 5 and 10 as n and d values respectively during our experiments. The motion history that we are concerned about is the visual representation of this history record. The intensity of a pixel in motion history representation is inversely proportional to the difference between the current time stamp and the timestamp at corresponding location in history record. Simply, only the recent change locations appear bright in the motion history representation. Past change locations fade slowly to zero while unchanged locations remain at zero. The amount of fading applied at each pixel location is directly proportional to the time elapsed since the occasion of change at that location. Fig. 2 and Fig. 3 display examples of extended motion histories that are generated by this module.

Fig. 2 Extended motion history of single occupant indicating two hand wave action occurring more than once.

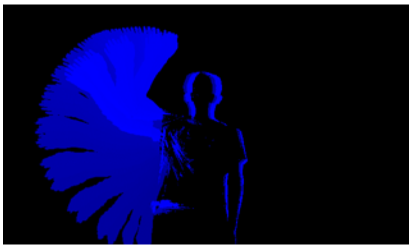


Fig. 3 Extended motion history of single occupant indicating the whole hand wave or the bidding adieu behavior.

3.2 Actor Segmentation

The motion history representation obtained from the acquisition module may incorporate information on multiple occupants or actors and may even have movements that cannot be construed as human. We need to segment the motion history to get individual motion maps and then identify potential human maps which can be used to estimate occupancy numbers and infer activities. Multiple maps may exist in a single frame of motion history in the form of unconnected non-overlapping blocks or connected overlapping blocks. We chose seeded region growing method for segmentation since it gives the best results in both cases of connected and unconnected blocks.

Region growing methods assume that adjacent pixels have higher probability of having comparable values. They compare each pixel with its neighboring pixels and mark all of them that satisfy a similarity condition as belonging to the same cluster. We used an 8 x 8 neighborhood lattice for our experiments with the similarity criterion of intensity difference being less than a threshold of 10% of peak intensity value. In the seeded region growing method, we need to input the pixel locations from which segmentation has to be initiated. These pixel locations are called seeds and the choice of seeds are crucial for exact segmentation of individual maps. Hence, to ensure a balanced selection, we compute histogram (intensity distribution) of the motion history and pick the locations of peaks and valleys as seeds. Once the region growing process terminates, we perform iterative erosion and dilation followed by a custom flood filling mechanism to fill any map area that is not completely grown into a solid block yet. After flood filling, we detect the resultant solid map blocks and draw detection boxes around them. It is likely that we might have multiple detections around each map due to inconsistencies that had stemmed in during the region growing and flood filling processes. To discard all duplicate detections and have only one box spanning the entire motion map block, we use non-maximum suppression. In the end, areas under the finalized detection boxes are cropped to get individual motion maps. To differentiate between human and non-human motion maps, we extracted Histogram of Gradients (HOG) descriptors from 50,000 examples of both types and trained a polynomial kernel SVM with hard negative mining. HOG is a representation of distribution of pixel strength gradients and edge directions in maps and hard negative mining is the process of iteratively re-training the SVM classifier with the misclassified examples of human / non-human motion maps. Our system can thus provide an estimate of occupancy number at the end of this module, which is the number of individual motion maps that are classified as human. Fig. 4 shows the entire workflow of this module.

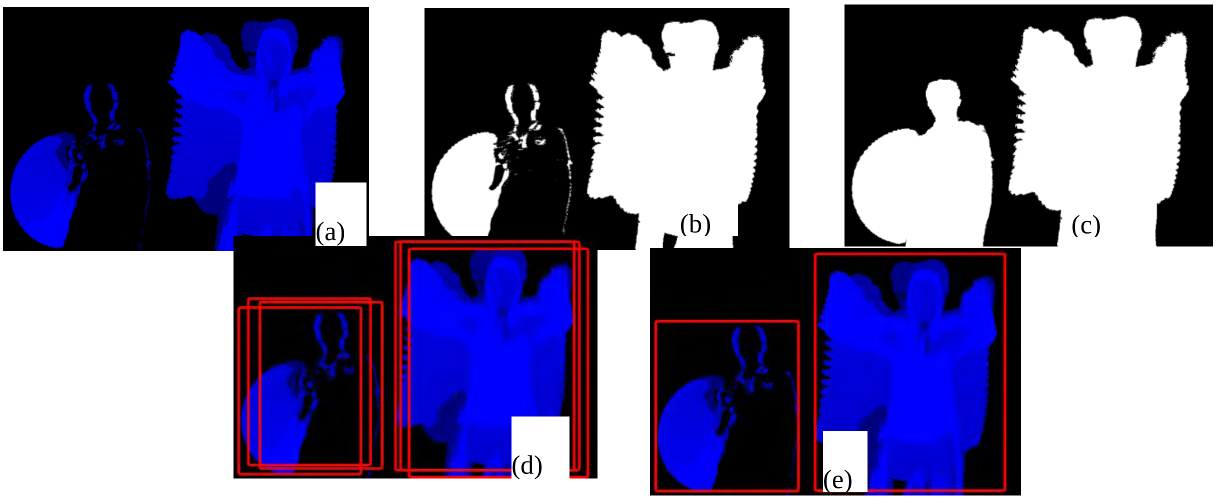


Fig. 4 Segmentation of individual Human Motion Maps. (a) shows input to the segmentation module, (b) shows the result of seeded region growing (c) shows the result of iterative dilation/erosion and flood filling, (d) shows the detection boxes around solid map blocks and (e) shows the final segmented Human Motion Maps. The map on the left shows a human lifting dumbbell and the map on the right shows a human performing squats.

3.3 Activity Prediction

Several Computer Vision Techniques can be used for activity prediction, once the individual Human Motion Maps are extracted from motion history. We employed four popular techniques of differing complexity, to identify activities from HMMs, based on the knowledge accrued from activity templates or example trainings. At the end of this module, we will have richer data about the state of the living space being monitored.

Histogram & Template Based: HOG descriptors and regional color histograms of Human Motion Maps are used for identifying the activities in Histogram based method. The maps are divided into four equal parts and color histograms computed for each part are concatenated together as a single histogram which is then appended with the map's HOG descriptors to form a feature vector. This feature vector is compared with the vectors extracted in a similar fashion from stored activity templates. Similarity is measured by Chi-squared distance and the template that is least distant to the current HMM denotes the activity being performed. Template based method works similarly where it uses the OpenCV's template matching functionality to find the best matching activity template. The approaches of these methods are simple which allows them to be implemented easily and operate nimbly.

Boosted Cascade training: Boosted cascade training works on the principle that several weak, rapid classifiers can be cascaded to build a single strong classifier. Also called Haar training, this method was first proposed in (Viola and Jones, 2001) and was improved in (Lienhart and Maydt, 2002) and (Liao *et al.*, 2007). The approach is to train a classifier with positive and negative examples of the entity to be identified. Positive examples are the images that have the entity present in them and negative examples are those that miss it. Once trained, the classifier can detect the presence of entity in unseen images by making several quick subsequent classifications. For our system, we trained the classifier successively to predict several activities using motion histories captured from many angles.

We also used OpenCV to create more synthetic examples from original examples.

Deep Learning: This is the latest and the most advanced of all the approaches discussed till now. The aim of deep learning is to let the machines/computers identify patterns on their own, by providing them huge troves of data. Several deep learning algorithms are inspired by biological systems (such as convolutional neural network which mimics the visual recognition process followed by human brain) and hence they tend to solve problems with intuition and give the best accuracy possible. We used the cutting-edge deep learning library open-sourced by Google called TensorFlow, for training a convolutional neural network classifier using positive and negative images of human motion maps, similar to those used for training a cascade classifier. Since training a deep learning classifier is compute-intensive, we used AWS EC2 GPU instances instead of using lab computers. We used a modified version of the CIFAR-10 (a classical machine learning problem) codebase that is available with TensorFlow for training our classifier.

4. RESULTS AND DISCUSSION

Our test environment was a modest community space with the dimensions of 30ft X 30 ft. We used a single RGB camera setup to record video streams and utilized the motion histories of 10 commonly observed actions for preparing our system. Ideally, the system should be able to recognize all of the 10 activities that it has knowledge on. F1 scores were used to compare the performances of motion analysis techniques after specific stages of classifier trainings/template additions. F1 score is the harmonic mean of precision and recall where precision is the ratio of number of correct positive predictions to the number of all positive predictions and recall is the ratio of number of correct positive predictions to the sum of number of correct positive predictions and incorrect negative predictions. The F1 scores logged during our experiments are presented in Table 1.

Table 1: F1 scores for various types of motion analysis systems

	Number of human motion categories that can be identified by the system				
	Two	**Four**	**Six**	**Eight**	**Ten**
Histogram Based	0.6241	0.5579	0.413	0.3867	0.3718
Template Based	0.5935	0.6149	0.5728	0.4712	0.4906
Haar training Based	0.6416	0.5932	0.5296	0.5639	0.5522
Deep Learning Based	0.8277	0.768	0.6891	0.6728	0.6596

It is apparent from the results that Histogram and Template based approaches perform the least despite their merits because even small variations in orientation and structure of the current motion histories significantly increase their distances from the stored templates. Cascade classifier performed reasonably well when it was trained to detect only a few activities but its performance degraded on subsequent trainings with the examples of more activities. Deep Learning method gave the best results of all owing to its flexibility and scalability. Fig. 5 shows a visual comparison of the performance of activity prediction techniques.

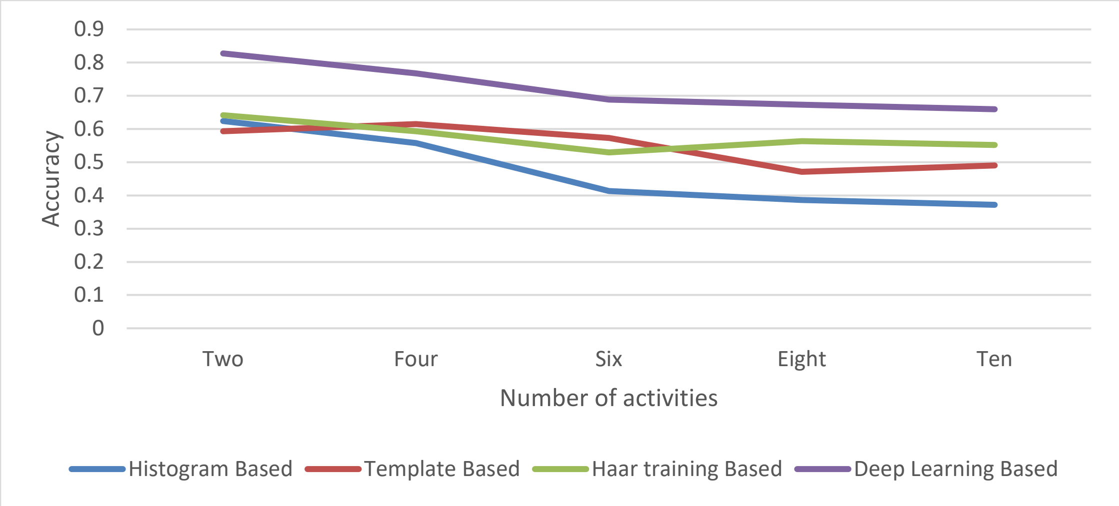


Fig. 5 Comparison of activity prediction accuracies achieved from several motion analysis techniques

5. CONCLUSION

A novel approach to occupancy sensing based on Human Motion Analysis is proposed in this paper. The approach uses a special representation called motion history, which enables us to estimate not only the number of occupants, but also the activities that are being performed by the occupants. With such detailed information about the state of living spaces, we can build advanced automation systems that provide utmost comfort in buildings while adopting the highest levels of energy efficiency. The paper also delineates the implementation methodologies that were followed when a functional system based on this approach was built. Four different activity prediction techniques were evaluated as part of this research and the evaluation results are included in this paper as well.

6. FUTURE WORK

The next phase of research would mainly focus on improving the accuracy of the current system by fine tuning the deep learning based activity prediction module. Also, the existing sensing system will be trained to recognize more human activities and even human behaviors. Research on a new taxonomy of human motion is already underway, which when completed would provide us an activity hierarchy for every recognized activity. This hierarchy could be used to predict the next possible activity based on current activity, thus giving our control systems a glimpse of the future.

7. ACKNOWLEDGEMENTS

The authors would like to acknowledge the support of Wagner Institute for Sustainable Energy Research.

8. REFERENCES

Aggarwal, J. K. and Xia, L. (2014) ‘Human activity recognition from 3D data: A review’, *Pattern Recognition Letters*. Elsevier B.V., 48, pp. 70–80. doi: 10.1016/j.patrec.2014.04.011.

Aggarwal, J. and Ryoo, M. (2011) 'Human activity analysis: A review', *ACM Computing Surveys (CSUR)*, 43(3), p. 16:1-16:43. doi: 10.1145/1922649.1922653.

Benezeth, Y., Laurent, H., Emile, B. and Rosenberger, C. (2011) 'Towards a sensor for detecting human presence and characterizing activity', *Energy and Buildings*, 43(2–3), pp. 305–314. doi: 10.1016/j.enbuild.2010.09.014.

Brown, N., Bull, R., Faruk, F. and Ekwevugbe, T. (2012) 'Novel instrumentation for monitoring after-hours electricity consumption of electrical equipment, and some potential savings from a switch-off campaign', *Energy and Buildings*. Elsevier B.V., 47, pp. 74–83. doi: 10.1016/j.enbuild.2011.11.023.

Cai, X. (2015) 'Attribute Mining for Scalable 3D Human Action Recognition', *MM '15 Proceedings of the 23rd ACM international conference on Multimedia*, pp. 1075–1078.

Dai, C., Zheng, Y. and Li, X. (2007) 'Pedestrian detection and tracking in infrared imagery using shape and appearance', *Computer Vision and Image Understanding*, 106(2–3), pp. 288–299. doi: 10.1016/j.cviu.2006.08.009.

Delaney, D. T., O'Hare, G. M. P. and Ruzzelli, A. G. (2009) 'Evaluation of Energy-efficiency in Lighting Systems Using Sensor Networks', *Proceedings of the First ACM Workshop on Embedded Sensing Systems for Energy Efficiency in Buildings*, pp. 61–66. doi: 10.1145/1810279.1810293.

Dollár, P., Rabaud, V., Cottrell, G. and Belongie, S. (2005) 'Behavior recognition via sparse spatio-temporal features', *Proceedings - 2nd Joint IEEE International Workshop on Visual Surveillance and Performance Evaluation of Tracking and Surveillance, VS-PETS*, 2005, pp. 65–72. doi: 10.1109/VSPETS.2005.1570899.

Dong, B., Andrews, B., Lam, K. P., Höynck, M., Zhang, R., Chiou, Y. S. and Benitez, D. (2010) 'An information technology enabled sustainability test-bed (ITEST) for occupancy detection through an environmental sensing network', *Energy and Buildings*. Elsevier B.V., 42(7), pp. 1038–1046. doi: 10.1016/j.enbuild.2010.01.016.

Ekwevugbe, T., Brown, N., Pakka, V. and Fan, D. (2013) 'Real-time building occupancy sensing using neural-network based sensor network', *IEEE International Conference on Digital Ecosystems and Technologies*, pp. 114–119. doi: 10.1109/DEST.2013.6611339.

Gavrila, D. M. and Munder, S. (2007) 'Multi-cue pedestrian detection and tracking from a moving vehicle', *International Journal of Computer Vision*, 73(1), pp. 41–59. doi: 10.1007/s11263-006-9038-7.

Jiang, W., Zicheng, L., Ying, W. and Junsong, Y. (2012) 'Mining Actionlet Ensemble for Action Recognition with Depth Cameras', *IEEE Conference on Computer Vision and Pattern Recognition (CVPR)*. doi: 10.1109/CVPR.2012.6247813.

Kim, D., Yun, W., Yoon, H. and Kim, J. (2014) 'Action Recogntion with Depth Maps Using HOG Descriptors of Multi-view Motion Appearance and History', *UBICOMM*, (c), pp. 126–130.

Korhonen, I., Pärkkä, J. and Van Gils, M. (2003) 'Health Monitoring in the Home of the Future', *IEEE Engineering in Medicine and Biology Magazine*, 22(3), pp. 66–73. doi: 10.1109/MEMB.2003.1213628.

Lam, K. P., Höynck, M., Dong, B., Andrews, B., Chiou, Y., Benitez, D. and Choi, J. (2009) 'Occupancy detection through an extensive environmental sensor network in an open-plan office building', *IBPSA Conference*, pp. 1452–1459. Available at: http://www.ibpsa.org/proceedings/BS2009/BS09_1452_1459.pdf.

Lam, K. P., Höynck, M., Zhang, R., Andrews, B., Chiou, Y.-S., Dong, B. and Benitez, D. (2009) 'Information-theoretic environmental features selection for occupancy detection in open offices', *Building Simulation 2009, 11th International IBPSA Conference*, pp. 1460–1467.

Laptev, I. (2005) 'On space-time interest points', *International Journal of Computer Vision*, 64(2–3), pp. 107–123. doi: 10.1007/s11263-005-1838-7.

Laptev, I. (2008) 'Learning realistic human actions from movies', *CVPR*, p. 26 pages in all.

Li, W., Zhang, Z. and Liu, Z. (2010) 'Action Recognition Based on A Bag of 3D Points.pdf', *Computer Vision and Pattern Recognition Workshops (CVPRW), 2010 IEEE Computer Society Conference on*, pp. 9–14.

Liao, S., Zhu, X., Lei, Z., Zhang, L. and Li, S. (2007) 'Learning Multi-scale Block Local Binary Patterns for Face Recognition', *Advances in Biometrics*, pp. 828–837. doi: 10.1007/978-3-540-74549-5_87.

Lienhart, R. and Maydt, J. (2002) 'An extended set of Haar-like features for rapid object detection', *Proceedings. International Conference on Image Processing*, 1, pp. 900–903. doi: 10.1109/ICIP.2002.1038171.

Masood, S. Z., Ellis, C., Nagaraja, A., Tappen, M. F., Laviola, J. J. and Sukthankar, R. (2011) 'Measuring and reducing observational latency when recognizing actions', *Proceedings of the IEEE International Conference on Computer Vision*, pp. 422–429. doi: 10.1109/ICCVW.2011.6130272.

Melfi, R., Rosenblum, B., Nordman, B. and Christensen, K. (2011) 'Measuring building occupancy using existing network infrastructure', *2011 International Green Computing Conference and Workshops, IGCC 2011*. doi: 10.1109/IGCC.2011.6008560.

Meyers, R. J., Williams, E. D. and Matthews, H. S. (2010) 'Scoping the potential of monitoring and control technologies to reduce energy use in homes', *Energy and Buildings*. Elsevier B.V., 42(5), pp. 563–569. doi: 10.1016/j.enbuild.2009.10.026.

Paul, M., Haque, S. M. E. and Chakraborty, S. (2013) 'Human detection in surveillance videos and its applications - a review', *EURASIP Journal on Advances in Signal Processing*, 2013(1), p. 176. doi: 10.1186/1687-6180-2013-176.

Pérez-Lombard, L., Ortiz, J. and Pout, C. (2008) 'A review on buildings energy consumption information', *Energy and Buildings*, 40(3), pp. 394–398. doi: 10.1016/j.enbuild.2007.03.007.

Shotton, J., Fitzgibbon, A., Cook, M., Sharp, T., Finocchio, M., Moore, R., Kipman, A. and Blake, A. (2013) 'Real-time human pose recognition in parts from single depth images', *Studies in Computational Intelligence*, 411, pp. 119–135.

Sminchisescu, C. (2006) '3D Human motion analysis in monocular video techniques and challenges', *Proceedings - IEEE International Conference on Video and Signal Based Surveillance 2006, AVSS 2006*. doi: 10.1109/AVSS.2006.3.

Sun, J., Wu, X., Yan, S., Cheong, L., Chua, T. and Li, J. (2009) 'Hierarchical Spatio-Temporal Context Modeling for Action Recognition', pp. 2004–2011. Available at: http://www.lv-nus.org/papers%5C2009%5C2009_C_16.pdf.

Tomastik, R., Lin, Y. and Banaszuk, A. (2008) 'Video-based estimation of building occupancy during emergency egress', *Proceedings of the American Control Conference*, pp. 894–901. doi: 10.1109/ACC.2008.4586606.

Viola, P. and Jones, M. (2001) 'Rapid object detection using a boosted cascade of simple features', *Computer Vision and Pattern Recognition (CVPR)*, 1, p. I--511--I--518. doi: 10.1109/CVPR.2001.990517.

Wang, J., Liu, Z., Chorowski, J., Chen, Z. and Wu, Y. (2012) 'Robust 3D action recognition with random occupancy patterns', *Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)*, 7573 LNCS(PART 2), pp. 872–885. doi: 10.1007/978-3-642-33709-3_62.

Xu, H., Lee, Y. and Lee, C. (2015) 'Activity Recognition Using Eigen-joints based on HMM', *URAI*, pp. 300–305.

Yang, X. and Tian, Y. (2012) 'Eigenjoints-based action recognition using naive-bayes-nearest-neighbor', *Computer Vision and Pattern Recognition …*, pp. 14–19. doi: 10.1109/CVPRW.2012.6239232.

Yang, X., Zhang, C. and Tian, Y. (2012) 'Recognizing actions using depth motion maps-based histograms of oriented gradients', *Proceedings of the 20th ACM international conference on Multimedia - MM '12*, (c), p. 1057. doi: 10.1145/2393347.2396382.

Zhu, G., Yang, M., Yu, K., Xu, W. and Gong, Y. (2009) 'Detecting video events based on action recognition in complex scenes using spatio-temporal descriptor', *Proceedings of the seventeen ACM international conference on Multimedia - MM '09*, p. 165. doi: 10.1145/1631272.1631297.

Part VII: Data Visualization and VR

BIM BASED VIRTUAL REALITY ENVIRONMENT FOR ENERGY CONSUMING BY END-USERS

Zhuoqian Wu*, Llewellyn Tang, Eugene Ch'ng, Shu Tang, Chao Chen, Weiqing Zheng

Department of Architecture and Built Environment, University of Nottingham, Ningbo, 315100, China

ABSTRACT: *Energy consumption is a global issue which is closely related to human behaviors. Virtual Reality environment is an ideal tool for people to learn energy management skills which is easily to use even for the aged. Various studies have been done to visualize the energy which is difficult to imagine and quantify but few methods provide an immersive 3D virtual world for energy. Meanwhile, ensuring the accuracy of the energy consumption presented in the virtual reality environment is a challenge.*

This paper presents a way to build a high immersive virtual reality environment for end-users to sense energy. Proposed virtual reality environment is based on Building Information Modelling (BIM) and a popular game engine. BIM are used to create the 3D model and simulate the energy consumption. The application of BIM enhance the accuracy of the model and energy performance results comparing with traditional 2D CAD method. The BIM data can be transferred into game engine automatically. A person can experience realistic first-person situations and control the appliances. The timestamped power consumption data of every facility and every room will be provided which educate the users a better usage of the appliances and thus help change the residents' usage patterns. It expected to allow the users adding or reducing the appliances. Moreover, the usage pattern can recorded and sent back to the designers automatically for a better design. A further study is to test this system in a pilot project.

KEYWORDS: *Building Information Modelling, Built Environment, energy optimization, end-user, Virtual Reality.*

1. INTRODUCTION

Reduction of the energy consumption and the natural resource depletion are required in the building life cycles as the architecture, engineering and construction (AEC) industry has been criticized as a major energy consumer and carbon emitter. Buildings account for close to 40% of the total energy consumption and 36% of greenhouse gas emissions (European Commission Buildings, 2015). A great deal of effort have been made on the design, construction, operation and their integrated processes, but traditional 2D Computer Aided Design (CAD) method cannot overcome several challenges. It needs a non-linearly, complex, iterative and integrated manner which support the processes more efficiently. The main challenges which the traditional 2D CAD method are facing are less of communication and low data management. On one hand, there is limited communication between the customers, designers and constructors, also between the engineers of various disciplines involved. Moreover, end-users participate the design process rarely and involving users' experience in the design is in the initial stage. Actually users' experience significantly influence the energy consumption as about 30% to 40% of the greenhouse gas are produced in the operation phase (United Nations Environment Programme, 2007). On the other hand, incompatible software tools and the missing integrated product and process model reduce the process efficiency.

Facing these challenges, the advanced manner apply Building information modelling (BIM) and virtual reality (VR) to build a virtual environment which is easily accepted by the users who do not have professional design experience. Therefore, users' experiment are involved from the initial phase and continually optimize the sustainable design throughout the process.

2. BUILDING INFORMATION MODELLING (BIM), USER CENTRED DESIGN (UCD) AND VIRTUAL REALITY (VR)

In this new method, there are three key factors, BIM, VR and UCD. BIM is the base which provides a platform to store and transfer all the building information and data. VR is the representation which represents the products and all the amendments. UCD is the concept which attends to change the design process from linear to complex.

2.1 Building Information Modelling (BIM)

BIM (Building Information Modelling) is defined as a digital representation of the physical and functional characteristics of a building. It shares the information of a building or facility. In the whole lifecycle, it can be used as a reliable information basis for making decision (NIBS, 2007). BIM is a kind of digital method to coordinate design, construction and management which reduces the risk in the whole process and improves the efficiency massively (Li, 2013). Much more than a software, BIM integrates all kinds of engineering data in a construction project based on the multi-dimensional digital technology (Juan Yang, 2009). BIM initially integrates multi disciplines attribute information and relationships of objects in one 3D model and then 4D and 5D elements, such as time and cost, can be added to the model. It has the advantages of visualization, coordinating all the profession, simulating the project, optimizing the building performance and giving the drawing. The BIM model can be used for sustainability simulation which reduces the human intervention and interpretation. Therefore, the costly and time-consuming sustainable design can be improved, so the energy optimization will be real implemented in the design phase and its efficiency will rise.

2.2 Virtual Reality (VR)

Virtual Reality (VR) is a technology that conveys the virtual information produced by the computer to man's senses through some media. The characteristics of VR include a real-time spatiality of three dimensions, interaction and the self-projection (Takuya Onoue, 2010).

In the hardware phase, display technologies are needed to immerse users into a virtual world. Oculus Rift, HTC Re Vive and Sony Morpheus are the major display technologies. Rift from Oculus is the most prominent device. It uses a single mobile phone display, derived from the Samsung Galaxy Note 3 device (1920x1080 pixels, overclocked at a 75 Hz refresh rate). Oculus Rift employing infrared LEDs for positional tracking. When the position of user's hand and body change, the moved blinking emitters will be filmed by an additional camera which is mounted in the front of the user, so the positional changes can be detected at 60 Hz. Although it sets the screen to black (pixels off) between two rendered frames to reduce the ghosting effects, giddy resulted from "low persistence" is still a problem of Oculus Rift. HTC Re Vive headset, short in HTC Vive, which is developed by HTC cooperating with a major games distribution company, is another important hardware in the head-mounted displays area. HTC Vive uses inside-out tracking approach to detect the positional changes. Two laser emitters are fixed in each corner of the room, which move an arc of laser light in a sweeping pattern. The headset can then track the exact position in the room via multiple, spatial distributed photo diodes, based on the time of signal received at each diode. This allows user not only moving the hand and head, but also moving freely in the room while on worry about the tracking issue. The problem is there is no currently available wireless display technology provides bandwidth or latency, so the headset is still limited by the cables. Sony Morpheus applies an expansive 5.7" OLED 1080p display running at up to 120 frames per second for user to be immersive in a seamless virtual world. Similar with the Oculus Rift, it has LEDs around the headset, whose motion would be traced by a camera, so the user's movement in the virtual environment would be incredibly precise detected.

In the software phase, it often uses an existing game engine which is used to power computer games. The reason to choose the game engine is that it can provide the most possible realistic user experience. Possible game engines are the Unity game engine (Unity Technologies, 2016) and the Unreal Engine 4 (Epic Games, 2016). They can work with BIM tools through a plugin. Unity is developed by Unity Technologies and used to develop video games for PC, consoles, mobile devices and websites, written in C#, while Unreal Engine 4 is developed by Epic Games, written in C++. Companied to Unreal Engine 4 (UE4), Unity is more mature, and has low development cost. It is more suitable for the beginners. The advantages of Unreal Engine are it produces more detailed graphics and it is completely open-source for subscribers. Moreover, it allows for communication between the servicers and the users, so it contributes the remote users to participating the building lifecycles. However, Unreal Engine is difficult for the beginners to apply.

2.3 User Centred Design (UCD)

User centred design (UCD) is a framework of processes (not restricted to interfaces or technologies) in which the needs, wants, and limitations of end-users of a product, service or process are given extensive attention at each stage of the design process. For instants, Bullinger et al. (2010) suggested an approach introducing user centred design (UCD) in the architectural planning process for overcoming the communication problems. The aim of their study is to change the traditional design process and involving of the utilization phase of the building to improve planning reliability and efficiency. A large scale 3D VE based building prototype was built for the non-professional users to understand the building design by applying immersive media technology tools. The users were involved from the beginning of the basic assessment phase stage to the integrated planning process stage and defined the building requirements including geometric volume layout, form variants and detailed planning. Their updating requirements were recorded and fed back to the planers and design experts to optimize the design. The design was represented by the virtual prototype of the building. "Centre of Virtual Engineering" placed on the extended grounds of the Fraunhofer Institute Centre in Stuttgart-Vaihingen, Germany was regarded as an ideal precedent to apply UCD approach as it had high impact on the architectural aspect. The IAO software VRfx which was used in the design of "Centre of Virtual Engineering" was suggested by Bullinger et al. (2010) because it not only ensured 3D data transformation with little effort between different 3D models, but also realistically depicted the appearance of materials and light situations.

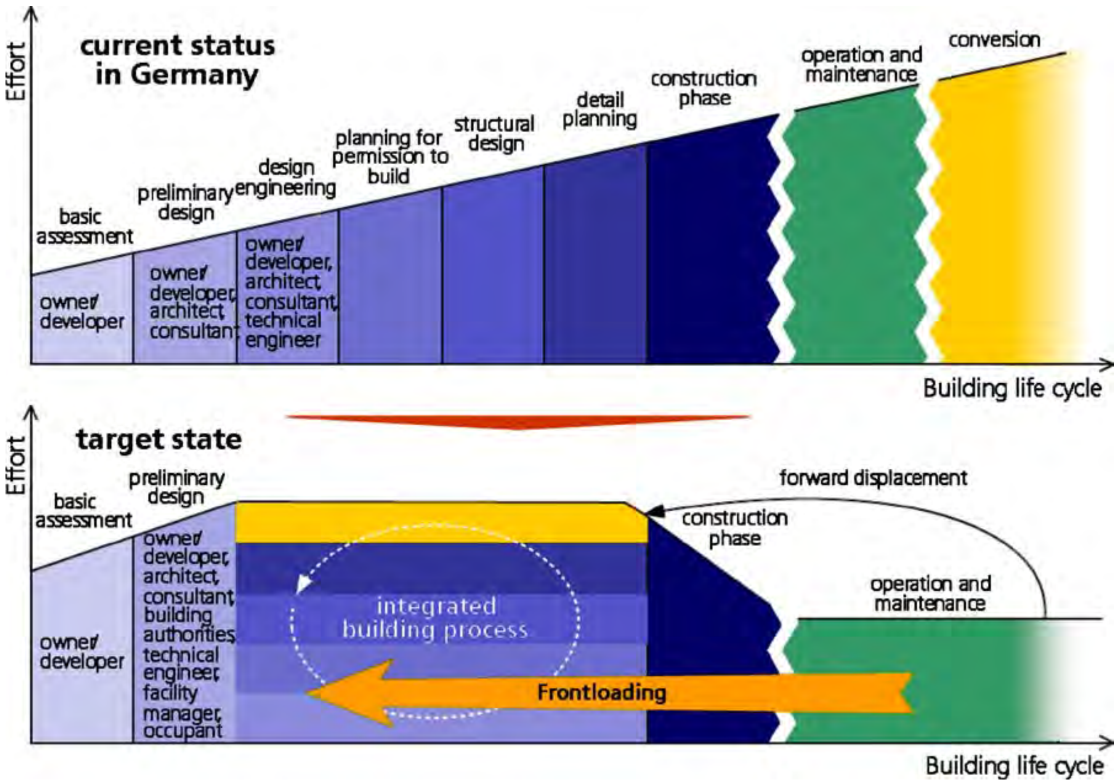


Fig. 2-1: Building life cycles with/without user participant

3. IMPLEMENTATION

During the sustainable design process, BIM tool and sustainability simulation tool and VR engine are used and a great deal of data should be transferred between these tools. The Industry Foundation Classes (IFC) data model regarded as official International Standard facilitates interoperability in the architecture, engineering and construction (AEC) industry, so it is used as the collaboration format during the implementation. Steel et al. (2010) concluded the IFC-based interoperability between ranges of BIM tools at four levels. File level interoperability was the ability of two tools to successfully exchange files. Syntax level interoperability was the ability that two tools could successfully parse those files without errors. Visualization level interoperability was the ability of two tools to faithfully visualize a model being exchanged. Semantic level interoperability related to the ability of two tools that could define and understand the models being exchanged coordinated. However several problems occurred during the data exchange process which was difficult to avoid to date. At file and Syntax level interoperability, file might fail to loading, render in 3D, or generate 2D drawing correctly due to the large size of the models and the restricted memory consumption. At visualization level, the models being exchanged from the IFC-compatible tools to some environmental or energy analysis programs which were not IFC-compatible and had proprietary formats had different format and those models might not visualize faithfully. Reliable model interoperability on a semantic level might forward design and constructing industry to BIM. However, different analysis tools understood the objects in the models with different encoding of the information. If one analysis tool encountered the encoding which it did not anticipate, the tool might gain an incorrect result. “Fixing” the model was needed for a correct result in the analysis model, but it was time consuming and reduced the value of the reused model. Moreover, some interoperation problems arose due to the coverage issues. On one hand, the analysis tool could not provide the IFC construct due to the shortcoming of the designer's tool palette, so the designer had to use an alternative modelling in the analysis tool which took error of the analyses result. On the other hand, the IFC had no construct to represent the designer's model, so the designer had to use an alternative representation of the model or use an IFC proxy object which might raise the latter problem that the analysis tools could not understand the construct. Furthermore, there were more complex problems due to the different representation of the model between design tools and simulation tools. Gap, overlap or inaccuracy of the objects might occur in the simulation tool while they were correct in the design tool. It needs to overcome these problems, so the design conception can be implemented and delivered to the users achieving energy optimization.

3.1 Building Information Modelling (BIM) to Building Energy Modelling (BEM)

A 3D BIM model with the building information such as geometry, material and topology is built in a building design software and then the BIM model is used in a building energy simulation software. The commonly used building design tools are Autodesk Revit, Bentley Microstation, Archi CAD and Tekla and the commonly used building energy simulation software involves of Autodesk Green Building Studio, Energy 10, HEED, Design Builder, Autodesk Ecotect, eQUEST, Integrated Environmental Solutions, Virtual Environment (IES-VE) and Energy Plus. As mention above, there is a challenge about the exchange of data between building design tools and sustainability analyses tools. In other words, the sustainability analyses tools lack of the compatibility with BIM-based design software.

Interoperability between BIM-based design and energy simulation tools is being researched in recent years. For instance, Ahn et al. (2014) aimed to develop an IFC–IDF interface that convert the building information from IFC to IDF, which is the input file of EnergyPlus. IfcRelSpaceBoundary which represented the definition of the space boundary was employed to organize the information, consisting of reference space information, related building elements information and connection geometry information. The geometry and material properties of IFC can be mapped to IDF with fully-automated (without extra input) or semi-automated (with extra input), using the EnergyPlus6.0 engine. On the other hand, instead of using standard data models, such as IFC, WoonSeong Jeong (2014) found that many problems occur in this period is that the building energy simulation tools fail to take advantage of object-oriented programming (OOP) and mapping from an object-oriented design model is not easy. They presented the BIM2BEM approach using C# programming to directly access the object-oriented data through Application Programming Interface (API). They created a Model View Definition (MVD) consisting of a process model and a class diagram. The process model facilitated the definition of the required building information and directed the object-mapping during the data transfer between BIM and BEM. The class diagram produced the wrapper classes intermediate between the BIM and BEM representing the information and object relationships. During the model translation, the wrapper classes enabled BEM to populate instantiated objects and compared them with the related instances and parameters that stored the values from BIM. In case of the mismatched semantics and behaviors, there was preprocesses for BIM to prepare the required information and assemble the instantiated objects.

3.2 Building Energy Modelling (BEM) to Building Information Modelling (BIM)

After the energy performance of the building is simulated, it proposes to allow the results being held in the BIM model. According to WoonSeong Jeong (2013), BIM Authoring Tools' Application API was used to visualize building energy simulation results in BIM. An external database was created to store and manage the object-based simulation results from the BEM. The information in the external database was translated into a range of prepared Energy Performance Indicator parameters of related components in BIM. Each parameter represented one of the building energy performances. Though the visibility setting, it created color-coded building components. The series and the level of the component color depended on the type of the building energy performance and the value of the parameters.

3.3 Building Information Modelling (BIM) to Virtual Reality (VR)

The game engine, such as Unity and UE4, are selected as the platform to interact between the professional designer and the end-user. Therefore, seamless data transmission between the BIM model with building energy simulation results and the game engine is necessary for the end-user having a deep immersion. Graphics (surfaces, lights, shaders and camera views), audio, physics will be integrated. It is also the challenge in a project.

In the system developed by Hilfert and König (2016) as shown in Figure 3 1, an OpenSource BIMServer was used to connect the BIM software (Autodesk Revit) and the game engine (UE4). The data in the BIM model was imported into the BIMServer. Through the repeated data update by the project manager, the data in the BIMServer was similar to that in the BIM model. The updated project was imported into the UE4 editor for further improvement. As the material libraries of BIM and UE4 were different, so there may be further materials needed for realistic display of a building in UE4. It prepared an additional material database in case different material was assigned or new material was defined.

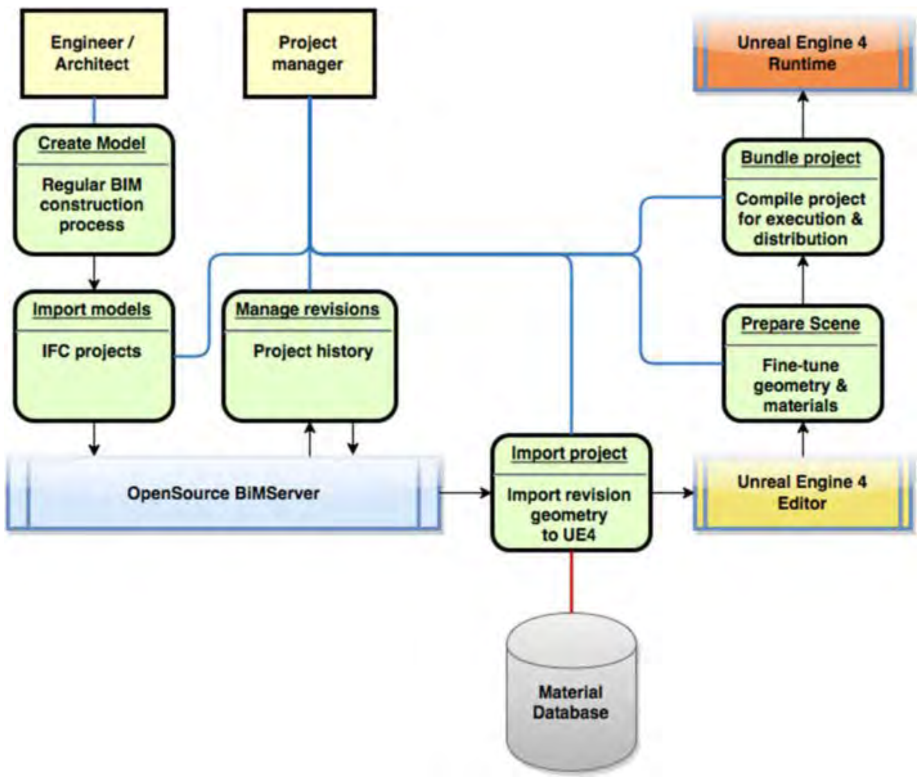


Fig. 3-1: Software architecture

As shown in Figure 3 2, Edwards et al. (2015) proposed a prototype which created a two-way data transferring channel and enabled the project been designed in Autodesk Revit being imported automatically into the game with no intermediate design steps. They created a Revit plugin which appears in the ribbon bar of Autodesk Revit as a button. It could access the BIM data through Revit API using C# language. The plugin contained the database and FBX format converter and worked as ‘micro’ web-server to convert the loaded BIM data from Revit building format to FBX format storing in the database. The FBX model was loaded into the Unity server’s memory through network and then was converted into the custom format generating the virtual environment. The end-user could load and be immersed into the virtual environment through the Unity clients.

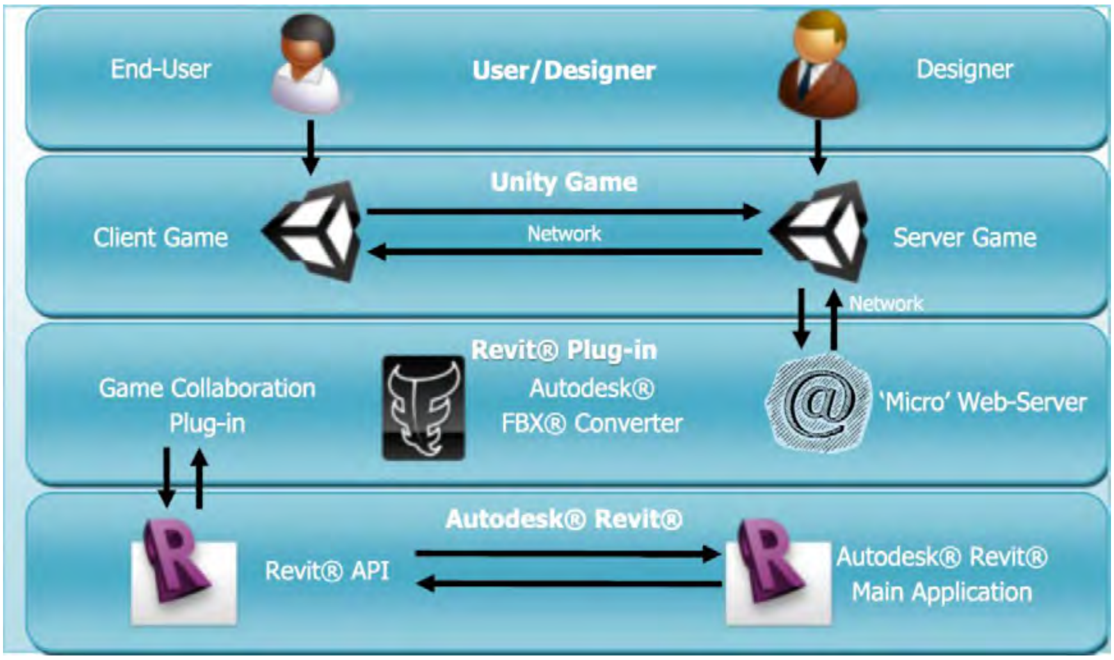


Fig. 3-2: System overall architecture

Yan et al. (2011) presented an interactive Design-Play approach including three main modules, BIM module, Crossover module and Game module. The three modules were separated but communicated with each other. The advantage was that the BIM application and the game framework were alterable leaving the other modules unaffected. Crossover module was utilized to translate the BIM format into the form that most game environment understood. After accessing the BIM data though the Revit API, it took care of the translation between high-level (such as connectivity relationships via door properties) and low-level representations (such as geometric model information). Before the model being rendered in the game environment, Crossover processed texture baking which was a common practice in game to achieve high-quality, real-time, interactive visualizations.

3.4 Users Participation

The virtual environment enables potential users to confront design as early as possible and provoke a discussion and feedback to capture resulting new requirements. The engineers can optimize the sustainable design according to the new requirements and the users' behavior recorded by the system. There is also an educational aim of the BIM-based virtual environment that the users may get a better picture of their energy usage patterns though the immersive experience.

The game-engine technology presented by Edwards et al. (2015) allowed multiple end-users be immersed in the virtual environment through the interface of Unity client using network. User could change or add elements in the virtual building according to their preferences. Because it used a two-way data transferring channel, the change would be synchronized back to the original BIM model for the designers optimizing the design. The Design-Play approach proposed by Yan et al. (2011) created avatars with first and third-person views for the users. Its game module had Components and Services properties which enabled custom-design in the game, such as loading content, unloading content and drawing. The users were allowed to simulate their behavior in the game and simulations were informed to BIM module. Therefore, the designers could process the iterative design until the energy performance of the building was satisfied. Chou et al. (2016) studied a system called iARTS (interactive Augmented Reality System) which integrated BIM with power consumption data and visualized the results in Unity to educate the users in the aspect of electricity usage patterns. Users would get an energy-saving tip when turned off the appliances and realize the appliances which can be used jointly for consuming PV-generated electricity at a maximum. More detailed and timestamped electricity consumption data for every appliance and every room would be provided through the forms of query forms, scenes retrieval and animations when the users could apply the aforementioned energy-saving tips for a better usage patterns.

4. CONCLUSION

Much of the energy consumption is due to the inadequate operation and maintenance. Therefore it desires to involve the end-users in the design process to use their experience as early as possible. As the users have no professional design skills, a friendly interface is needed for them to simulate their behavior. BIM-based virtual reality environment proposed in this paper allows users to interact with a design which is achieved by the use of a game engine that provides intuitive controls and an immersive environment for the unprofessional users to engage with the building and add to the design. One of the major challenge is to seamlessly integrate the BIM tool, the BEM tool and the game engine. IFC–IDF interface, BIM2BEM approach, Revit API, OpenSource BIMServer, Revit plugin, Crossover module and network are considered to translate the BIM data into the game service and provoke a feedback from the users automatically. On the other hand, the end-users would be educated in the aspect of the energy usage patterns by combining the spatiotemporal energy consumption data with the given energy-saving tips in different realistic scenarios. The further study is to select the most appropriate method and test it in a pilot project.

ACKNOWLEDGEMENT

The work presented in this paper was undertaken under the aegis of the BIM-GIS Application in Green Built Environment Project, funded by Ningbo Science and Technology Bureau (2015B11011).

5. REFERENCES

AHN, K.-U., KIM, Y.-J., PARK, C.-S., KIM, I. & LEE, K. (2014). BIM interface for full vs. semi-automated building energy simulation. Energy and Buildings, 68, Part B, 671-678.

EUROPEAN COMMISSION BUILDINGS. (2015). Available: https://ec.europa.eu/energy/en/topics/energy-efficiency/buildings.

BULLINGER, H.-J., BAUER, W., WENZEL, G. & BLACH, R. (2010). Towards user centred design (UCD) in architecture based on immersive virtual environments. Computers in Industry, 61, 372-379.

CHOU, C.-C., CHIANG, C.-T., WU, P.-Y., CHU, C.-P. & LIN, C.-Y. (2016). Spatiotemporal analysis and visualization of power consumption data integrated with building information models for energy savings.

Resources, Conservation and Recycling.

EDWARDS, G., LI, H. & WANG, B. (2015). BIM based collaborative and interactive design process using computer game engine for general end-users. Visualization in Engineering, 3, 1-17.

EPIC GAMES. (2016). Available: https://www.unrealengine.com/what-is-unreal-engine-4.

HILFERT, T. & K NIG, M. (2016). Low-cost virtual reality environment for engineering and construction. Visualization in Engineering, 4, 1-18.

JUAN YANG, X. Z. (2009). Integrated model of construction project information and supported technology standard. Construction Technology.

LI, Z. (2013). Application of BIM in the integration of architectural design and construction management in China. Urbanism and Architecture.

NIBS (2007). National Building Information Modeling Standard Version 1-Part 1：Overview．Principles，Methodologi.

UNITED NATIONS ENVIRONMENT PROGRAMME. (2007). Assessment of policy instruments for reducing greenhouse gas emissions from buildings. Budapest.

STEEL, J., DROGEMULLER, R. & TOTH, B. (2010). Model interoperability in building information modelling. Software & Systems Modeling, 11, 99-109.

TAKUYA ONOUE, N. Y., SHINJI YOSHIDA, TOMOHIRO FUKUDA (2010). Visualization technique of outdoor thermal environment using a VR avatar Proceedings of the 10th International Conference on Construction Applications of Virtual Reality (CONVR). 502 ed.

UNITY TECHNOLOGIES. (2016). Available: http://unity3d.com/cn/.

WOONSEONG JEONG, J. B. K., MARK J. CLAYTON, JEFF S. HABERL, ANDWEI YAN (2014). Translating Building Information Modeling to Building Energy Modeling Using Model View Definition. The ScientificWorld Journal.

WOONSEONG JEONG, J. B. K., MARK J. CLAYTON, JEFF S. HABERL, WEI YAN (2013). Visualization of Building Energy Performance in Building Information Models.

YAN, W., CULP, C. & GRAF, R. (2011). Integrating BIM and gaming for real-time interactive architectural visualization. Automation in Construction, 20, 446-458.

DEVELOPMENT OF A SIMPLIFIED ACOUSTIC VISUALIZATION SYSTEM USING KINECT SENSORS

Ryo Yamasaki, Nobuyoshi Yabuki, Tomohiro Fukuda, and Ali Motamedi

Osaka University, Japan

ABSTRACT: *It is important to identify noise sources to solve noise pollution problems. However, due to the properties of sound, such as invisibility, diffraction, and interference, it is often difficult to identify the location of noise sources by human ears. Some researchers have already developed systems for detecting and visualizing the location of the sound source, such as Sound Camera, by employing microphone arrays. However, such systems are generally very costly. Thus, the aim of this research is to develop a low-cost and simple acoustic visualization system using Microsoft Kinect. Although Kinect is able to detect sound pressure level, frequency and one-dimensional direction of the sound, it cannot detect the two-dimensional location of the sound source in its camera feed. It only detects the horizontal angle of the sound source with respect to its body. Furthermore, the center position of the camera and microphone array are different. This research solved these problems by deploying two perpendicularly attached Kinect units and by correcting the error of the sound source position. Additionally, the developed system can measure the distance to the sound source using the depth sensor of Kinect, which is not generally available in other systems, and can provide output visualizations of sound data.*

KEYWORDS: *Noise Pollution Problem, Sound Source Location, Microphone Array, Acoustic Visualization, Kinect, Augmented Reality*

1. INTRODUCTION

Noise disturbance is commonly considered as a type of pollution in an urban environment. Specially, the construction noise often causes severe problems for residents and workers. It is important to identify the locations of noise sources in order to take effective measures to reduce the noise pollution. Additionally, finding the locations of sound sources can be used for detecting unusual or sudden noises in the construction site for applications such as the maintenance of equipment. However, sound waves are not visible and have properties, such as diffraction and interference, which makes it difficult to identify the location of their origin by human ears.

This problem can be solved by using existing sound data visualization systems. In these systems, sound data is obtained using a microphone array, which is a unit with plural microphones. They can display the location of a sound source by superimposing the sound data on real images. *Sound Camera* (Tominaga et al., 2003) or *Noise Vision* (Takashima et al., 2008) are examples of sound data visualization systems. They are mainly used for the evaluation of sound insulation or room acoustics. However, such devices are generally very costly due to the use of specialized microphone array systems. Therefore, applications of such systems are generally limited to large scale construction sites or factories, and they cannot be used for everyday purposes.

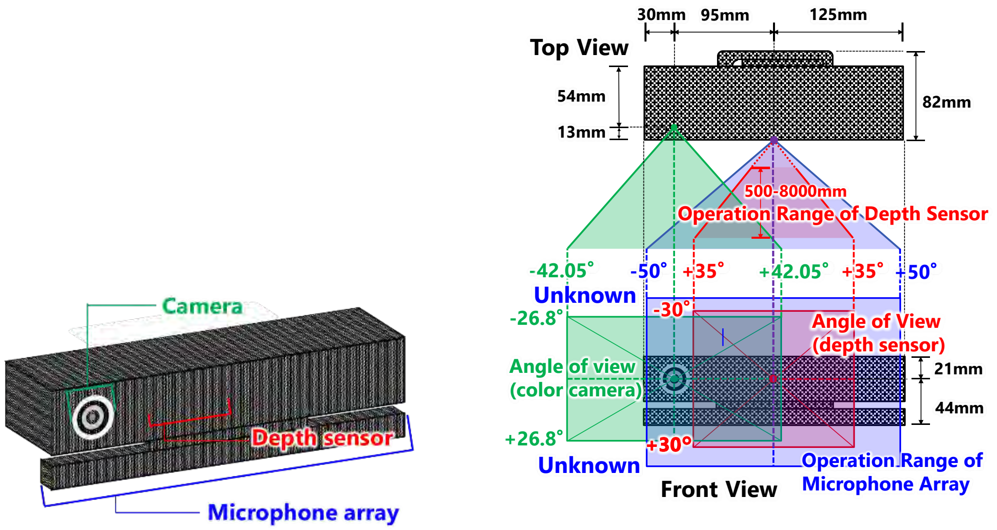
The aim of this research is to develop a low-cost and simple acoustic visualization system for identifying the location of a noise source. This research proposes using Microsoft Kinect (Microsoft Inc., 2014b), which is developed as a game controller for general consumers. Kinect has functions to control game objects by recognizing gestures, facial expressions, and voice using its built-in video camera, depth sensor, and microphone array.

Some researchers investigated low cost systems for detecting and visualizing sound sources. For example, Steered Response Power using the PHAse Transform (SRP-PHAT) method, (DiBiase, 2000) is applied to sound data obtained by microphones of Kinect, and estimates the three-dimensional location of the sound source (Seewald et al., 2014). However, the accuracy is not very high, and lacks an easy data presentation method for users. Galatas et al. (2013) detected locations of risk factors and people who are crying for help by using microphone array and the depth sensor of Kinect. However, their system is designed for rescue operations and is not tuned for detecting noise sources. Iyama et al. (2014) developed a system to visualize acoustic data using the depth sensor and video camera of Kinect and Microcone (Biamp Systems, 2012), which is a low cost microphone array. This system can help users to identify the sound and collect information of the sound, such as the location of the sound source and the changes of the sound pressure level. However, this system does not show the dominant frequency data and does not work in real-time.

Our proposed system provides information, such as three-dimensional location of the sound source, volume and dominant frequency in real-time. Although the accuracy of the system is not higher than that of existing systems, it is very cost efficient. Additionally, while available devices generally have difficulty operating in places that are influenced by reverberation such as indoors, this system has a high accuracy in such areas.

2. KINECT SENSOR

Microsoft Kinect has functions to estimate the arrival direction of the sound, to digitize received audio signals, to capture video images, and to store depth data, in order to identify gestures and voice. Kinect v2 is used in this study. A summary of its specifications is presented in Table 1 and Figure 1.



(a) (b)

Fig. 1 Position and range of Kinect v2 sensors

Table 1 Kinect v2 specifications

	Range	Resolution or Data Format
Sound Direction	Horizontal: 100°(±50°) Vertical: unknown	Only horizontal to its body, by the 5°
Digital Sound Data		16kHz, 32bit-float PCM
Video Moving Image	Horizontal: 84.1°(±42.05°) Vertical: 53.8°(±26.9°)	1920×1080 (pixels)
Depth Image	Distance: 0.5m～8.0m Horizontal: 70°(±35°) Vertical: 60°(30°)	512×424 (pixels)

As shown in Table 1 and Figure 1, the center position of the depth sensor, microphone array, and the center position of the video camera of Kinect v2 are different. Besides, Kinect only detects the horizontal angle of the sound source with respect to its body.

3. THE PROPOSED SYSTEM DESIGN

The proposed system estimates the three-dimensional location of the sound source by using the microphone array and the depth sensor of Kinect, and displays the estimated result by superimposing Augmented Reality (AR) graphics on the moving image obtained by the video camera of Kinect.

As explained in Section 2, Kinect only detects horizontal angle of the sound source with respect to its body. Therefore, by deploying two perpendicularly attached Kinect units, the two dimensional arrvial direction of the sound source can be potentially estimated. Figure 2 shows the data flow and the process flow of our proposed system. The PC which displays the AR graphics is referred to as the Master-PC, and the second PC as the Slave-PC. Additionally, the Kinect unit which is connected to the Master-PC is referred to as the Master-Kinect, and the second Kinect as the Slave-Kinect. Among all the depth data obtained by the Master-Kinect, the system treats the depth data corresponding to arrival direction of the sound as the distance to the sound source to estimate the three-dimensional location of the sound source. Furthermore, the Slave-PC calculates amplitude and the dominant frequency from digital audio data obtained by the Slave-Kinect. The Master-PC creates an AR graphics by using the data obtained by Kinect units and the data calculated by each PC. Thus, the system displays the sound data by superimposing a graphic on the real moving image obtained by the video camera of the Master-Kinect and displays numerical acoustic data on the camera feed.

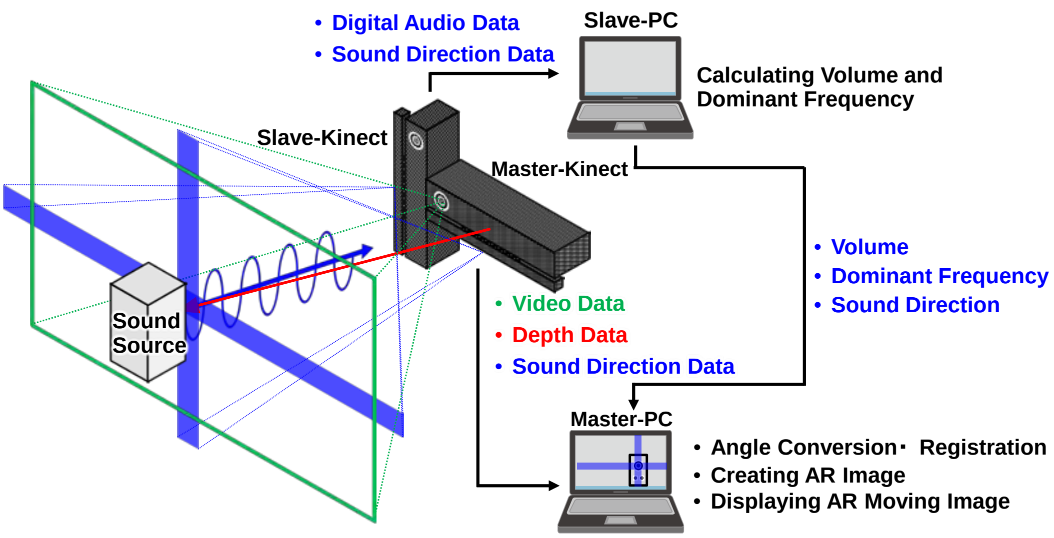
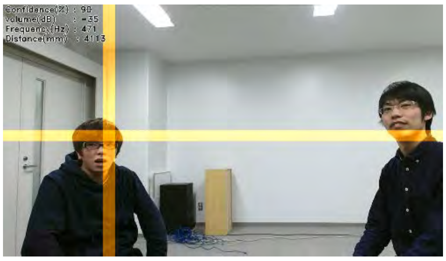


Fig. 2 Data and process flow of proposed system



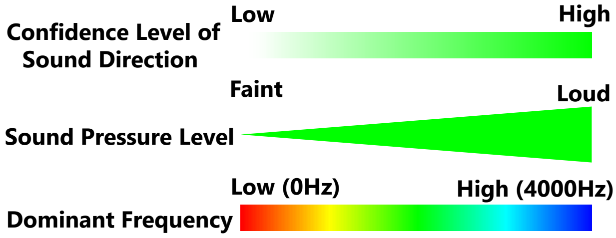


Fig. 3 Sample of output system

Fig. 4 Legend for AR lines

Figure 3 shows a sample output of the system. It provides a two-dimensional location indicator for the location of the sound source which is the intersection of two lines on 1920×1080 pixels video images. The data related to the confidence percentage of sound direction calculation, amplitude, dominant frequency, and the distance to the sound source are also provided in the upper left corner of window as numerical values. The confidence level of the sound direction is calculated automatically by the Master-Kinect. In addition, the texture, thickness, and the color of lines, which indicate the location of the sound source, vary to visually convey the numerical values. The texture density shows the confidence level of location estimation, the thickness of lines shows the amplitude, and the colors show the dominant frequency (Fig. 4). This system can detect only one sound source at any given time. It works near-real-time and approximately one second delay exists from the time sound was emitted by the sound source to the time this system displays lines.

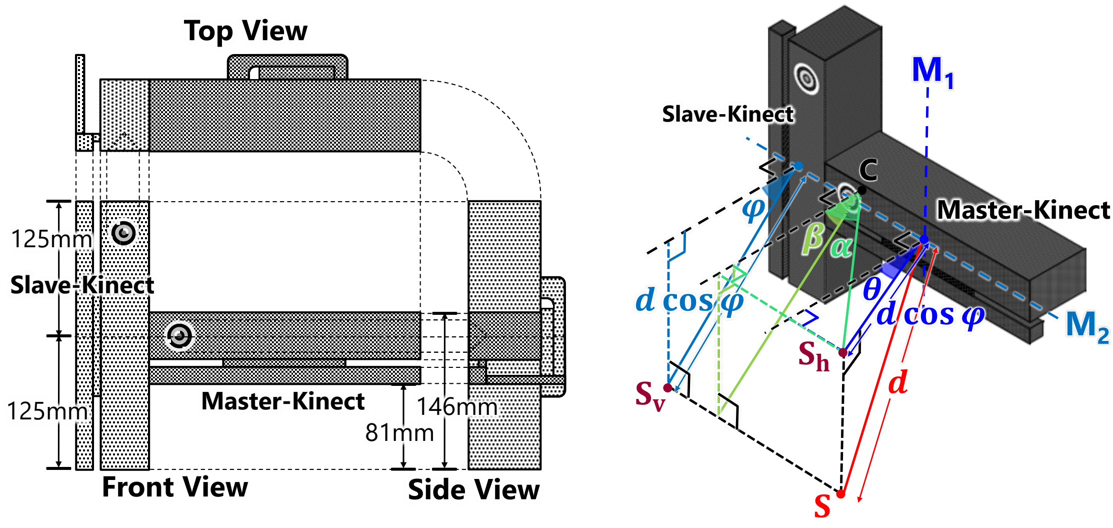
As shown in Figure 1, center positions of microphone array, video camera, and the depth sensor of Kinect are different. Therefore, in order to correctly display the sound direction superimposed on the real-time video images, it is necessary to adjust sound direction on the video.

In this system, two Kinects in a positional relation shown in Figure 5 are used. The angles to the sound source from the center position of camera α and β (α: horizontal to the Master-Kinect, β: vertical to the Master-Kinect) are calculated using Equations 1 and 2, respectively. θ is the sound direction obtained by the Master-Kinect, and

φ is the sound direction obtained by the Slave-Kinect, and d is the depth data corresponding to the sound direction obtained by each Kinect. M_1 is center axis of the sound direction data obtained by the Master-Kinect and M_2 is center axis of the sound direction data obtained by the Slave-Kinect. C is center position of camera of the Master-Kinect. S is location of the sound source, and S_h is the location of the sound source projected on the horizontal plane, and S_v is the location of the sound source projected on the vertical plane. For the calculation of α, the sound source is projected on a horizontal plane using φ (Fig. 6-a). After that, α is calculate from θ (Fig. 6-b). Additionally, in calculation of β, the sound source is projected on a vertical plane by using θ (Fig. 6-c). Then, β is calculate from φ (Fig. 6-d). In order to display sound direction correctly, it is necessary that the sound source exists in the range of 0.5m to 8.0m distance from the system where Kinect can measure depth data.

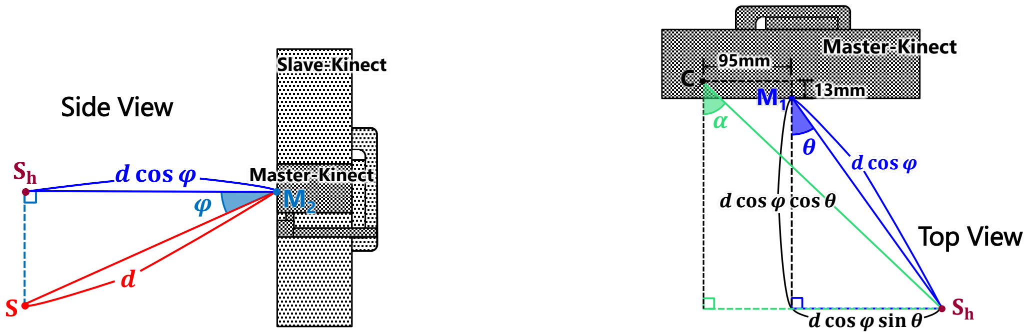
$$\alpha = \arctan\left(\frac{d\cos\varphi\sin\theta+95}{d\cos\varphi\cos\theta+13}\right) \quad \text{Equation 1}$$

$$\beta = \arctan\left(\frac{d\cos\theta\sin\varphi}{d\cos\theta\cos\varphi+13}\right) \quad \text{Equation 2}$$

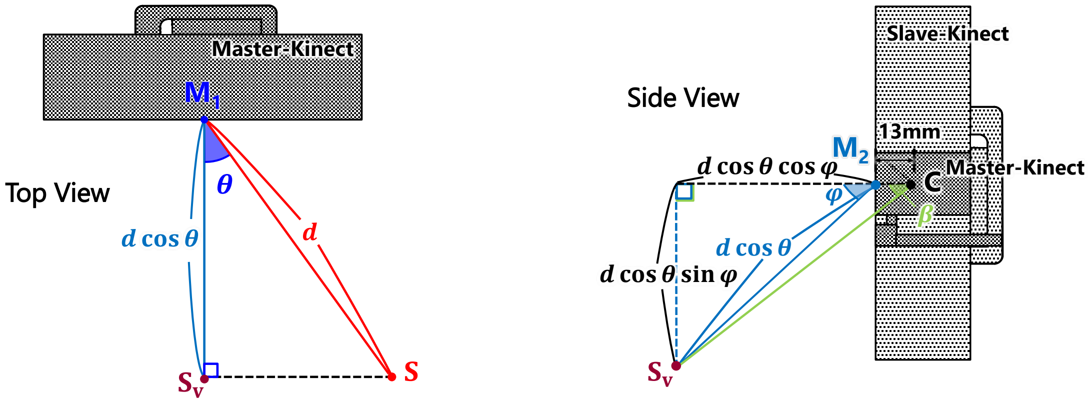


(a) (b)

Fig. 5 Positional relation of two Kinects in the proposed system and the location of the sound source



(a) (b)



(c) (d)

Fig. 6 Calculation of α and β

For the development of the system, C++ programming language and Kinect for Windows SDK 2.0 (Microsoft Inc., 2014a) were used. To create AR graphics, OpenCV, which is an open source image processing library, was used (OpenCV, 2014). To calculate the dominant frequency, the system uses the General Purpose FFT (Fast Fourier/Cosine/Sine Transform) Package (Ooura, 2006).

4. PROTOTYPE SYSTEM AND CASE STUDY

Figure 7 shows a photograph of our prototype system. Two perpendicularly attached Kinect v2 units and two regular PCs are used in our prototype system with Windows 8.1, Intel Core i5 (3.4GHz) Processor with 8.00GB of RAM. For the generation of sound signals, an application named *WaveGene* is used (efu, 2013), and *Olasonic TW-S7* speaker was used for playing the sound (Fig. 8). All target sounds used in our experiments were 16bit digital audio signal with 44,100Hz sampling rate. The experiments were carried out at Osaka University (Suita campus), M3-410 (Fig. 9) for indoor tests and M3 Building parking lot (Fig. 10) for outdoor tests.

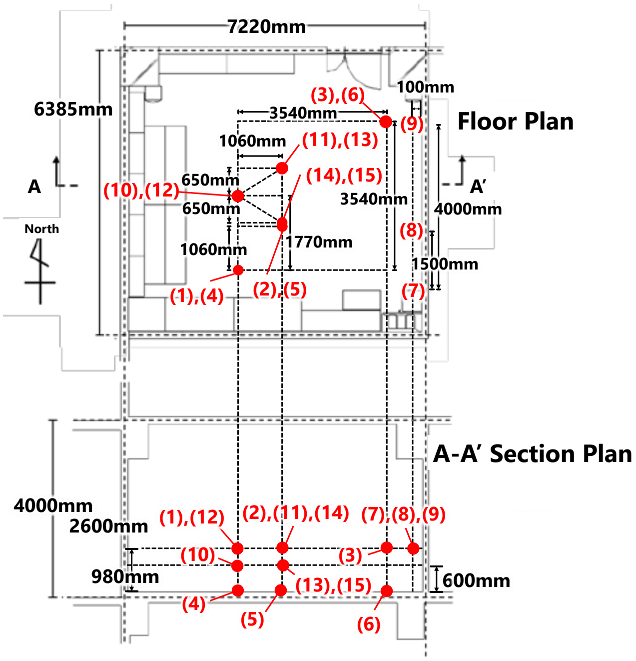
Fig. 7 Prototype System Fig. 8 Speaker Fig. 9 Setup for the Experiments

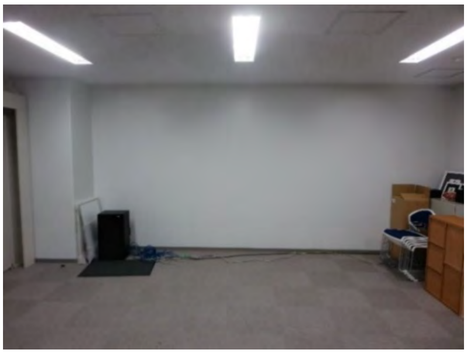
The first experiment targeted to verify the influence of reverberation on the accuracy. Hence, the sound direction errors were examined in different conditions. Sound signals, which have approximately the same strength at each frequency band in the range of 0Hz to 22,050Hz (in a form of white noise), were used as the target sound. The target sound has more than 10 dB higher Sound Pressure Level (SPL) than that of the background noise.

The second experiment targeted to verify the system's requirements for the difference between the sound pressure level of the detected sound signal and that of the background noise. Hence, the relationships between the sound pressure level of the detected sound signal and the sound pressure level of the background noise in different conditions were examined. In this experiment, a white noise or monotonous sine wave signals were used as the target sound. The setup of the experiments is shown in Figure 9. While conducting both experiments, cardboard plates were placed behind the speakers to correctly obtain the depth value *d*.

5. RESULTS

Figure 10 and 11 show layouts of indoor and outdoor experiment areas, respectively. The numbers on the figures show the locations of sound sources and the prototype system in our experiments. In Figure 11, the values next to the numbers indicates the heights from the ground. The results of the first experiment are shown in Figure 12. The relative vertical error percentage shows the vertical distance (i.e. number of pixels) between the calculated location of the sound source in the image and the real position of the speaker in the output image divided by the total number of pixels in the vertical direction (i.e. 1080) of the output image. The results of the second experiment are shown in Table 2. The positional relations between the sound source and the prototype system are indicated in the horizontal axis. For example, (1) => (2) refers to an experiment where the prototype system was located at point (1) and the speaker was at point (2).





(a) (b)

Fig. 10 Floor plan, section plan, and picture of M3-410

(a) (b)

Fig. 11 Location of the outdoor test

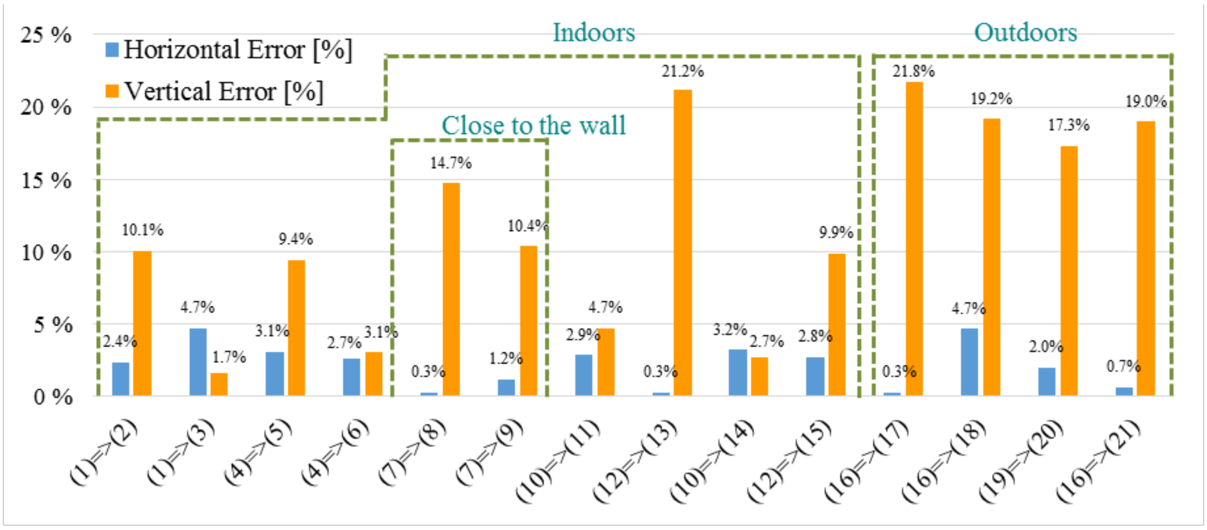


Fig. 12 The sound direction relative error percentage

Table. 2 Relationship between the SPLs of detected sound signals and the background noise

	SPL of Background Noise [dB]	SPL of Detected Sound Signal [dB]	SPLs Difference [dB]
(1)=>(2), (White Noise)	46.84	48.64	1.80
(1)=>(3), (White Noise)	47.88	51.66	3.78
(10)=>(11), (White Noise)	49.94	51.28	1.34
(12)=>(15), (White Noise)	51.50	53.96	2.46
(1)=>(2), (200Hz Sine)	48.88	59.98	11.10
(1)=>(2), (1000Hz Sine)	50.30	55.48	5.18
(1)=>(2), (4000Hz Sine)	47.48	49.52	2.04
(16)=>(17), (White Noise)	67.98	70.98	3.00

The results of the first experiment, presented in Figure 12, show that the average value of the horizontal error in 10 indoor tests is higher comparing with the error in four outdoor tests. However, the average of vertical error in the indoor experiments is lower comparing with the outdoor experiments. In the experiments that were conducted close to the wall ((7) => (8) and (7) => (9)), the average vertical accuracy was lower than that of points which are far from the wall. The difference between indoor and outdoor accuracies can be related to the fact that the background noise is louder outdoors, and Kinect is optimized as a controller of the game to be played in a room. The difference between accuracies when close to the wall and otherwise can be related to the influence of reflections from the walls. Additionally, vertical errors were generally larger comparing with the horizontal errors, and the accuracy of the system outdoors was lower than that of indoors. More investigation to identify the causes for such differences is required.

The accuracy of existing systems may be higher than that of the proposed system. However, available systems generally have difficulty operating in places that are influenced by reverberation such as interior spaces. Although the accuracy lowers when the system is located close to the wall, this system has a higher average vertical accuracy indoors than that of outdoors. The horizontal accuracy is relatively high regardless of indoor or outdoor setting. Thus, in the case of indoor use, this system can be advantageous over existing devices.

The results of the second experiment presented in Figure 12 shows that the system is able to detect the sound even when sound pressure level difference between the detected sound signal and the background noise was less than 10dB. In Japanese Industrial Standards (JIS) Z8731 (JIS, 1999), when the sound pressure level is measured, the influence of the background noise should be considered if the sound pressure level difference between the detected sound signal and the background noise is less than 10dB. The system is able to detect such sound sources, which have small SPL differences with the background noise. However, results of 200Hz sine wave shows that the detection sensitivity to sound, which comprises only of low frequency, is low. Thus, for applications in which low-frequency noise should be detected, this system requires improvement.

6. CONCLUSION AND FUTURE WORK

In this study, an acoustic visualization system was developed in order to assist users identifying the locations of noise sources using a low cost system based on Kinect sensors. Although, Kinect can detect only horizontal angle of the sound source with respect to its body, the two-dimensional sound source direction was calculated in our system by using two perpendicularly attached Kinect units. In addition, in order to correctly superimpose the sound direction data on video images captured by Kinect, a calculation method and an AR visualization method were proposed. Furthermore, a function to estimate three-dimensional locations of the sound sources by using depth data obtained by Kinect was proposed.

Although the accuracy of this system may be lower than that of existing systems, the system is low cost and is advantageous in the case of indoor use. This system is able to detect the sound which is strongly influenced by background noise, however, it is still unsuitable for the detection of low frequency noise.

Improving the accuracy and reducing the time delay are future work for this research. In addition, this system can only detect one sound source at any given time, and there are limitations for the operating range of sensors. Finally, this system can be further improved by incorporating other functions of Kinect such as 3D shape scanning.

7. ACKNOWLEDGEMENT

This work was supported by JSPS KAKENHI Grant Number JP26-04368.

8. REFERENCES

Biamp Systems (2012). Innovative Microphones for Groups [online], Available at: http://www.dev-audio.com/, [Accessed 27 July 2016].

DiBiase J. H. (2000). A high-accuracy, low-latency technique for talker localization in reverberant environments using microphone arrays, PhD Thesis, Brown University.

efu (2013). WaveGene [online], Available at: http://efu.jp.net/soft/wg/wg.html, [Accessed 27 July 2016].

Galatas G., Ferdous S., and Makedon F. (2013). Multi-modal person localization and emergency detection using the kinect, *International Journal of Advanced Research in Artificial Intelligence* Vol. 2, No. 1, 41-46.

Iyama T., Sugiyama O., Otsuka T., Itoyama K., and Okuno H. G. (2014). Visualization of auditory awareness based on sound source positions estimated by depth sensor and microphone array, *IEEE/RSJ International Conference on Intelligent Robots and Systems*.

JIS (1999). JIS Z 8731 Kankyouonsouon no Hyouji, Sokuteihouhou (Method for measurement and indication of the environment noise), 15.

Koike H. (2012). Kenchiku no Souonmondai ni Taisuru Ongentansasyuhou no Tekiyoujirei ni Tsuite (Measurement of the building noise using the noise source identification technique), *Summaries of technical papers of annual meeting Architectural Institute of Japan Toukai Branch,* 201-204.

Microsoft Inc. (2014a). Kinect for Windows SDK 2.0 [online], Available at: https://www.microsoft.com/en-us/download/details.aspx?id=44561, [Accessed 27 July 2016].

Microsoft Inc. (2014b). Kinect for Xbox One [online], Available at: http://www.xbox.com/en-US/xbox-one/accessories/kinect, [Accessed 27 July 2016].

Ooura T. (2006). General Purpose FFT (Fast Fourier/Cosine/Sine Transform) Package [online], Available at: http://www.kurims.kyoto-u.ac.jp/~ooura/fft.html, [Accessed 27 July 2016].

OpenCV (2014). OpenCV [online], Available at: http://opencv.jp/, [Accessed 27 July 2016].

Seewald L. A., Gonzaga L., Veronez M. R., Minotto V. P., and Jung C. R. (2014). Combining SRP-PHAT and two Kinects for 3D Sound Source Localization, *Expert Systems with Applications*, Vol. 41, No. 16, 7106-7113.

Takashima K., Nakagawa H., and Williams E. G. (2008). Vector intensity measurement with a rigid spherical microphone array in a vehicle cabin, *Journal of the Acoustical Society of America,* Vol. 123, No. 5, 3312.

Tominaga D., Nogami H., Yamashita Y., Zaima T., and Owaki M. (2003). Gazou to Otojyouhou Wo Kumikonnda Onngenntansasisutemu no Kaihatsu to Tennbou (Development and prospects of sound source exploration system incorporated an image and sound information), *Research report collection of Architectural Institute of Japan Hokuriku Branch,* Vol. 46, 123-126.

IMMERSIVE VIRTUAL ENVIRONMENT AS AN APPARATUS FOR OCCUPANT BEHAVIOR STUDIES

Sanaz Saeidi & Yimin Zhu

Louisiana State University, Baton Rouge, LA, USA

Joon-Ho Choi, Chen Zhong & Qi Wang

University of Southern California, Los Angeles, CA, USA

ABSTRACT: *Until recently, the importance of occupant behavior to building energy consumption and prediction has been "re-discovered". This worldwide renewed interest is largely caused by a collective understanding that in addition to engineering and economic approaches for improving building energy efficiency, there is another approach with high potential and low cost – better understanding and handling of building occupant behavior. Occupant behavior is a complex issue, affected by many contextual factors. Although re-construction of certain contextual factors such as building designs or social settings for research may be difficult in reality, it is relatively easy and low cost using newer innovations such as immersive virtual environment (IVE).*

Therefore, the purpose of this study is to understand whether immersive virtual environment (IVE) evokes different participant perceptions and experiences from what is typical in naturalistic environments, or in-situ. By demonstrating that subjects in IVE and in-situ experience similar psychological and physiological responses to same experimental stimuli, evidence of ecological validity may be established for occupant behavior studies, when similar levels of the sense of presence are translatable between IVE and in-situ. These findings help to determine the feasibility and the effectiveness of using IVE as an apparatus for occupant behavior studies. Participant reflections of the experiment experience are used to detect errant sources of method bias and to establish face validity. A virtual environment of a climate chamber at the University of Southern California (USC) was created and student subjects were recruited to perform an initial study. Results of the study are reported and recommendations for future studies are discussed.

KEYWORDS: *Building Energy; Immersive Virtual Environment; Occupant Behavior; Thermal Comfort.*

1. INTRODUCTION

Following the challenges for sustainability and the emerging understanding of considering the impact of human factors on building performance, research interest on occupancy behaviors has become increasingly extensive. There have been a number of studies focusing on the significance of occupancy behaviors on building performance and energy efficiency (e.g., Al-Mumin et al., 2003; Dietz et al., 2009; Raaij, 1983). Energy efficiency has been widely studied and practiced using engineering and economic approaches, however, those approaches are only effective if the human behavior has been taken into account. That is to say, when occupants are uncomfortable with the indoor environmental quality, they are prone to choose other alternative means to satisfy their comfort. In essence, designs which fail to meet the impact of the future occupants, are less likely to reach their full energy-saving potentials. Therefore, the match between the predicted building energy performance and the behavior of the potential occupants has to be the ambitious target of any sustainable design. Considering the fact that re-construction of certain contextual factors such as building designs or social settings for performing researches may be still difficult to do in reality, this study puts forward the possibility to use a recent useful medium, Immersive Virtual Environments (IVE), which has a high capacity to develop dynamic stimulus environments. Advancements in computer power, graphic rendering, display technology, wireless tracking, haptics, voice recognition and so on have brought about extremely immersive virtual settings which are able to provide real-time multisensory feedback. According to Sanchez-Vives & Slater (2005) “IVE attraction lies in the tendency for individuals to react in virtual reality as they would in the real-life situation”. In recent years, application of IVE’s has made enormous contribution in researches which need to measure the human-related factors and replicate real life behaviors. Extensive use of IVE in social science has resulted in effective interventions; such as virtual reality exposure therapy for anxiety and phobias (e.g., Wiederhold and Wiederhold, 2004), stress management (e.g., Meehan et al., 2002; Serino et al., 2014), testing delusional beliefs and treating paranoid disorders (e.g., Freeman et al., 2008), treatment of acrophobia (e.g., Hodges et al., 1994) and flying (e.g., Wiederhold et al., 2002). Within the domain of education, there has also been successful practices in generating immersion for the trainees (e.g., De Leo et al., 2014; Tichon, 2007) . In design and engineering domains, various IVEs have been applied to the studies of human behavior in emergency situations such as evacuation from tunnel fire (e.g., Kinateder et al., 2014; Marsh et al., 2014), and hotel fire evacuation (e.g., Kobes et al., 2010), and building design and analysis such as home design (e.g., Mackie et al., 2004), the review of full scale physical mock-ups of hospital patient rooms (Dunston et al., 2011; Tutt et al., 2013). In line with the previous studies, this study tries to determine the feasibility and the effectiveness of using IVE as an apparatus for assessing occupant thermal comfort through measuring the psychological and physiological responses to same experimental stimuli. In particular, this research looks forward to explore whether IVE evokes different participant perceptions and experiences from what is typical in naturalistic environments. The experimental stimulus in this study is the environmental condition i.e., temperature change in this case, related to occupant thermal comfort. Overall, it is intended to discover whether IVEs can produce comparable perceptions and experiences as what is typical in the physical environment. There is certainly essential need for solid evidence of ecological validity to accredit intensive occupant behavior studies using IVE. To that end, it is necessary to measure the individuals’ level of presence—sense of being there. The term presence is generally used to address the human feelings and perceptions of a virtual environment (Barfield et al., 1995). The reason behind finding participants’ sense of being there is that the more a person feels present in a virtual environment, the more his/her responses would match those in the physical environment (Villani et al., 2012). In 2004, OMNIPRES project published a comprehensive and useful guide to which a good measure of presence should abide (van Baren & IJsselsteijn, 2004). The measures have been classified into two subjective and objective corroborative groups. In this study, the Independent Television Commission-Sense of Presence Inventory (ITC-SOPI; Lessiter et al., 2001) was used to measure the subjective effects felt within individuals’ experience in IVE--sense of being there. In addition to the questionnaires, several researchers in their virtual reality treatment urge to screen individuals’ physiological responses as an objective tool for testing the level of presence. According to Meehan et al. (2002), “to the degree that a virtual environment seems real, it will evoke physiological responses similar to those evoked by the corresponding real environment”. In this study Heart Rate and Skin Temperature has also been monitored. Besides, subjects’ Thermal Comfort vote (7-point ASHRAE thermal sensation and satisfaction with temperature) was recorded on a specific time points and temperature level (ASHRAE, 2013). According to the ANSI/ASHRAE Standard 55-2010, thermal comfort is defined as "that condition of mind which expresses satisfaction with the thermal environment and is assessed by subjective evaluation (Huizenga, 2011).

2. OBJECTIVE

The purpose of the study is to understand whether IVE evokes different participant perceptions and experiences from what is typical in naturalistic environments, or in-situ. By comparing the construct measures and participant perceptions gathered in the IVE and in-situ, the research team tries to see how different the environmental factors could be perceived in the two experimental settings. Eliciting similar psychological and physiological responses to same experimental stimuli, temperature, in comparable IVEs and in-situ environment will then produce clear evidence for the ecological validity of the experiment. Given that, the research team hypothesizes that IVE is able to replicate mundane realism with regards to setting, stimuli, and response.

3. METHOD

3.1 Experiment Design

This study employed a within-subject design and participants were assigned to the experimental setting in random order. Experimental setting, in-situ vs. IVE, and the environment temperature are the independent variables of this study. Dependent variables are divided into both subjective and objective measures. Subjective measures include the participants' thermal comfort, thermal sensation and satisfaction with the temperature as well as their level of presence. Objective measures consist of the physiological responses of their bodies—skin temperature and heart rate. To collect skin temperature from each human subject, chest was selected as a representative spot to measure the skin temperature. This selection was made with consideration of convenience for sensing and adoption rate in previous 16 thermoregulation models(Choi et al., 1997). Each test consisted of two sessions, the in-situ and the IVE which both took place in a climate chamber located in the University of Southern California (USC), School of Architecture. The study protocol was approved by the Institutional Review Board of USC (IRB# 16-00104). Experiments were conducted over a total of two months, March and April 2016. Each subject took part in both two sessions, one for the in-situ and one for the IVE. The sessions were carried out on the same day, one immediately after the other. The experiments were carried out with counterbalancing to tackle the order effect; half of the subjects started with the in-situ, and the other half started with the IVE.

3.2 Subjects

The experiment was conducted with 17 subjects, 6 female, 11 male; they were all undergraduate and graduate students in USC. They attended the experiment voluntarily. Their age ranged from 21 to 28 (median=24) years old. Participants were recruited using flyers and word of mouth on USC campus. Data analysis relevant to the questionnaire surveys were performed with the collected data from all of the participants. However, the carried out physiological data analyses was based on the data acquired from only 12 subjects (5 females, 7 males) due to a sensing system issue, but the sample size is still meaningful to use t-statistics.

3.3 Equipment and Experiment Environment

3.3.1 Climate chamber

The entire experiment, both the in-situ and the IVE sessions, was performed in the climate chamber. The USC climate chamber relies on a heat-balance that provides a carefully controlled environment which is capable of making its occupants shiver or perspire. The air speed in the chamber was controlled at less than 0.2 m/s by ASHRAE-55. A chair and a desk were placed in the center of the room, and data collection equipment was installed. To collect indoor environmental data, the indoor temperature was monitored in the center of the chamber and maintained at 1.6 m high. Relative humidity and CO2 densities were measured as well in order to sustain consistent experimental conditions. The surface wall temperature and mean radiant temperature were also monitored to prevent radiant asymmetry, based on the ASHRAE-55. The relative humidity and CO2 density were maintained around 30~40% and 700~900 ppm during the monitoring experiment.

3.3.2 Virtual Reality tools and IVE setting

In order to build the virtual environment of the experiment, 3D model of the interior of the climate chamber was created in AutoCAD and then imported into a game engine—Unreal Engine 4. Most textures were created externally within an image-editing application (Photoshop) and then imported into Unreal Editor and applied onto the objects and surfaces. Lights and shadows were essentially placed into the model in UE4. A virtual reality headset, Oculus Rift DK2, was used to bring a high level of immersion to the virtual scene (Fig.1). The resolution of Oculus Rift DK2 is 960 x 1080 per eye and was the latest version of the head mount display of the time of this research. The created IVE of this study was sufficiently realistic and almost comparable with the physical version of it (Fig.2).

Fig. 1: Oculus Rift DK2

Fig. 2: IVE view, climate chamber’s 3D model

3.3.3 Physiological monitoring tools

Physiological monitoring in this study was limited to heart rate and skin temperature monitoring. A wireless heart rate instrument was used because of its accuracy and ease of the use (Fig. 3). Skin temperature data was collected by using surface sensors (Model: STS-BTA), which measured skin temperature on direct contact with the skin surface. The collected heart rate and skin temperature were automatically transmitted to the DAQ system in the computer, and recorded as a data file through an interface developed by the research team (Fig. 4). The air temperature, relative humidity, CO_2 density, and air speed were also measured with the same system.

Fig. 3: Heart rate monitoring tool

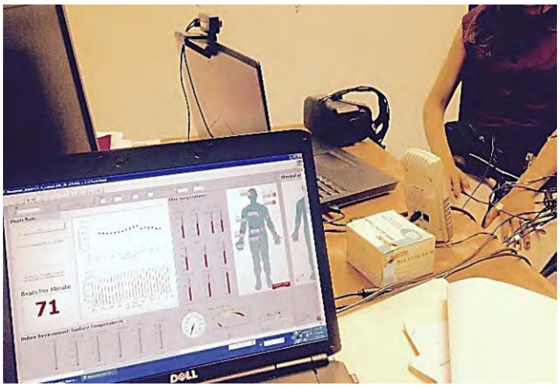


Fig.4: Environment and skin temperature monitoring system

3.3.4 Procedure

On the day of experiment, participants were provided with the informed consent; the consent form was read to the subject and her/his signature was obtained. The research assistant then signed and dated the form. Only after the subject has given her/ his written consent the experiment could began. They were then given a demographic questionnaire. This questionnaire was a part of ITC-SOPI questionnaire asking for information such as age, gender and occupation, plus for information on the subject's knowledge and level of computer experience as well as their prior experience with 3D images and Virtual Reality. Each experiment had two sessions, one in the IVE and one in the in-situ setting. The duration of each session was between 30 to 40 minutes. Both sessions took place in the climate chamber. The in-situ context was in fact the chamber's interior, while the IVE was the virtual representation of the chamber's interior (Fig.2 &6). In both tests, subjects sat on a chair, relaxing and listening to a very soft background music. Once ready, experimenters assisted them to put on the heart rate sensor on their chest and adjust the length of the chest strap, if necessary. Afterwards, skin sensor wires in 9 parts of subjects' bodies were taped onto the surface of their skin; forehead, upper arm, wrist, hand, chest, belly, waist, back neck and neck (Fig. 4). Experimenters were told to be sure to tape the thermistor end (the tip) of the sensor directly to the right position on the skin surface. After reassuring that the heart rate sensor, wiring and the software were working correctly, they would click the collect button on a computer to start collecting data. In the beginning of each session, there was 15-20 minutes standby at around 75F for the adjusting process and consistency by minimizing any variant condition of a metabolic rate and a preceding thermal status across the subjects before the test. With the start of the session, temperature began to gradually increase and once the indoor temperature was stabilized, inquiries concerning the *Thermal Sensation* and *Thermal Satisfaction* were collected every 5 minutes along the experiment. Subjects were assisted by the experimenters when answering the questions, i.e., in both in-situ and IVE, questions were read to the subjects and their answers were recorded (Fig.5). The ASHRAE thermal sensation numerical scale shown in Table 1 was used for the purpose of measuring the subjective physiological sensory related to the environment temperature.

Table 1: ASHRAE thermal sensation scale

Value	**Thermal Scale**
3	Hot
+2	Warm
+1	Slightly Warm
0	Neutral
-1	Slightly Cool
-2	Cool
-3	Cold

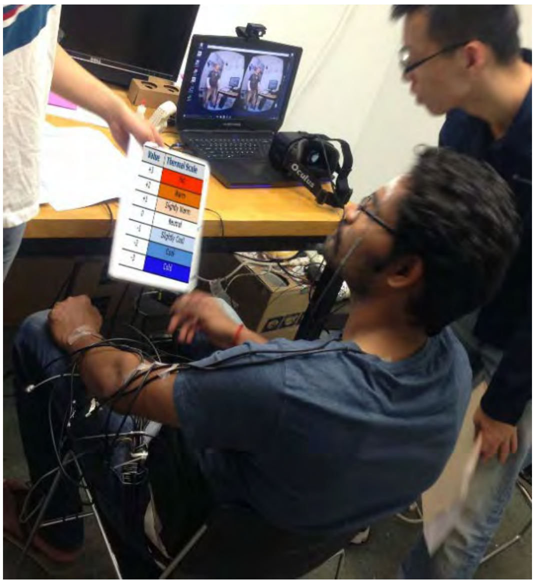


Fig. 5: Thermal sensation inquiry in in-situ setting

Fig. 6: IVE experimental setting

The other commonly used scale which was administered to this study was the satisfaction with the environment temperature (7-point thermal satisfaction scale ending with choices: "Very Satisfied" and "Very Dissatisfied"). Besides, subjects were allowed to explain their dissatisfaction by answering open-ended questions. Subject's physiological responses, skin temperature and Heart Rates, were logged every minute for the duration of experiment. When the temperature reached 85F, collecting data would be over. When an IVE test was involved the presence questionnaire, ITC-SOPI, was administered immediately after the IVE trial. The ITC-SOPI questionnaire measured the subjective quality of individuals' experience in IVE which included 44 items with five-point Likert scales. It breaks down into the level of Engagement with the virtual scene, Spatial Presence, Naturalness of the virtual scene as well as the Negative Effects of the virtual scene on participants.

4. DATA ANALYSIS

All of the participants were able to fully complete the sessions. The collected physiological data was imported from the database and integrated with the subjective recorded data. To examine the impact of IVE and determine the relationship between the collected data in the in-situ setting and IVE, pairwise comparisons of the dependent variables across the experimental setting in different temperatures were performed. To establish the relationship between the participants' subjective votes on their thermal sensation and their level of satisfaction with the temperature across the two experimental settings, data was initially plotted using clustered column charts (Fig. 7 & 8).

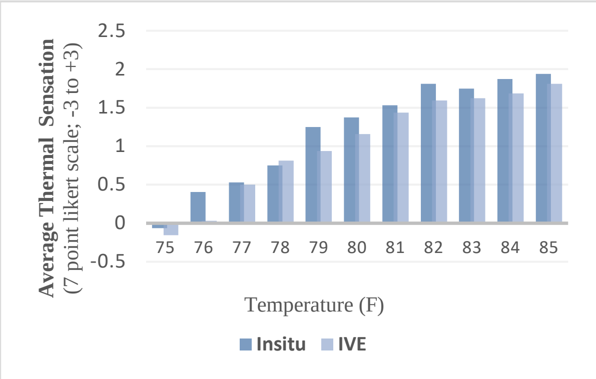


Fig. 7: Thermal sensation in in-situ and IVE

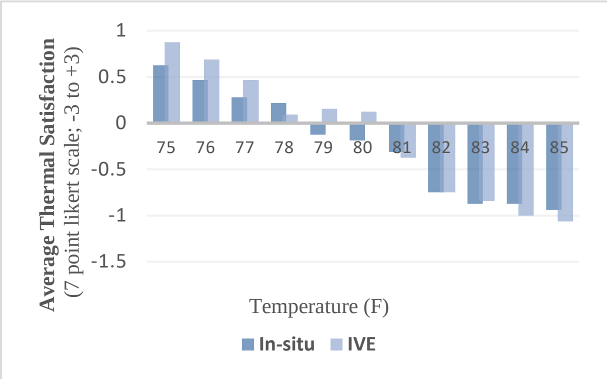


Fig. 8: Satisfaction with temperature in in-situ and IVE

The plotted data (Fig. 7 & 8) revealed a very similar pattern in both settings and Mann-Whitney U test results revealed that there was no significant difference among the recorded measures across in-situ and IVE. Figure 9 depicts Spearman's rank order correlation analysis of each of the thermal sensation and satisfaction with the temperature across the in-situ and IVE experimental settings. Strength of the correlation in this analysis is defined based on Cohen's criteria (Pallant, 2007); correlation is weak if $\pm 0.1 \leq \rho \leq \pm 0.29$; moderate if $\pm 0.3 \leq \rho \leq \pm 0.49$; and strong if $\pm 0.5 \leq \rho \leq \pm 1$. Results of the correlation analysis indicate that there was acceptable (moderate or strong) association of the ranks between individuals reported thermal sensation along the session except in the 76F temperature point. For the other subjective dependent variable, Satisfaction with Temperature, a moderate correlation in the beginning of the session was observed which is proceeded by a weak correlation on the 78F to 80F temperature points and followed by a moderate to pretty strong correlation for the session.

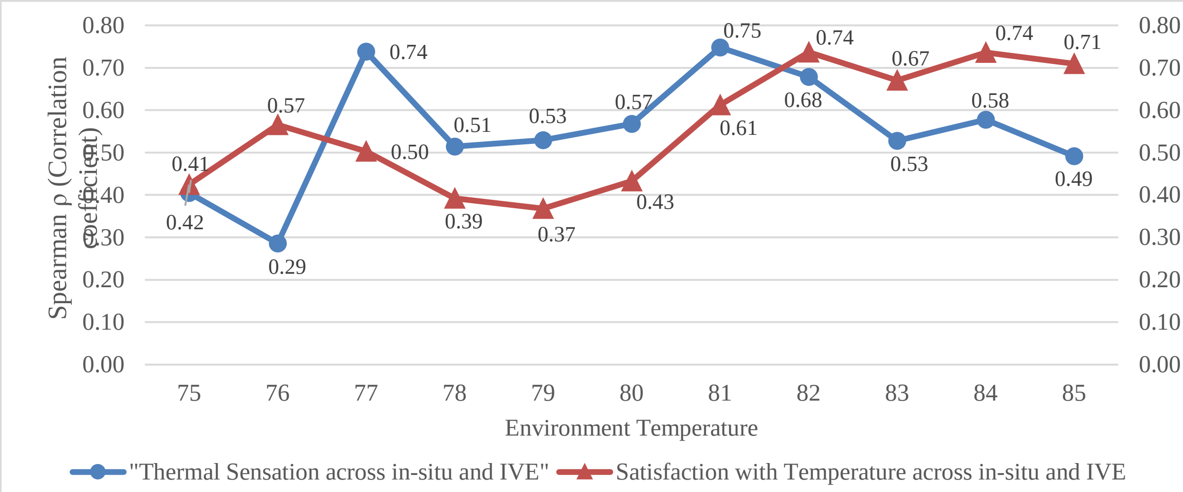


Fig.9: Spearman's rank order correlation of Thermal Sensation and Satisfaction with the Temperature between the in-situ and IVE (95% CI)

The average heart rate of the in-situ group was slightly lower than the recorded average heart rate in the IVE. However, this difference is not statistically significant (p=0.91). In contrary, the measured skin temperature of the in-situ group was slightly higher than that of the IVE group, nonetheless, this difference was not statistically significant as well (p=0.70). Therefore, these comparisons based on the aggregated data could not reveal any significant difference between the two test settings. Figure 10 & 11 shows the mean and range of the data for these two variables.

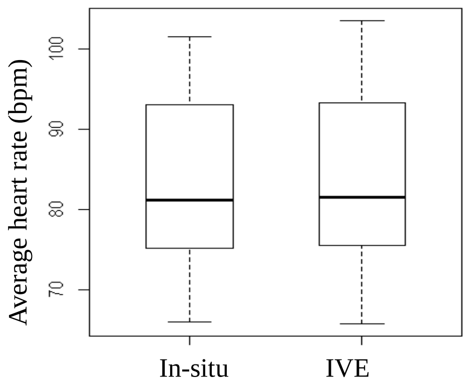


Fig. 10: Comparison of the heart rate (bpm)

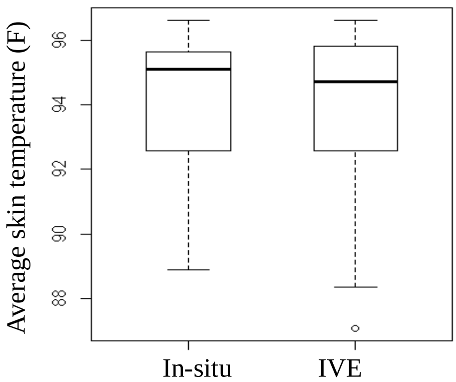


Fig. 11: Comparison of the skin temperature (F)

The two-sample t-tests examined whether there was significant difference between the physiological variables of the study across the in-situ and IVE experimental settings. The t-tests were performed using the average recorded heart rate and skin Temperature and the results are shown in Table 2.

Table 2: Two sample *t*-test of Heart rate in the in-situ vs. IVE settings

	Heart rate (bpm)					**Skin temperature (F)**				
	N	Mean	St.Dev	t	*p*-value	N	Mean	St.Dev	t	*p*-value
in-situ	12	82.54	11.21	-0.12	0.91	12	94.05	2.40	0.38	0.70

IVE	12	83.09	12.03		12	93.62	3.04

Association between the measured subjective dependent variables (thermal sensation and satisfaction with temperature) and the physiological variables of the study (heart rate, and skin temperature) has not been reported in this paper due to some missing data in some certain temperature points for heart rate and skin temperature—minor data collection errors must have happened due to a subject's quick movement, abrupt gesture, dry skin, etc.

Additionally, for assessing the quality of the IVE and subjects' level of presence, the responses to the ITC_SOPI questionnaire was analyzed and compared with the previously conducted studies. The internal reliability coefficient (Cronbach's alpha) were calculated for each of the four ITC-SOPI items. Alphas were pretty close to Lessiter et al.'s (2001) study. There was no statistical inconsistency among the items and they had almost similar loadings. The alpha and the mean score of the four factors are respectively given as follow: Engagement (13 items) = 0.84, 3.44 ± 0.48; Spatial Presence (19 items) = 0.93, 3.37 ± 0.55; Naturalness (6 items) = 0.86, 3.52 ± 0.61; Negative Effects (6 items) = 0.79, 2.61 ± 0.62. The above statistical tests were also compared with the results of other similar studies (e.g., De Leo et al., 2014; Nisenfeld, 2003).

5. RESULT AND DISCUSSION

In this study, participant responses to the experiment experience were used to assess the ecological validity of the experiment. The subjective votes for thermal sensation and satisfaction with the temperature revealed that, except for the beginning of the sessions, there was a high correlation between the recorded votes across the test settings. More prominently, the physiological responses, as control factors, strongly supported the hypothesis of the study. It is revealed that neither the heart rate nor the skin temperature difference between In-situ and IVE were statistically significant. To sum up, the analyzed data indicated that being exposed to IVE and having a head-mount display on face, does not cause interference with the thermal comfort of human subjects in the IVEs. Nonetheless, further studies on more physiological factors are essential, and additional human subject experiments are required to more confidently validate and generalize the findings of this study. Given the results of the presence questionnaire along with the comparable physiological measures (as another commonly used factor of the quality of virtual environments) between the two experimental settings, the authors conclude this study's IVE was able to replicate mundane realism and evoke enough level of presence. Moreover, the similarity of the subjective reports on the thermal sensation and Satisfaction with Temperature across the test settings indicate that the IVE setting did not make change in subject individuals' thermal comfort. The conducted experiment puts forward the IVE as a viable way to study the real world human thermal comfort related experiments. The findings from this study provide useful insight that can be leveraged to replicability of human thermal comfort and occupancy behavior studies in IVE.

6. FUTURE STUDIES

Future studies will more extensively investigate occupant thermal comfort in IVE through setting up more immersive and interactive virtual settings accompanying with various environmental manipulations. This study measured the biofeedback while subjects merely involved sitting and having minimum level of energy expenditure.

However, more researches are needed to test human thermal comfort in IVE's that could replicate wider range of actions (moderate-to-vigorous physical activity) such as walking and performing daily indoor activities. Those data could then feed into the findings of this study and would help to more strongly validate the effectiveness of IVE. Furthermore, for generalizing the results of this research, assessing the impact of potential occupants on the findings of this study would be necessary and it has to be more extensively investigated in separate researches.

7. ACKNOWLEDGEMENT

This research was supported by National Science Foundation (NSF) award # 1338851. The authors gratefully acknowledge the financial support for travel funding and expenses for publishing the results of this research. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of NSF.

8. REFERENCES

Al-Mumin, A., Khattab, O. & Sridhar, G. (2003). Occupants' behavior and activity patterns influencing the energy consumption in the Kuwaiti residences. Energy and Buildings, 35(6), pp.549–559.

ASHRAE (2013). Standard 55-2013-Thermal environmental conditions for human occupancy. ASHRAE. Atlanta, USA.

Van Baren, J. and Ijsselsteijn, W. (2004). Measuring Presence: A Guide to Current Measurement Approaches. Deliverable 5, OmniPres Project IST-2001-39237. Online: http://www8. informatik. umu. se/~ jwworth/PresenceMeasurement. pdf (19. 08. 2011).

Barfield, W. et al. (1995). Presence and performance within virtual environments. Virtual environments and advanced interface design, pp.473–513.

Choi, J.K. et al. (1997). Evaluation of mean skin temperature formulas by infrared thermography. International journal of biometeorology, 41(2), pp.68–75.

De Leo, G., Diggs, L.A., Radici, E. and Mastaglio, T.W. (2014). Measuring sense of presence and user characteristics to predict effective training in an online simulated virtual environment. Simulation in Healthcare, 9(1), pp.1-6.

Dietz, T., Gardner, G.T., Gilligan, J., Stern, P.C. and Vandenbergh, M.P. (2009). Household actions can provide a behavioral wedge to rapidly reduce US carbon emissions. Proceedings of the National Academy of Sciences, 106(44), pp.18452-18456

Dunston, P.S. et al. (2011). An immersive virtual reality mock-up for design review of hospital patient rooms. In Collaborative Design in Virtual Environments. Springer, pp. 167–176.

Freeman, D. et al. (2008). Virtual reality study of paranoid thinking in the general population. The British Journal of Psychiatry, 192(4), pp.258–263.

Hodges, L.F. et al. (1994). Presence as the defining factor in a VR application.

Huizenga, C. (2011). ASHRAE Thermal Comfort Tool CD, Version 2: Maintains Consistency with ANSI/ASHRAE Standard 55-2010.

Kinateder, M., Müller, M., Jost, M., Mühlberger, A. and Pauli, P. (2014)(De Leo et al. 2014). Social influence in a virtual tunnel fire–Influence of conflicting information on evacuation behavior. *Applied ergonomics*, *45*(6), pp.1649-1659.

Kobes, M. et al. (2010). Exit choice,(pre-) movement time and (pre-) evacuation behaviour in hotel fire evacuation—Behavioural analysis and validation of the use of serious gaming in experimental research. Procedia Engineering, 3, pp.37–51.

De Leo, G. et al. (2014). Measuring sense of presence and user characteristics to predict effective training in an online simulated virtual environment. Simulation in Healthcare, 9(1), pp.1–6.

Lessiter, J. et al. (2001). A cross-media presence questionnaire: The ITC-Sense of Presence Inventory. Presence, 10(3), pp.282–297.

Mackie, C. et al. (2004). Desktop and immersive tools for residential home design. In Proceedings of CONVR Conference on Construction Applications of Virtual Reality. pp. 63–70.

Marsh, K.L. et al. (2014). Crowd Guidance in Building Emergencies: Using Virtual Reality Experiments to Confirm Macroscopic Mathematical Modeling of Psychological Variables. In Pedestrian and Evacuation Dynamics 2012. Springer, pp. 197–212.

Meehan, M. et al. (2002). Physiological measures of presence in stressful virtual environments. ACM Transactions on Graphics, 21(3), pp.645–652.

Nisenfeld, S. (2003). Using reality to evaluate the ITC presence questionnaire. Unpublished Master Thesis.

Pallant, J. (2007). SPSS survival manual: a step by step guide to data analysis using SPSS. Step by step guide to data analysis using the SPSS program, p.2007. Available at: http://solo.bodleian.ox.ac.uk/primo_library/libweb/action/search.do?dscnt=1&vl(drStartDay6)=00&vl(60606418UI3)=all_items&scp.scps=scope:(OULS),scope:(NET)&tab=local&srt=rank&mode=Advanced&vl(1UIStartWith1)=contains&tb=t&indx=1&vl(drEndYear6)=Year&vl(freeT.

Van Raaij, W.F. and Verhallen, T.M. (1983). A behavioral model of residential energy use. Journal of economic psychology, 3(1), pp.39-63. Sanchez-Vives, M. V & Slater, M. (2005). From presence to consciousness through virtual reality. Nature Reviews Neuroscience, 6(4), pp.332–339.

Serino, S. et al. (2014). Toward a validation of cyber-interventions for stress disorders based on stress inoculation training: a systematic review. Virtual Reality, 18(1), pp.73–87.

Tichon, J.G. (2007). Using presence to improve a virtual training environment. CyberPsychology & Behavior, 10(6), pp.781–788.

Tutt, D. et al. (2013). Journeys through the CAVE: The use of 3D immersive environments for client engagement practices in hospital design. In Proceedings 29th Annual ARCOM Conference, Association of Researchers in Construction Management, Reading. pp. 2–4.

Villani, D. et al. (2012). May I experience more presence in doing the same thing in virtual reality than in reality? An answer from a simulated job interview. Interacting with Computers, 24(4), pp.265–272.

Wiederhold, B.K. et al. (2002). The treatment of fear of flying: A controlled study of imaginal and virtual reality graded exposure therapy. IEEE Transactions on Information Technology in Biomedicine, 6(3 SPEC.), pp.218–223.

Wiederhold, B.K., Jang, D.P., Kim, S.I. and Wiederhold, M.D. (2002). Physiological monitoring as an objective tool in virtual reality therapy. CyberPsychology & Behavior, 5(1), pp.77-82.

VIRAPH: ENHANCING ARCHITECTURAL DESIGN VISUALIZATION WITH RESULTS OF VISIBILITY GRAPH ANALYSIS

Peiman Amini-Behbahani

University of Newcastle, Australia

Ning Gu

University of South Australia, Australia

Michael Ostwald

University of Newcastle, Australia

ABSTRACT: *Visibility graph analysis (VGA) is an approach based on the space syntax theory to a quantitative and detailed analysis of visual properties in the built environment, offering an understanding of how the space may be used and perceived by its occupants. The VGA measurement results are usually visualized through colored and gridded floor plan. Presently, depthMap is the most common software for performing VGA across the field. However, the set of values which it hands out is limited to the means and sums (e.g., mean depth or total depth). The individual point-to-point or room-to-room ("interspatial") relations are not explored by the exported results – visualized or tabulated – of this software. In order to explore these relations, a new software package, Viraph, is developed by the authors. Viraph offers a relatively faster and interactive way of extracting different levels of depth between portions of the space. This paper presents the technical and interface features of Viraph through a case study of Francis Little House (designed in 1902 by Frank Lloyd Wright). In addition, the paper discusses potential applications for the point-to-point and interspatial visual relations in architectural design analysis.*

KEYWORDS: *Space syntax, visibility graph analysis, Viraph, Francis Little House.*

1. INTRODUCTION

Visibility graph analysis (VGA) is an approach based on the space syntax theory to a quantitative and detailed analysis of visual properties in the built environment, offering modelling and understanding of how the space may be used and perceived by its occupants (Ostwald, 2011). Like other techniques of space syntax, VGA is also based on the gross geometry of built environment that is usually limited to permanent boundaries. The abstracted space is further articulated into a fine grid and converted into a graph in which the vertices represent the grid cells (Turner, Doxa, O'Sullivan & Penn, 2001). The connection (edges of the graph) between any two vertices is defined as the Boolean state of their mutual visibility (though there can be a metric limit for a visible distance). Hence a number of calculations can be performed on the grid to obtain certain space syntax measures. The bases for all measures are either connectivity or depth. Connectivity value for a grid cell is the number of visible grid cells to it, or the number of edges connected to the corresponding vertex. This measure shows the area visible from a point in the space. Depth (D) is the shortest distance between to grid cells or vertices. In VGA usually two non-metric definitions of depth are used: step and angular. Step depth is the minimum number of edges between two vertices. In the space, this number indicates the number of turns (plus one) a person must take to reach from one point to another. The angular depth is the smallest degree of turns a person must take for the same task. This depth value is represented by the unit of 90° (e.g., $D = 1.5$ indicates a sum of 135° turns) (Turner, 2001a). Studies have shown that syntactic turns like these may indicate the likely paths which people may take. The depth value is usually represented as mean depth (*MD*) that is the average of all depths from one grid cell to the rest of the grid. *MD* may reveal degrees of privacy and permeability in different parts of the space.

VGA results are usually visualized by assigning colors to grid cells. The colors represent the respective values of a measure (be it *MD*, connectivity, etc.). Presently, the main software for performing VGA is depthMap (the latest version is called depthMapX, Varoudis, 2014). depthMap was developed in 2001 at University College London (Turner, 2001b). It has gained almost universal acceptance in the field. It performs most of VGA measurements efficiently and fast on a low-end desktop or notebook computer. However, depending on the geometry of the floor plan (or street plan) the measurement may take a relatively long time (up to hours) on such systems. This issue may negatively affect a study in two regards: it slows down the research process or the researcher may reduce the grid resolution to get a faster but less detailed result. This became the motivation for the authors to devise an alternative and faster tool, leading to the making of Viraph (standing for *Vis*ibility gr*aph*). During the process of making and testing Viraph, a number of possible measurements emerged which were gradually added to the software. This paper introduces the technical features of Viraph (including comparing its results with depthMap's) and the features regarding the emerged possibilities. It should be noted that the presented version of Viraph slightly differs (for the better) from the one reported in the first author's PhD thesis (Amini Behbahani, 2016). These features are demonstrated through a case study – Francis Little House, designed by Frank Lloyd Wright in 1902.

The paper is structured in three further sections. The first section presents the computational basis of Viraph, its user interface and the comparison of its results and depthMap's in three respective subsections. The second section discusses the new VGA measures and their possible use in future research. Finally, the last section summarizes and concludes the paper.

2. TECHNICAL FEATURES

In this section, the technical features of Viraph are explained. The section is devised into three subsections. The first subsection presents the geometrical and algorithmic basis of the pathfinding operations. This subsection only focuses on the angular shortest path as the main issue regarding its time taken for calculation. The focus of the section is only on Viraph, as the authors were not able to find the algorithm behind depthMap's calculation. The second subsection compares the duration of calculation and accuracy of results of Viraph with those of depthMap and the third subsection presents the user interface of the software.

2.1 Calculation of angular path

The basis of the calculation of the angular depth in Viraph is to divide the space into arbitrary convex areas (not to be confused with convex mapping of space syntax). Considering that all points inside a convex area are visible to each other, the border between two convex areas is also mutually visible to both areas. This axiom leads to two other obvious axioms:

- The shortest angular path between any two points in the respective convex areas always passes the borders between them (if there is no other convex area in the system).
- Therefore, the shortest path between any two points in the space will pass through a number of borders between convex areas, as long as the points are not located in the same convex area (Figure 1).

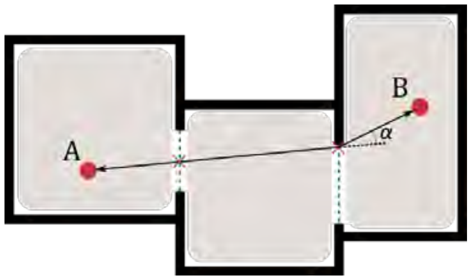


Figure 1. The shortest path between two points (A and B) always passes through the borders (dashed lines) between the convex areas.

Another axiom is the fact that in a concave quadrilateral, ABCD, (Figure 2), the angle δ at the concave vertex D is always larger than the angle β on its opposing convex vertex B. This indicates that the supplementary angle of δ will be smaller (δ'). This smaller supplementary angle (δ') is the angular depth between vertexes A and C, and so, the path ($\overrightarrow{ADC}$) is the shortest path between the two points.

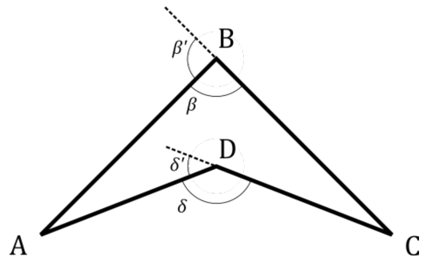


Figure 2. Path $\overline{ADC}$ is the shortest path between A and C.

It is possible to draw similar concave quadrilaterals for any mutually invisible points in two convex areas (Figure 3). In any case, the shortest path always passes either B or D ($\overrightarrow{ABC}$) or ($\overrightarrow{ADC'}$) in Figure 3. In other words, the end points of the borders between convex areas are crucial in forming the shortest angular paths. In a larger set of convex areas where the shortest path will pass multiple borders, this premise will still be applicable because even if a segment of the shortest path passes through the middle of one or more area borders, it simply means that the two sides of that segment are inside a same imaginary convex area (because they are mutually visible). Therefore, the crossed area borders are irrelevant and unnecessary to be considered.

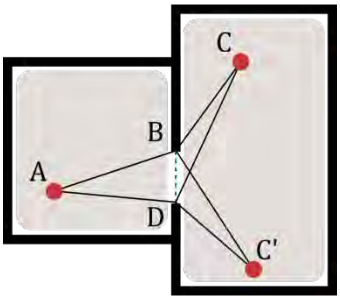


Figure 3. Points B and D are defining the shortest angular path from A to C and C' respectively.

Therefore, in order to find the shortest angular path between any two points, it is only necessary to search the set of border end points. For this purpose, Viraph creates a graph with *2n* vertices representing lines between any two mutually visible border end points (except the end points of the same border). Each line is recorded as two vectors of opposite directions. Thence, two databases are made: a $k \times 2n$ table (k is the number of grid cells) that contains the supplementary angle made by any vector and any grid cell, and a $2n \times 2n$ table which contains the angular depth between all the vectors. The tables are represented by α and β in the following pseudo-codes, respectively. For the second table, the angles between the adjacent continuing vectors are calculated directly without pathfinding. For the rest of the angular depths, a variant of Dijkstra's algorithm (1959) for weighed graphs is used to fill the second table. Pseudo-code 1 shows the general outline of the pathfinding algorithm.

Pseudo-code 1. The pathfinding algorithm for depth between the connecting lines of the borders

```
for each Vi in graph {
    empty(queue)
    for each N in graph {
       N.angle = 0
       unmark(N)
    }
    queue.add(Vi)
    mark(Vi)
    min = 0
    while queue is not empty {
      for each Vj in queue {
        for each unmarked Vk in Vj.neighborhood {
          if α(Vj, Vk) + Vj.angle <= min {
            min = α(Vj, Vk) + Vj.angle
            J = Vj
            K = Vk
          }
        }
     }
```

```
        mark(K)
        α(K , Vi) = min
        K.angle = min
        if not J.containsUnmarked() {
           queue.remove(J)
        }
    }
```

After obtaining the angular depth between all vectors and between vectors and grid cells, the depth between any two grid cells is calculated by checking all connected vectors to those grid cells as in the following pseudo-code 2.

Pseudo-code 2. The algorithm for finding the shortest path between grid cells.

```
for each Ci in grid {
   for each Cj in grid {
      if visible(Ci, Cj) {
        min = 0
      } else{
        min = -1
        for each Vi in Ci.neighborhood {
          for each Vj in Cj.neighborhood {
            if (α(Vi,Vj)+β(Ci, Vi)+β(Cj,Vj) <  min) or (min < 0) {
              min = α(Vi,Vj)+β(Ci, Vi)+β(Cj,Vj)
            }
          }
        }
      depth(Ci, Cj) = min
      }
      MDi += min / (k – 1)
   }
}
```

While the above algorithms are faster than that of depthMap in some situations, they still take a considerable amount of time and memory. To address this issue, an approximation of border ends is considered. In this regard, the border couplet between two convex areas are combined into one and their medial line is considered as the new border. The end points of this line inherit the visual properties of both endpoints of the original border cells (Figure 4). This treatment significantly reduces the number of connecting lines (vertices of the second graph) and so increases the calculation speed. However, it also reduces the accuracy of the results. The speed and accuracy of the results of both treatments are discussed in the next subsection.

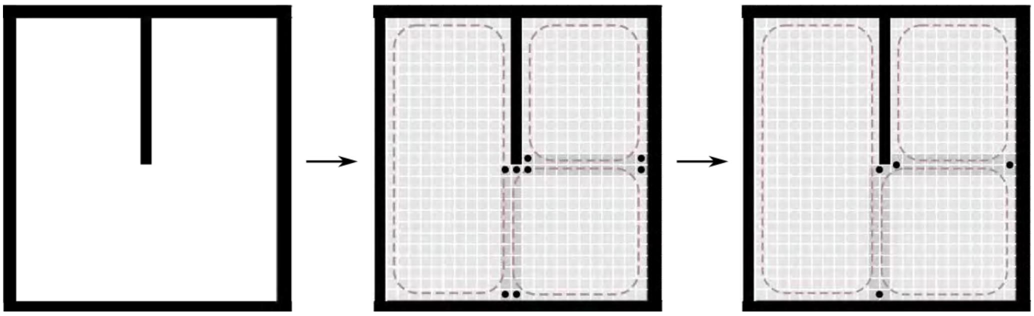


Figure 4. The accurate (middle) and combined (right) border ends (shown as black dots).

2.2 Comparing results

In this subsection Viraph is compared with depthMap (version X) in regard to the speed of calculation, accuracy, and memory usage. Regarding the accuracy, depthMap's results are taken as benchmark. Considering that the main focus of this paper is on the potential usages, the comparison in this section would be brief and limited to only one case. The calculation of the angular depth is done for the first floor of the Francis Little House (floor plan adopted from Futugawa, 1987) on a Dell Latitude 6420 with i5-2430 CPU, operating on Microsoft Windows 7 64bit. Table 1 shows different features of the calculation. The results are shown for both Viraph conditions, with accurate border ends (A) and combined border ends (C). The comparison of the accuracy of the results is based on matching the geometrically closest points on either grids to each other. Once corresponding points are found, three comparisons are done for their *MD* values. First, the absolute difference between the values are measured. Second, the relative difference is measured (as percentile difference between corresponding values). Third, the values' ranking is considered (i.e., to see what rank the n^{th} visually significant point in depthMap has in Viraph's results).

Table 1. Comparison between Viraph and depthMapX in regard to features of calculation.

Item	depthMapX	Viraph (A)		Viraph (C)	
Grid resolution (*k*)	2150	2099		2099	
Unit size (AutoCAD units)	40	40.7		40.7	
Average unit point diff. (δ)	-	42%		42%	
Average absolute difference	-	0.045 turn	or 4.0°	0.025 turn	or 2.2°
Average relative difference	-	6.6%		3.6%	
Percentage of +5% differing results	-	64%		22%	
Percentage of +10% differing results	-	14.8%		3.5%	

Rank difference (%)	-	2.3%	or 50 ranks	2.5%	or 55 ranks
Calculation duration	28:10 min	7:42 min	×3.6 faster	1:32 min	×18 faster
Memory used	72MB	273MB		230MB	

The results show that Viraph is significantly faster than depthMapX (3.6 times in the condition A and 18 times in the condition C). However, it also consumes more memory (3 to 4 times) although a large portion of this memory is because Java's Garbage Collector does not return the used memory to the operating system. In addition, a part of the used memory is also related to retaining the point-to-point depth data for the interactive features as explained in Subsection 3.2. Regarding the correspondence of the results with those of depthMapX, the combined-border condition (C) scored better in both absolute and relative comparisons (3.6% or 2.2° difference compared to 6.6% or 4.0°). Majority of results (64%) for the condition A had more than 5% relative difference. This does not necessarily indicate the inaccuracy of the results in the condition A but possible difference in grid positioning. There was a 42% difference (δ, out of maximum 71%, or half the length of a diagon) in defining the location of unit points between the two applications. This difference could be partially related to the rounding of coordinates by 10 in depthMapX while Viraph used real numbers. Regarding the difference in ranking of the grid cells, conditions A and C had 2.3% (50 ranks) and 2.5% (55 ranks) ranking differences from depthMapX results, respectively (i.e. if the point V_i has the 100th largest *MD* in depthMapX results, it would have the 50th or 150th largest *MD* in condition A). However, this difference is not necessarily significant as the *MD* values are very close to each other in depthMapX results (an average point has 64 other points with *MD* values of only ±0.01 or ±0.9° differences).

2.3 User interface

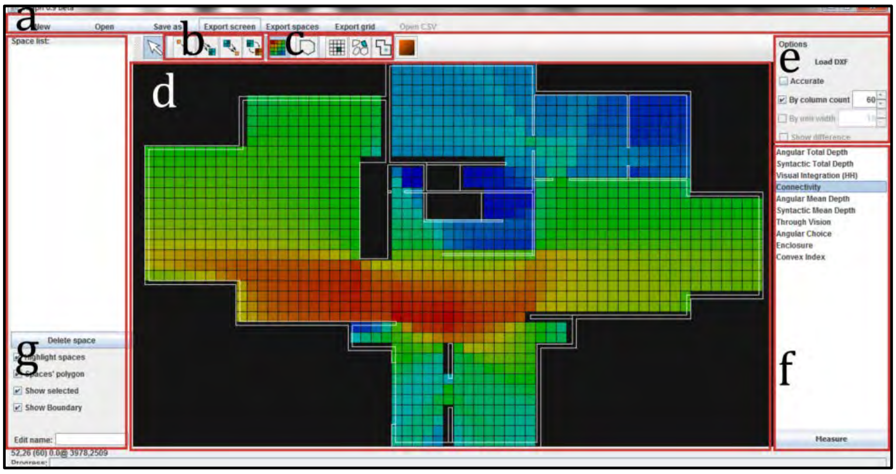


Figure 5. Viraph's user interface.

Viraph is developed in Java platform and thus can be operated on any device and operating system with JRE (version 7+). Figure 5 shows Viraph's user interface. In this figure labels represent: a) main menu, b) display modes, c) operations (selecting inside, drawing spaces, etc.), d) main display panel, e) plan and grid options, f) measures and calculations, g) list and options of spaces.

3. CAPABILITIES

While the initial reason of creating Viraph was to have a faster angular VGA calculation, a number of potentially useful features have emerged during its development. In this section, two of them including interspatial relations and interactive visualization are discussed.

3.1 Interspatial depth and visibility

VGA measures in depthMap software are mainly represented as a collective value (mean or total) for a single spot. The importance of the one-spot mean depth is usually for identifying the least and most visually integrated spots. The collective depth values are obviously obtained from the values of individual point-to-point depths. However, the individual point-to-point depths are not usually a matter of research interest because there is rarely a semantic importance to the visual relationships between such single points in the space.

On the other hand, at least in theory, the visual depth between two rooms or portions of space reveals the degree of visual connection and possible flow of visual information between them. This type of visual depth may be useful to analyze the visual interaction between rooms. In this paper, this visual relation is called *interspatial depth*. The challenge is that despite its theoretical prominence, to the authors' knowledge this measure is not explored by the literature and is not provided by depthMap results.

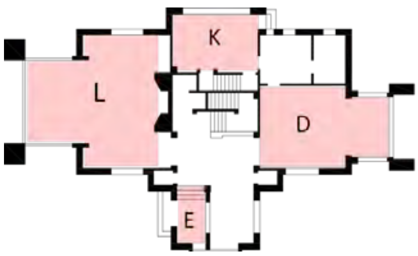
To address this issue, a feature has been added to Viraph to calculate the visual depths between the portions of a visibility grid which are defined by the user as polygons. The formulation for this measure is simply the measurement of the average of step and angular depth values between all grid units of two portions of the visibility grid. Equation 1 shows the formula for calculating interspatial depth (*ID*) between two spaces (*a* and *b*). In this equation, V_a and V_b are points (grid units) in spaces *a* and *b* respectively, and $D(x, y)$ is the visual depth between any *x* and *y*. These depth values are recorded within the process of finding the mean depth (precisely as variable `min` at line 42 in the code in Subsection 2.1). This equation is valid also for step depths and any other measure like connectivity (where *V* values would be either 0 or 1). Notwithstanding the theoretical validity of interspatial depth, the significance of this measure is not yet verified independently.

(1)

$$ID_{a,b} = \sum_{i=1}^{k_a} \sum_{j=1}^{k_b} D(V_{a,i}, V_{b,j}) \,/(k_a k_b)$$

In order to demonstrate the possible use of this measure, a case study was carried out for Francis Little House of the Prairie Style. One of the key values of domestic architecture in that era and style was the segregation of functions, people's genders and classes (Volz, 1992; Grier, 1992) which comes generally under the concept of domesticity, the separation of public and private life (Rosner, 2005). A typical house was generally divided into three carefully segregated zones including social, service and private zones (Cromley, 1996). The social zone included all spaces which were accessible by visitors, such as entry, dining and living rooms and hall. This zone was also where the most of social interactions between family members occurred. The service zone included kitchen and supplementary spaces (e.g., pantry, laundry, etc.) whose main role was to provide food as well as accommodate servants. Finally, the private zone hosted bedrooms and similarly personal spaces. This zone was usually placed on the second level of the house (as in the case of this paper). Regarding segregation, the service zone was considered undesirable because of odor and mess, and was occupied by the lower class servants (Whelan, 2011; Cromley, 2012). This particularly mattered for living room (or parlor) and entry rather than dining room (which was functionally related to kitchen). Since the last quarter of the 19th century and especially in Frank Lloyd Wright's opinion there should have been a closer interaction between family members and so the relevant social spaces in the first level of the house (Maddex, 2002).

In the case study, the angular visual depth between four major functional spaces (living room, dining room, kitchen and entry) were obtained. Figure 6 displays the results of the measurement (the mentioned space are labelled by their first letter). The interspatial depths from kitchen to living room and entry were the highest (2.07 and 1.31, respectively) that indicated lowest degree of visual interaction between the "messy" kitchen and these two social spaces, as expected. On the other hand, the interspatial depth between any two of entry, living and dining rooms were much lower (0.25 to 0.52) which also reflected the architecture of that era: the kitchen was visually distant from the living room and entry while the three social spaces were closely interacting. Overall in our case study, this measure successfully demonstrates a cultural characteristic of the era in this particular house.



Relation	Depth
L-D	0.52
L-K	2.07
D-K	0.60
E-L	0.25
E-D	0.49
E-K	1.31

Figure 6. Angular interspatial depth between major spaces on the first level of Francis Little house.

3.2 Interactive visualization

Mean depth of a point in the space reveals an overall degree of visual relation between that point and the rest of the space. However, it does not provide any information on how the rest of the space is viewed from that point. The measure of interspatial depth addressed this issue for any two portions of the space. However, the exported results (as a spreadsheet) could only be useful when the number of portions are small enough to comprehend them without using a data analysis software. When the number of portions are higher (to the maximum of *k*), it is possible to use a visual representation of the results the same way the colors on the grid are used in depthMap.

For this purpose, Viraph provides an interactive visualization of the results based on the selected *display modes*. A display mode defines the types of two portions of the space for which the results are displayed. In the present version, there are four display modes: point-to-point, point-to-space, space-to-space and mean value. The point-to-point display mode enables the user to see the visual relation between any point and the rest of points in the space, individually, by simply hovering mouse cursor on that point. The point-to-space display mode shows the average of a measure for a portion of space (as defined polygons) from the viewpoint of the cursor's position. The space-to-space mode is similar to the point-to-space mode except that it visualizes the interspatial value if the cursor position is part of a defined portion. Finally, the mean value mode is the same as the existing visualization in depthMap: only showing the mean value for each point.

The potential advantage of the display modes is to understand the visual relations from different points in the space in a very rapid way (all the interactive calculations for the point-to-point depths are already included in the mean depth calculation explained in Section 2). One other potential use is to analyze visual properties of space from the viewpoints of different people. For example, Figures 7 and 8 show the angular depth and connectivity from the visitor's and servant's viewpoints of the house respectively. Both figures show the space-to-point where respective spaces are outlined by dashed boundaries. The boundaries show an estimated approximate movement path of the servants or short-term visitors (excluding those who may stay for dinner). In Figure 7 the darker shades represent visually deeper areas while in Figure 8 the lighter shades indicate the less connected areas.

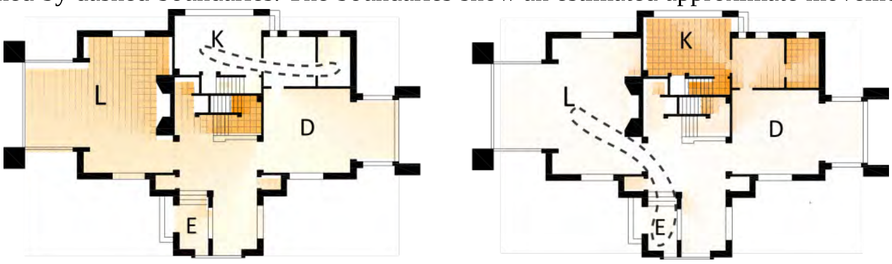


Figure 7. The space-to-point visualization of angular depth for servant's view (left) and visitor's view (right).

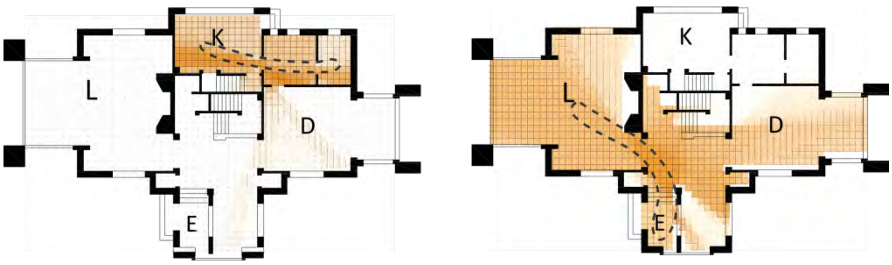


Figure 8. The space-to-point visualization of connectivity for servant's view (left) and visitor's view (right).

The figures show a clear difference between the visual experiences of servants and visitors. In both measures, the service area is the most distant or least visually connected to the likely movement path of a visitor. Meanwhile, the service area does not visually interact with the social area of the house except the dining room which is functionally related to it. Overall, the results suggest the usefulness of this feature of Viraph in the context of analyzing Francis Little House.

4. CONCLUSION

This paper has presented Viraph, a new software for analyzing visual properties of the space. This software offers alternative platform for visibility graph analysis (VGA) that is used to model and understand certain visual properties of the built environment. Viraph features three major capabilities including faster calculation of the angular measures, different approach to clustering and averaging of the results, and interactive visualization of the results through its interface. In this regard, it has the potential to contribute to space syntax research and building analysis. Firstly, it makes analysis more time efficient especially on low-end systems commonly used by students and researchers. The higher calculation speed, particularly in the combined-border mode, makes the analysis more suitable for testing a larger number of designs (e.g., outcomes of generative design procedures).

Another contribution of Viraph is its new measures (e.g., interspatial depth). These measures provide new perspectives to understanding visual relationship between different portions of the space. As briefly demonstrated in the case study of this paper, such measures can be used for studying aspects of space which were not directly quantifiable by the existing methods. The third contribution of Viraph to VGA is the interactive visualization which allows the user to visually analyze different measures. This feature enables a quick analysis of the visual features without the need to refer to the extensive exported results in a spreadsheet file.

Nevertheless, Viraph is limited in regard to its significantly higher memory usage. This issue can be partially resolved by more suitable memory management options in future versions. The current version of the software also uses arbitrary convex boundaries for the pathfinding. It is possible to use an automatic space syntax convex mapping (e.g., medial axial skeleton by Mirranda-Carranza and Koch, 2013) to combine the usefulness of VGA and convex mapping that is extensively used in space syntax studies for analyzing programmatic configuration of the built environment (Ostwald, 2011).

The software and a brief guide are temporarily uploaded on *sourceforge.net* website, accessible to public through the following URL: https://sourceforge.net/projects/viraph/. This version is not yet tested extensively and may be unstable, especially with larger grid resolutions (>4000 units).

5. REFERENCES

Amini Behbahani, P. (2016). *Spatial Properties of Frank Lloyd Wright's Prairie Style: A Topological Analysis* [PhD thesis]. University of Newcastle, Australia.

Cromley, E. C. (1996). Transforming the food axis: houses, tools, modes of analysis. Material Culture Review, 44(1), 8–22.

Cromley, E. C. (2012). Frank Lloyd Wright in the Kitchen. *Buildings & Landscapes: Journal of the Vernacular Architecture Forum*. 19 (1), 18-42

Dijkstra, E. W. (1959). A note on two problems in connexion with graphs. Numerische Mathematik, 1, 269–271.

Futugawa, Y. (ed.) (1987). Frank Lloyd Wright monograph 1901–1906. Tokyo: A. D. A EDITA

Grier, K. C. (1992). The decline of memory palace: the Parlor after 1890. In (Eds.), American Home Life: 1880–1930 (pp. 49–74). Knoxville: University of Tennessee Press.

Maddex, D. (2002). Frank Lloyd Wright: inside and out. London: Pavilion.

Miranda Carranza, P., & Koch, D. (2013). A computational method for generating convex maps using the medial axial transform. Paper presented in *the Ninth International Space Syntax Symposium, Seoul, South Korea*. Retrieved from http://www.sss9.or.kr/paperpdf/mmd/SSS9_2013_REF064_P.pdf

Ostwald, M. J. (2011a). The mathematics of spatial configuration: revisiting, revising, and critiquing justified plan graph theory. *Nexus Network Journal*, *13*(2), 445–470.

Rosner, V. (2005). *Modernism and the architecture of private life*. New York: Columbia University Press.

Turner, A. (2001a) Angular analysis. Paper presented in the Third International Space Syntax Symposium, Atlanta. Retrieved from http://www.ucl.ac.uk/bartlett/3sss/papers_pdf/30_Turner_angular.pdf

Turner, A. (2001b) A program to perform visibility graph analysis. Paper presented in the Third International Space Syntax Symposium, Atlanta. Retrieved from http://www.ucl.ac.uk/bartlett/3sss/papers_pdf/31_turner.pdf

Turner, A., Doxa, M., O'Sullivan, D., & Penn, A. (2001). From isovists to visibility graphs: a methodology for the analysis of architectural space. *Environment and Planning B: Planning and Design*, *28*(1), 103–121.

Varoudis, T. (2014). *depthmapX* – Multi-platform spatial network analysis software. URL: https://varoudis.github.io/depthmapX/

Volz, C. M. (1992). The modern look of early twentieth-century house. In J. H. Foy & T. H. Schlereth (Ed.), *American Home Life: 1880–1930* (pp. 25–48). Knoxville: University of Tennessee Press.

Whelan, L.B. (2011). *Class, Culture and Suburban Anxieties in the Victorian Era*. New York: Routledge.

INTEGRATING BUILDING INFORMATION MODELING AND GAME ENGINE FOR INDOOR LIGHTING VISUALIZATION

Worawan Natephra, Ali Motamedi, Tomohiro Fukuda, Nobuyoshi Yabuki

Division of Sustainable Energy and Environmental Engineering, Osaka University, Osaka Japan.

ABSTRACT: *The quality of lighting has been considered as one of the key parameters for improving human comfort. Recent advances in lighting simulation tools allow users to use Building Information Modeling (BIM) plug-ins for the lighting analysis. Although such tools enable analyzing and visualizing indoor lighting factors quantitatively and qualitatively, they do not provide an interactive environment for changing design parameters. In Addition, their visualization environment does not allow users to experience visual phenomena such as glare. This research proposes a framework for integrating BIM and Virtual Reality for indoor lighting design feedback. The research utilizes an interactive and immersive Virtual Reality environment for a realistic visualization of lighting conditions. The developed prototype system simulates daylighting and artificial lights of a designed building and visualizes a realistic lighting environment using head-mounted-displays. The system also allows a user to interact with design objects and provides real-time feedbacks. Moreover, it helps design stakeholders to better comprehend the design and improve the lighting conditions of their designs to achieve a higher degree of visual comfort for future occupants.*

KEYWORDS: *Building Information Modeling, game engine, indoor lighting design, virtual reality, lighting design optimization, design feedback*

1. INTRODUCTION

There is a growing trend of utilizing computer simulation for lighting analysis based on Building Information Modeling (BIM). A number of existing commercial lighting simulation tools that are compatible with the BIM (e.g., Lighting Analysis in Revit, Lighting Assistant in 3ds Max, Radiance, Daysim and DesignBuilder) have been widely used in visualizing, identifying, and examining indoor lighting performance. The conventional lighting analysis outputs often comprise quantitative and qualitative data, and the visualization features are mainly based on static two-dimensional (2D) images. Some lighting analysis tools, such as Elumtools and Dialux, provide three-dimensional (3D) visualizations and a walkthrough feature. However, such BIM tools can only present a static output with no interaction between the users and the environment (e.g., Bille et al., 2014; Kumar et al., 2011). Hence, they are inadequate for dynamically updating or changing design scenarios in real-time (Kensek et al., 2013). Another limitation of traditional tools is that designers are unable to directly experience some lighting phenomena, such as brightness, glare, or insufficient illumination, which may affect visual perception of the occupants. Consequently, utilizing each of the simulation applications aforementioned has been constrained by simulating only a static 3D model with no capability for providing a timely feedback when comparing multiple designs scenarios.

In addition, while utilizing BIM and its plugins, tasks related to preparing lighting simulation and sharing the information between different tools are very time-consuming (Huang et al., 2008). Furthermore, for achieving a photo-realistic output, the rendering step takes a large amount of time. Conversely, game engines are designed for creating dynamic activities, interacting with objects (Edward et al., 2015) and giving an accurate and timely feedback when users interact with the building elements in a virtual environment. Therefore, coupling BIM and game engines can extend the capabilities of the BIM and make it more powerful to solve above-mentioned issues.

This paper presents a framework for integrating BIM and the game engine to create real-time visualizations of indoor lighting by utilizing an interactive and immersive Virtual Reality (VR) environment. It also provides qualitative and quantitative outputs related to the lighting design. BIM database and scripting features of the game engine are utilized to create a robust prototype system for quickly performing calculation and image rendering. Using VR technology, designers are enabled to perceive realistic lighting scenes of their design. Tools such as Autodesk Revit, Unreal Engine, and its scripting environment were used in our experiments to create an interactive environment that allows to quickly update lighting scenes interactively, which facilitates comparing different designs scenarios. The main contribution of this paper is to create a new method and a tool for visualizing the lighting design by allowing users to explore their designed space, to analyze and assess lighting quality and visual comfort in a virtual environment. The applicability of the method is verified in a real-world case study.

2. LITERATURE REVIEW

2.1 Lighting Design Review in the Architecture, Engineering, and Construction industry (AEC)

Lighting design, including daylighting and artificial lights relies on a combination of specific scientific principles, standards and conventions, and aesthetic (Benya et al., 2001). Five physical parameters influence occupants' visual comfort in architectural spaces: lighting illuminance levels, lighting distribution (diffusion), Correlated Color Temperature (CCT), brightness ratio, and glare (e.g., Fielder et al., 2001; Descottes et al., 2011). Designers need to ensure that the visual comfort parameters comply with the lighting design guidelines, building regulations, and design requirements and recommendations. Visual perception describes an interpretation capability of people to visually perceive their surrounding environment. Regarding human visual perception, the most important variables are CCT and illuminance level (Shamsul et al., 2013).

Lighting simulation plugins for BIM have functions to review different designs for improving lighting for the occupants. There are two different types of lighting simulation plugins compatible with BIM: external and internal plugins. The internal plugins or internal extensions can be added to BIM applications, such as Revit, and provide the highest degree of interoperability with them (Nasyrov et al., 2014). External plugins are needed for data exchange across platforms to perform simulations and visualizations. Although quantitative results are the main output of these plugins, the qualitative results, such as aesthetic, are hard to quantify (Phillips et al., 2000; Sorger et al., 2016). The simulation using traditional tools visualizes the qualitative result mainly on the basis of 2D rendered images. In addition, the simulation feature in these tools, such as Radiance, is time-consuming and not easy to use for real-time simulations (Hu et al., 2011).

Collaborating with computer game environment is a new capability of BIM technology that can provide participants the ability to observe the facility and experience its surrounding environment before it is constructed (Figueres-Munoz et al., 2015). Coupling the game engine and BIM can create a highly interactive environment with a digital geometry model that is derived from the BIM software. Figueres-Munoz et al. (2015) investigated that the integration of BIM and gaming technology has the potential for combinatorial innovation.

A number of previous research studies have proposed methods for integrating game engine, BIM, and VR experience for various purposes, such as design review (e.g., Shiratuddin et al., 2011), construction management (e.g., Bille et al., 2014), education (e.g., Wu et al., 2015), energy conservation (e.g., Niu et al., 2015), real-time architectural visualization (e.g., Yan et al., 2011), and CFD design feedback (e.g., Hosokawa et al., 2016).

2.2 Users' Visual Perception and Lighting Design Metrics in the Game Environment

The experience of virtual reality is based on the users' perception of the virtual world (Mihelj et al., 2013). The VR technology enables the creation of very realistic models and makes the scene look real (Stahre et al., 2006). Immersion (perception) and real-time interaction (action) are two properties of the VR. VR allows users to experience an artificial environment through human senses (Souha et al., 2005).

In the game environment, lighting plays a significant role in making realistic scenes. The game engine technology has lighting features that resemble real-world lightings (Shiratuddin et al., 2011). Lighting simulation in game engines can produce realistic scenes based on the inverse square law, which describes that the illumination intensity varies directly with the luminous intensity on a surface and is inversely proportional to the square of the distance between light source and the surface (IESNA, 2000; de Rousiers et al., 2014). Other lighting metrics, such as luminous flux and light color are also provided in the game engine. Luminous flux (light output or intensity), measured in lumen (lm), is to determine the quantity of light that emits from the lamp to illuminate the entire scene. The light color is expressed as color temperature (Kelvins). The advanced dynamic lighting feature in game engines provides the capability for pre-visualizing various designs. Consequently, the lighting features in game engines can be replaced with the conventional methods, which enable faster lighting simulation when changing parameters. Moreover, it is possible for players to perceive the characteristics of light to determine which design pattern is more appropriate for the users.

As mentioned in Section 2.1, the illumination level and CCT are two variables that have a significant influence on human visual perception. The illuminance value is an indicator of verifying the quantity of light in a given environment, and its required range depends on types of work tasks (IESNA, 2000). International lighting standards and building regulations specify the level of illuminance required to provide visual comfort to facilitate human visual performance. CCT describes the characteristic of light colors. Color temperature plays a particularly important role in both physical properties of light and physiological and psychological response of human perception when the light enters the eyes (Shamsul et al., 2013; Descottes et al., 2011).

3. PROPOSED METHOD

The proposed method comprises six major steps (shown in Fig. 1). The first step is to create the building model using a BIM software. The model data is then exported to the game engine (Fig. 1a). The second step is to setup the game environment to simulate various scenarios and to support interaction with users. Additional adjustments are also performed on the imported model in the game environment (Fig. 1b). Setting up the game environment to interact with the design using scripting is also performed in this step. The third step is the visualization of lighting performance, which is focused on lighting illumination (showing with false colors), brightness of artificial light sources, and lighting atmosphere (Fig. 1c). In this step, lighting simulation is done in the game environment using embedded physics engine. The fourth step is to use immersive visualizations provided in the third step to identify and analyze the performance of the lighting design by visually analyzing lighting conditions, examining visual comfort level to reach an optimum lighting design, and analyzing quantitative information and comparison (Fig. 1d). If the design is not satisfactory, the system provides a possibility to update parameters for simulating new scenarios and visualizing lighting results properly. Hence, the fifth step is to readjust design parameters, if lighting output is not satisfactory (Fig. 1e). The sixth step is to update new design parameters in the BIM after the lighting results are satisfactory for designers and users (Fig. 1f).

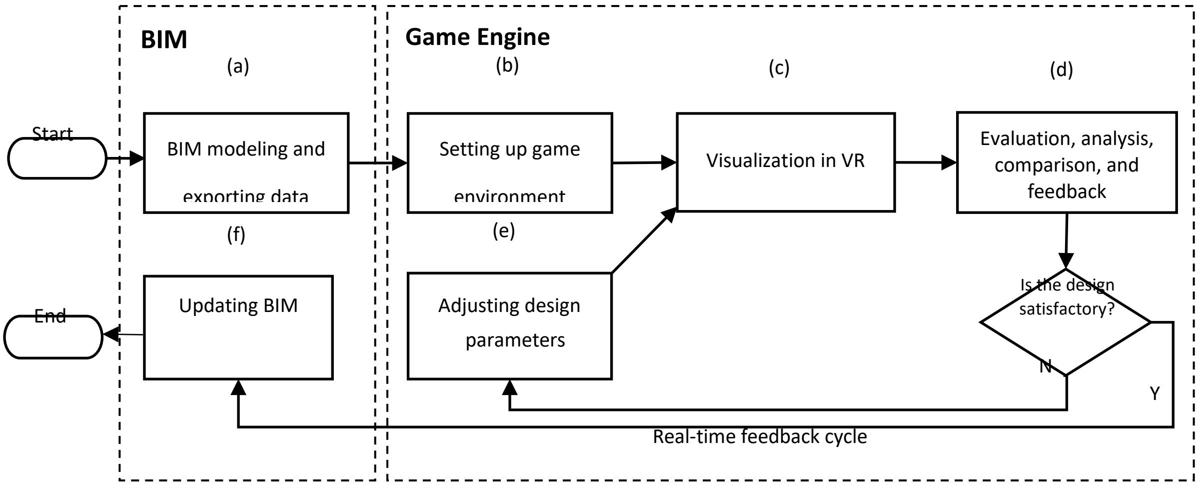


Fig. 1 Overview of the proposed method

After creating an interactive virtual environment in step (b), the game engine allows to interactively explore a 3D space through Head Mounted Display (HMD), which is responding to the motion and rotation of the user's head. Through an immersive VR environment, players can experience a lifelike sense of lighting in game scenes. Mouse and keyboard are used as the input controllers to help users navigating with the first-person perspective. Users' avatar can see surrounding environment in the scene by HMD, which helps to perceive lighting phenomena, such as glare, that is caused by excessive luminance in the Field of View (FOV).

4. PROTOTYPE SYSTEM

The developed prototype system follows the main steps shown in Fig. 2. In our prototype system, BIM model is created using Autodesk Revit (Version 2015). The geometry and material properties of building elements are modeled (described in Section 5.1). A static mesh is then created after exporting FBX file from Revit to 3ds Max. Unreal Engine is chosen as the game authoring environment in our experiment. The game environment is created by manually inputting data, such as adding materials and establishing lighting sources (artificial lights and daylight). The user interface in Unreal Engine is then set up by configuring initial parameters using visual scripts.

This allows users to change parameters of the environment to analyze outcomes. In this step, the user can set parameters and interact with the game environment using input devices, such as a mouse and a keyboard. After setting up the parameters, the simulation is run. Simulation enables users to immediately view quantitative and visualization outputs. Users can then analyze lighting performance by comparing the results of different designs through HMD. The system allows users to redefine parameters and change scenarios until the design is approved.

Graphical User Interface (GUI)

The game engine and the VR technology give users a semi-realistic sense of brightness and darkness when users are performing the walkthrough in virtual reality environment scenes. With the real-time interaction support, our prototype system supports interactivity with which users can experiment and adjust lighting or building parameters.

Unreal Motion Graphics (UMG) is a visual User Interface (UI) in Unreal Engine, which is used to create various UI elements in our system. Visual scripts and graphics are used to construct the interface. The user interface is composed of eight main components that are shown on the display screen. Users can interact with game objects through a set of buttons and dialog boxes.

The following interactions are supported: (a) *First-person movement*: to control the movement of the users' avatar when they are walking in the design space; (b) *User interface control*: to customize parameters, such as time (to observe the dynamic of sunlight), lighting fixtures and light bulb types (to visualize the difference of light outputs), lighting intensity and color temperature (to observe the difference lighting appearance and illuminance level). Fig. 2 shows the GUI interface of our system. The game environment menus enable players to change input parameters and freely navigate game objects using input controllers. Several widgets are created that are shown in Fig. 2; 1) *Minimap*: to show the layout of furniture and the position of user; 2) *Lighting intensity menu*: to change the intensity of light sources; 3) *Compass*: to show the orientation of user when moving; 4) *Color temperatures control*: to change color of the light; 5) *Lighting fixture types menu*: to choose lighting fixtures; 6) *Moving and rotation tools*: to move and rotate the light source, lighting fixtures, and furniture, which are determined as game objects; 7) *Material types menu*: to change the material of indoor envelopes; 8) *Lighting illuminance legend*: to help to measure illuminance level (for false color views).

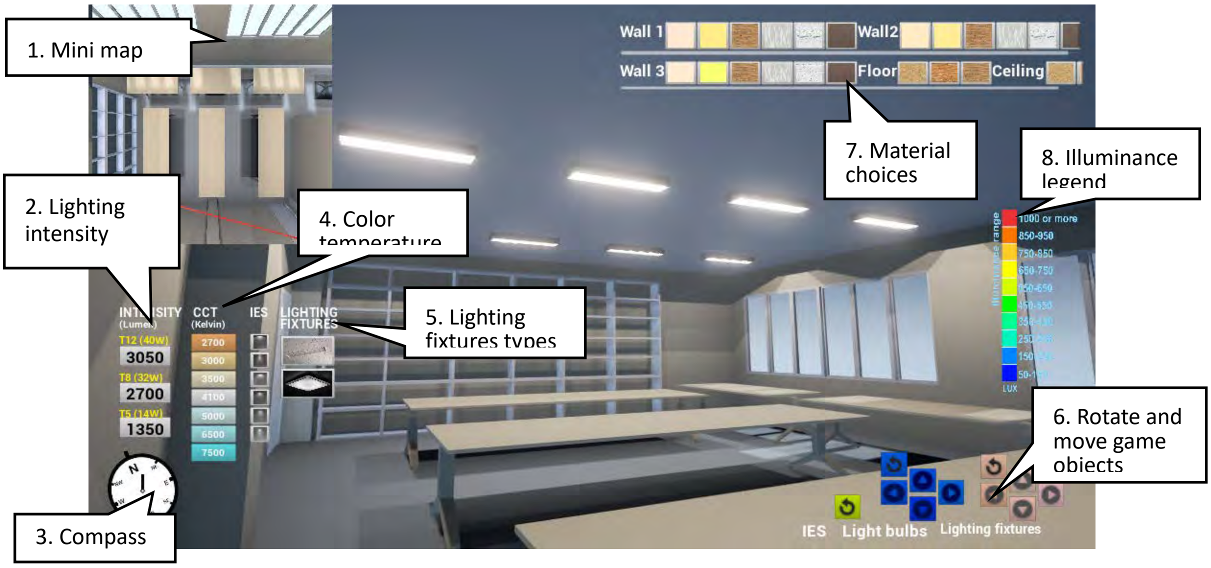
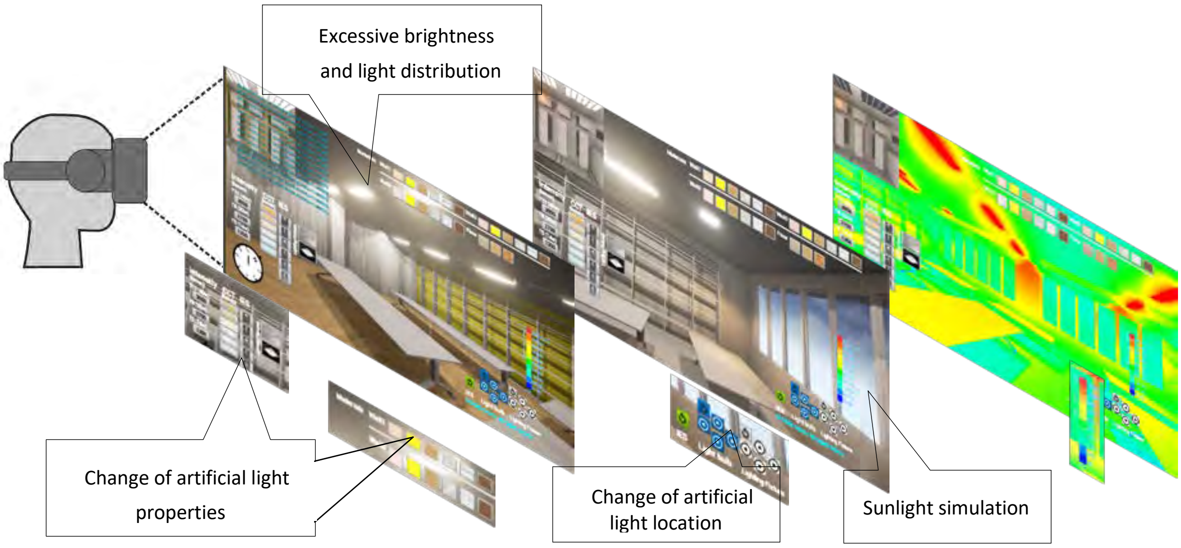


Fig. 2 Screenshot of the main interface of the prototype system

Keyboard and mouse are used to change the view angle and to change design parameters in our system. Having false colors visualized as color textures in the 3D game environment provides users with the capability of analyzing illuminance when walking in the virtual space. The following visualization scenarios are supported: 1) Visualizing the sunlight and artificial lights when adjusting properties, time, and positions (Fig. 3b); 2) Observing the mood and atmosphere of the entire room; 3) Perceiving phenomena of excessive brightness of light sources (strong contrast between objects in the human field of vision) that may lead to discomfort (Fig. 3a); 4) Visualizing quantitative and qualitative data, such as illuminance levels (Fig. 3c).



Scene A : changing materials

Scene B : changing and moving lighting fixture

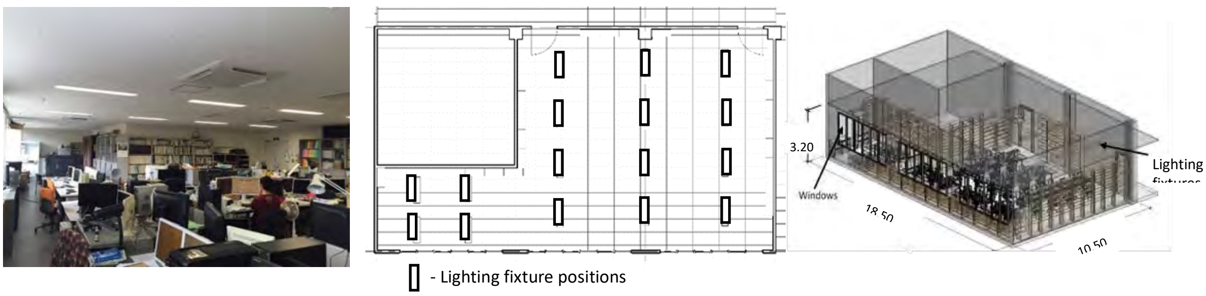
Scene C : illuminance using false colors

Fig. 3 Example scenes in the system

5. CASE STUDY

5.1 BIM modeling and Game Engine Integration

An office room on the 4th floor of the M3 building at Osaka University, Japan was chosen as the experimentation area. The experimentation room has a typical rectangular shape, as shown in Fig. 4a. The BIM model of this room was created based on 2D CAD drawings using Autodesk Revit Architecture 2015 (Fig. 4c). The BIM model contains geometric and non-geometric information of all components, such as lighting intensity, and lighting color temperature. Fig. 4b shows the 2D plan of existing lighting fixtures. The room has 16 lighting fixtures with 32 tubular fluorescent (T8) lamps of 32W.



(a) Photograph of the room

(b) Positions of lighting fixtures

(c) 3D BIM model

Fig. 4 Case study room

In order to transfer the geometry information from Autodesk Revit to Unreal Engine, the building geometry information is needed to be transformed to a static mesh. Fig. 5 shows the process of transferring information, in which FBX file format is used to export the model from BIM application to the game engine.

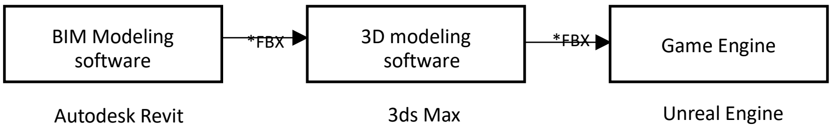


Fig. 5 A BIM model transfers to the game environment

Due to the the lack of full interoperability between BIM and game engine, some important information, such as material textures, color temperature, light intensity, and lighting distribution are lost while exporting data to the game engine. The lost data are required to be properly redefined.

5.2 Setting up the Game Environment

3D objects are automatically created in Unreal Engine after importing 3D geometries from the BIM application. In order to add sunlight, a directional light is added as an actor (Fig. 6a). Visual scripting is used for creating formulas for controlling yaw and pitch of the sun. Although lighting equipment and their position are successfully imported into Unreal Engine, some of their properties are not transferred. Thus, light bulbs are manually added to the game environment (Fig. 6a). In addition, lighting intensity, color temperature, and lighting profiles are manually configured by referencing from the BIM database. Fig. 6b shows a screenshot of an example of visual scripting.

(a) Setting up light sources

(b) An example of visual scripting (Blueprint)

Fig. 6 Unreal Engine configuration

5.3 Creating Interactive Environment

The visual scripting is used to create the Graphical User Interface (GUI) for supporting users' interaction with the virtual environment for adjusting parameters (e.g., light intensity and color temperature). A set of widgets is placed on the screen. The designers can change and preview the lumen outputs and color temperatures (Fig. 7c and 7e) of a given lamp by pressing the buttons (Fig. 7a and 7b). To change the position of lighting equipment, a widget to change the coordinate of lighting fixtures and to move and rotate them is programmed (Fig. 7d).

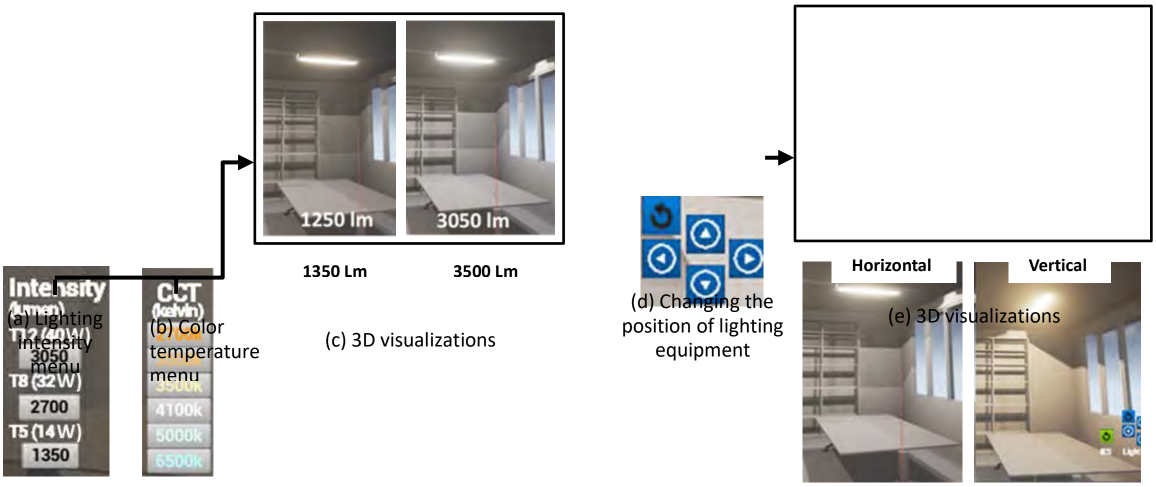
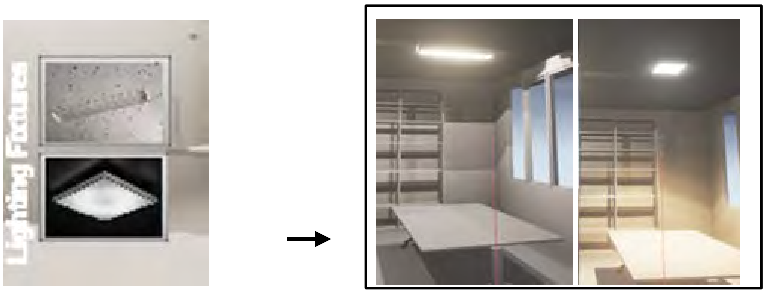


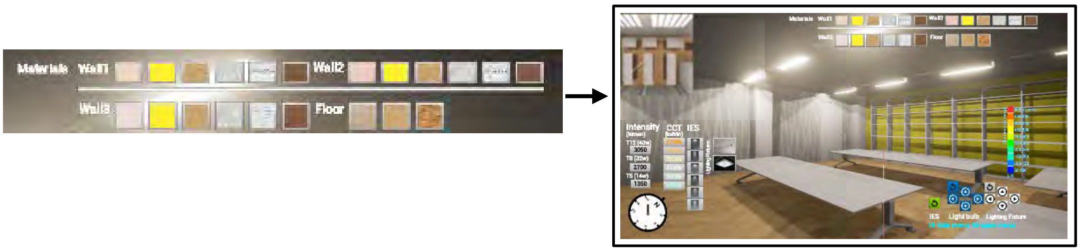
Fig. 7 GUI for lighting fixtures setup

The lighting equipment designed in the BIM application is imported into the game environment. However, additional lighting equipment items are modeled and added as alternative equipment repository. A new type of light equipment can be replaced using the GUI (Fig. 8a). Materials and textures of the indoor envelopes can also be modified using the developed widget (Fig. 8c). These features allow users to modify the design and instantly see the effect of their modification in the simulated environment. Fig. 8c and 8a show the results of simulation after properties are changed.



(a) Lighting Items

(b) 3D visualizations



(c) Material options

(d) 3D Visualization

Fig 8. Lighting fixture and material setup GUI

5.4 Lighting Design Visualization and Analysis

In order to analyze lighting condition, lighting illumination, visual comfort, daylight availability, and aesthetic were focused in the case study. Fig. 9 shows an example of the illumination visualization output over time. An expert can visually observe the amount of light at different times of a day. The illuminance scenes are generated in real-time and are presented using false colors to identify patterns of insufficient illumination or possible sources of problems. Additionally, visualizing and analyzing the amount of daylight illuminations throughout the day are useful to plan for improving the use of daylighting in an effective way to reduce the energy consumption. The results of our case study showed that the working zone that is close to windows can use daylight starting from 9.00 a.m. and the zone that is farther from the windows require artificial light throughout the day.

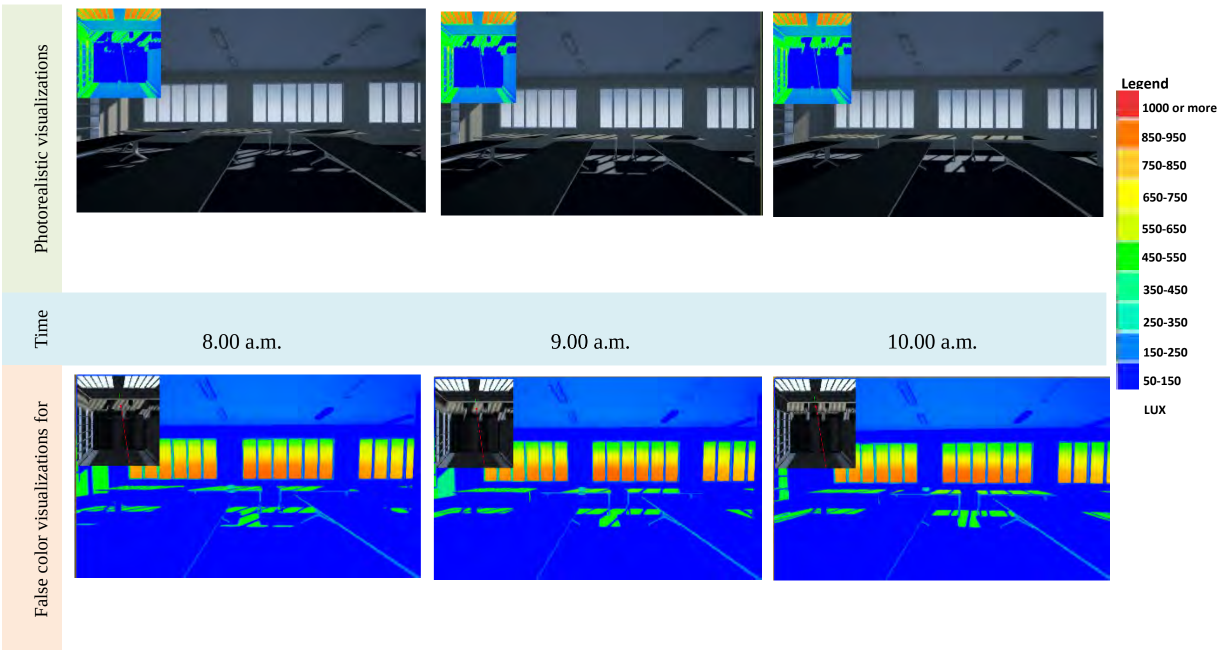


Fig. 9 Example of the illumination visualization output

In our prototype system, users can set the date and time and daylight will be automatically adjusted. Additionally, the user can interact with the lighting switches to turn them on/off using a keyboard. Shortcuts are also defined using visual scripting for an easier operation. In order to verify the performance of artificial lights, a simulation has been performed. The results showed that the illuminance levels in the working areas are between 450 to 500 Lux throughout. It confirms that the current lighting condition of the office areas for computer tasks satisfies the minimum standard requirements, which describes illumination levels of 300 to 400 Lux for typical open space offices (IESNA, 2000) (Fig. 10).

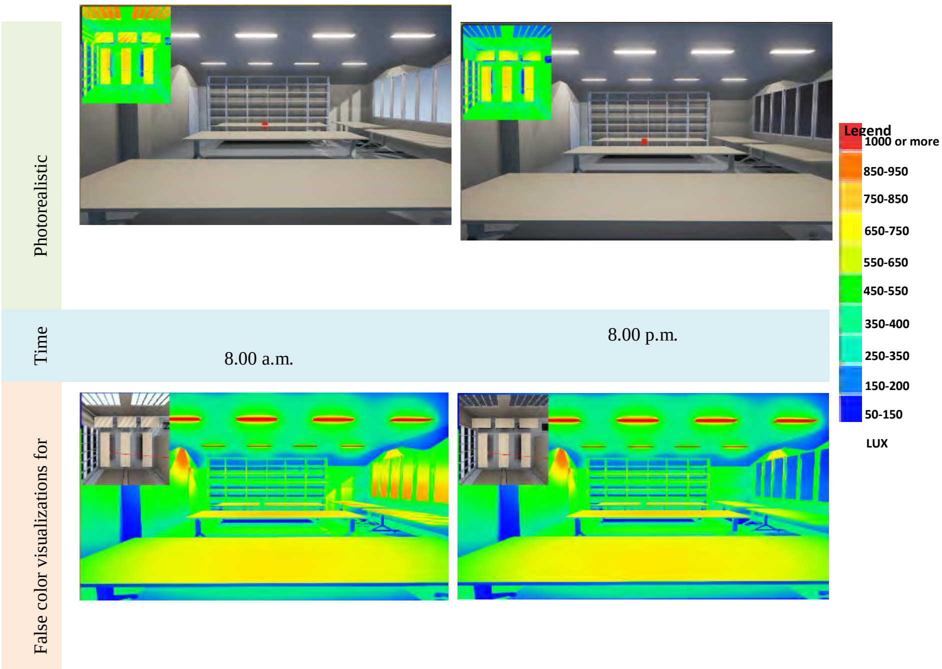
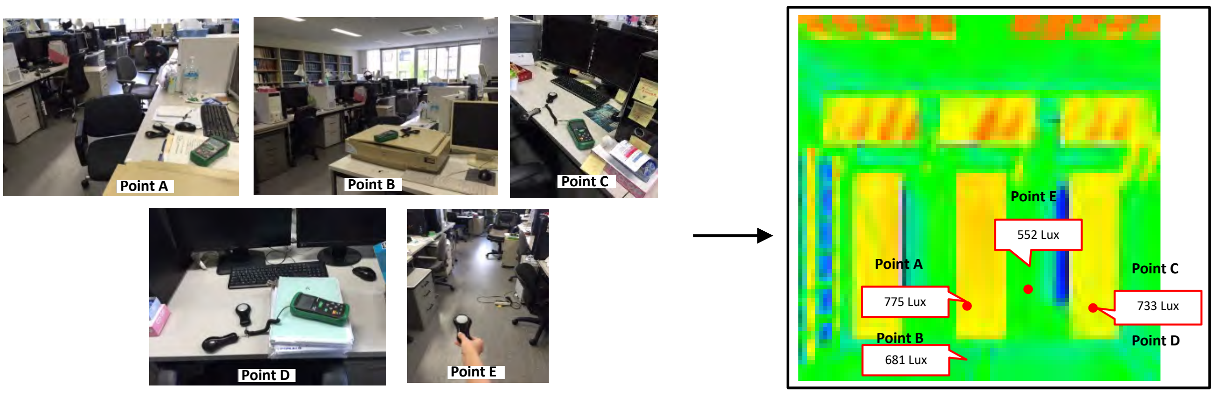


Fig. 10 Lighting illumination level outputs during daytime (left) and nighttime (right)

In order to validate the accuracy of lighting simulation, lighting illumination levels measured by our system and the actual site were compared. The actual illuminance was measured in several locations in the room on the horizontal plane using a light meter (CEM DT-1308 light meter (accuracy ±5%)) (Fig. 11). The measurement performed at 10.00 a.m. by turning on the artificial lights. There are no obstructions between artificial lights and the working desks. The results showed that illuminance levels measured at the work desks were approximate between 681-775 Lux (Point A to D). The illuminance level on the circulation area (Point E) was at 552 Lux. The system simulated the illuminance outputs in the range of 650-850 Lux and the illuminance levels on the circulation area were in the range of 450-550 Lux (Fig. 10). Fisher et al., (1992) recommended an acceptable error range between measurements and simulation is 10% for average illuminance calculations and 20% for each measurement point. Therefore, the error of the system is within the acceptable range.



(a) Measurement points

(b) Simulation results with actual illuminance levels

Fig. 11 Measurements of actual illuminance

5.5 Discussions

Providing useful quantitative and qualitative outputs, such as illumination level, lighting mood, and aesthetic for designers are major concerns in the design process. A good lighting design aims not only at creating appropriate visual conditions, which allow users to work effectively under comfortable conditions but also enhancing the comfortable feeling of the space. The visual appearance of lighting design and layers of lights, such as ambient light, accent light, task light, and decorative light can be easily previewed in the system.

The main limitation was an inadequate data exchange compatibility between BIM and the game engine. Although the geometry of the model can be exchanged between BIM and Unreal Engine, many types of information such as properties of light fixtures, materials and textures were not transferred. Thus, user has to manually define bulbs and recreate textures in the game environment. Additionally, a large portion of BIM model that contains complex geometries, such as furniture models, were not transferred to the game engine. Therefore, creating simple polygon models should be considered in the modeling process. This limitation may be fixed in the new version of the application. In order to accurately perceive lighting phenomena, HMD, such as Oculus Rift DK2, with high resolution of the display screen are required. For simulating the changes of daylight, our simulation is valid only for the time duration and the season of our case study. The locations of furniture items that are directly imported from the BIM cannot be changed in our current implementation. Another limitation is that after lighting design is finalized by designers and clients, the user needs to manually update design parameters in the BIM.

6. CONCLUSIONS AND FUTURE WORK

This paper investigated a method for creating BIM-based lighting visualizations for lighting performance analysis and visual comfort evaluation. The resulting prototype system has the potential for serving as a tool for visualizing lighting conditions and identifying flaws of lighting design in an immersive virtual game environment. The proposed method has been verified in a case study in a campus building. A 3D BIM model was created using Revit, and was exported to Unreal Engine. The developed tool uses VR technology to provide users with the ability to visualize lighting phenomena contributing to achieving visual comfort. Unreal Engine scripting was used to create an interactive environment that provides users with controls, which is useful for lighting design review and real-time analysis. Our initial results showed that the data can be successfully integrated. Quantitative and qualitative outputs can be used for light performance analysis and visual comfort evaluation. Automatic synchronization with the BIM database, developing a method for lighting energy feedback visualization as a real-time dashboard, and creating a sun path system to improve the accuracy of the daylight analysis will be the future work of this study.

ACKNOWLEDGMENTS

This work was supported by Japan Society for the Promotion of Science Research Fellow (JSPS) KAKENHI Grant Number JP26-04368.

7. REFERENCES

Benya, J., Heschong, L., McGowan, T., Miller, N., & Rubinstein, F. (2001). Advanced Lighting Guilelines (2001st ed.). New Buildings Institute.

Bille, R., Smith, S. P., Maund, K., & Brewer, G. (2014). Extending Building Information Models into Game Engines, *Proceedings of the 2014 Conference on Interactive Entertainment*, 1–8.

de Rousiers, C. & Lagarde, S. (2014). Moving to Physically Based Rendering, *Proceedings of ACM SIGGRAPH 2014*, Vancouver, Canada, 119.

Descottes, H. & Ramos, C. E. (2011). Architectural Lighting Designing with Lighting and Space. (B. Casbon, Ed.). New York: Princeton Architectural Press.

Edwards, G., Li, H., & Wang, B. (2015). BIM based Collaborative and Interactive Design Process using Computer Game Engine for General End-Users, *Visualization in Engineering*, Vol. 3.

Fielder, W. J. (2001). The Lit Interior. Architectural Press.

Figueres-Munoz, A. & Merschbrock, C. (2015). Overcoming Challenges in BIM and Gaming Integration: the Case of a Hospital Project, *Building Information Modelling (BIM) in Design, Construction and Operations*, Vol. 149, 329–340.

Fisher, A. (1992). Tolerances in Lighting Design. *Proceedings of the CIE Seminar on Computer Programs for Light and Lighting*. Vienna, Austria: CIE.

Hosokawa, M., Fukuda, T., Yabuki, N., Michikawa, T., & Motamedi, A. (2016). Integrating CFD and VR for Indoor Thermal Environment Design Feedback, *Proceedings of the 21st CAADRIA*, Melbourne, Australia, 663-672.

Hu, J. & Olbina, S. (2011). Illuminance-based Slat Angle Selection Model for Automated Control of Split Blinds. *Building and Environment*, Vol. 46, 786–796.

Huang, Y. C., Lam, K. P., & Dobb, G. (2008). An Scalable Lighting Simulation Tool for Integrated Building Design, *Proceedings of the SimBuild 2008*, Berkeley, USA, 206-213.

IESNA. (2000). The IESNA Lighting Handbook. (J. Block, Ed.) (9th ed.). Newyork: The Illuminating Engineering Society of North America.

Kensek, K. M. & Noble, D. E. (2013). *BIM in Current and Future Practice, Journal of Chemical Information and Modeling*, Vol. 53. New Jersey: John Wiley & Sons.

Kumar, S., Hedrick, M., Wiacek, C., & Messner, J. I. (2011). Developing an Experienced-Based Design Review Application for Healthcare Facilities Using a 3D Game Engine, *ITcon*, Vol. 19, 85–104.

Mihelj, M., Novak, D., & Beguš, S. (2013). Virtual Reality Technology and Applications. Springer Science & Business Media.

Nasyrov, V., Stratbücker, S., Ritter, F., Borrmann, A., Hua, S., & Lindauer, M. (2014). Building Information Models as Input for Building Energy Performance Simulation – the Current State of Industrial Implementations. *eWork and eBusiness in Architecture, Engineering and Construction*, 479–486.

Niu, S., Pan, W., & Zhao, Y. (2015). A Virtual Reality Supported Approach to Occupancy Engagement in Building Energy Design for Closing the Energy Performance Gap, *Procedia Engineering*, Vol. 118, 573–580.

Phillips, D. (2000). Lighting Modern Buildings (1st ed.). Oxford: Architectural Press.

Shamsul, B. M., Sia, C. C., Ng, Y. ., & Karmegan, K. (2013). Effects of Light's Colour Temperatures on Visual Comfort Level, Task Performances, and Alertness among Students. *American Journal of Public Health Research*, Vol. 1, 159–165.

Shiratuddin, M. F. & Thabet, W. (2011). Utilizing a 3D Game Engine to Develop a Virtual Design Review System, *ITcon*, Vol. 16, 39–68.

Sorger, J., Ortner, T., Luksch, C., Schwärzler, M., Gröller, E., & Piringer, H. (2016). LiteVis: Integrated Visualization for Simulation-Based Decision Support in Lighting Design. *IEEE Transactions on Visualization and Computer Graphics*, Vol. 22, 290–299.

Souha, T., Jihen, A., Guillaume, M., & Philippe, W. (2005). Towards a Virtual Reality Tool for Lighting, *Proceedings CAAD Futures, Vienna*, 115–124.

Stahre, B. & Billger, M. (2006). Physical Measurements vs Visual Perception, *Proceeding of CGIV,* Leeds, UK, 146–151.

Wu, W. (2015). Design for Aging with BIM and Game Engine Integration Design for Aging with Building Information Modeling and Game, *Proceeding of 122nd ASEE,* Seattle, USA.

Yan, W., Culp, C., & Graf, R. (2011). Integrating BIM and Gaming for Real-Time Interactive Architectural Visualization. *Automation in Construction*, Vol. 20, 446–458.

APPLICATION OF REAL-TIME VIRTUAL REALITY STREAMING MOBILE DEVICES FOR INTEGRATED PROJECT DELIVERY

Ali Ghaffarianhoseini, Tongrui Zhang, Dat Tien Doan, Attiq Ur Rehman, Nicola Naismith, John Tookey, James Rotimi,

Department of Built Environment Engineering, School of Engineering, Computer and Mathematical Sciences, AUT University, Auckland, New Zealand

Kai Wang, Fukun Ruan, Guoyong Wang, Wange Zhang, Bobing Li

Shanxi Bimcraft Technology Co., Ltd, China

Tianming Yu, Zhentao Mu, Yicao Qi

Shenyang Huayu Architectural Design CO., LTD, China

Amirhosein Ghaffarianhoseini,

Department of Geography, Faculty of Arts and Social Sciences, University of Malaya (UM), Malaysia

Keyu Chen

The Hong Kong University of Science and Technology, Hong Kong Special Administrative Region

ABSTRACT: *Researchers have indicated promising futures concerning the application of Virtual Reality (VR) for Architecture, Engineering and Construction / Facilities Management (AEC/FM) as an industry. Technological advancements have allowed for utilization of highly-efficient computer-based cloud servers. To cater for this potential, contemporary AEC/FM practices demand application of a higher quantity and more advanced mobile devices. Conventionally, contractors often rely on printed drawings, slides and videos to facilitate/inform on-site workers. These methods can be out of date and fail to account for variabilities in usage patterns. On the other hand, establishment of comprehensive VR scenes requires expensive hardware not perfectly suitable for on-site conditions, most specifically in conventional circumstances. Moreover, development of all-inclusive VR frameworks including various components namely: video roaming, VR scene creation, AEC/FM simulation, etc are usually not cost-effective and require considerably time/energy consuming efforts. Correspondingly, this research proposes an integrated methodology for utilizing BIM models in Unreal Engine 4 or Unity 3D for mobile streaming services. Initially, BIM models for this research are generated by designers using Autodesk Revit. Subsequently, digital point-cloud terrain models from Satellites are transformed into GPS Elevation Fitting Models in World Machine. Next, BIM and GPS Elevation Fitting Models are integrated in Unreal Engine 4 or Unity 3D. Then, the Virtual Reality scenes are projected by GeForce Experience. Finally, Stream Theater is used in mobile devices such as mobile phones, pads, etc. to receive frames from the cloud server. Eventually, the proposed* *methodology is validated in the Bailintou Monastery project. The results of this research are expected to significantly reduce the work redundancy and hardware requirements while promoting the visualization of VR-based project presentations and user mobility adaptions.*

KEYWORDS: Mobile Cloud Streaming; Virtual Reality (VR); Building Information Modeling (BIM); Integrated Project Delivery (IPD).

1. INTRODUCTION

As the nature and complexity of communication within AEC/FM projects has changed significantly in recent years (Goulding et al., 2014), VR technologies offer emerging potential for AEC/FM industry (Marc, 2014). Conventionally, 2D has been used by construction contractors as the principal means of communicating design information in the construction industry (Cory, 2001, Schantz, 1989, Watson and Anumba, 1991). This method of communication is not flexible enough and can fail to account for variabilities in usage patterns (Aouad et al., 2013, Watson and Anumba, 1991). Shiratuddin (2015) indicated that conventional two-dimensional (2D) diagrams used in textbooks are not sufficient for conveying the actual representation of the building system in contrast VR technologies show excellent performance in construction training and education. Marc (2014) examined the benefits of VR for design review, and found that VR can bring a better understanding of the design, more involvement within the design review process, an increase in useful feedback on the design and more efficient design review meeting to the design projects.

Advances in computer hardware and software have allowed for utilization of highly-efficient computer-based cloud servers (Koutsabasis et al., 2012). To meet the requirements of VR, the application of higher quantity and more-advanced mobile devices is essential (Shiratuddin, 2015). However, on-site conditions are not always suitable for VR applications for a number of reasons, onsite hardware and software conditions are always not sufficient enough for the implementation of VR. On-site engineers are usually not IT experts or specialists in software technologies , additionally the development of all-inclusive VR frameworks are usually not cost-effective and require considerably time/energy including various components: video roaming (Tian et al., 2011), VR scene creation (Shiratuddin, 2015), and AEC/FM simulation (Goulding et al., 2014), etc Woksepp and Olofsson (2008) indicated that there is a need to reveal the attitudes of the average person working at a construction site rather than of an IT expert, the condition of an average construction site instead of a lab and the actual benefits for normal projects and find solutions based on it. Thus, a solution that can largely decrease the demand of hardware requirements, software skill needed, and development costs is needed in BIM level 3.0. In addition, it will offer an innovative way to excel in construction management (Goulding et al., 2014). Meanwhile, the adoption of this solution in the paradigm of Integrated Project Delivery (IPD) holds potential. This study provides a current literature review concerning related technologies such as Building Information Modeling (BIM), mobile cloud streaming, VR and IPD. It goes on to provide a solution to solve the hardware problems by integrating BIM, VR and mobile cloud streaming in IPD. A case study of the Bailintou Monastery will be used to validate the effectiveness of the solution. Finally, the study discusses the results in context and draws conclusions based on it with several limitations and futuristic works.

2. METHODOLOGICAL APPROACH

This study will explore the use of a real-time mobile cloud streaming method in IPD project in through analysis and induction and validation process. Firstly, analysis is a classic research method by dividing a complex topic or substance into several key parts to gain a better understanding of the topic. This technique has been applied in many fields, especially in the study of workflow logic, and it has been widely adopted in literary review. This study mainly divides the background of the proposed method into four main technologies, including Building Information Modeling (BIM), Virtual Reality (VR), mobile cloud streaming and Integrated Project Delivery (IPD) and makes analysis on the trend of AEC industry related to the topic of this paper. Secondly, induction is a way of reasoning using known facts to produce general laws. This study has drawn the technological roadmap of the proposed method. Thirdly, validation is a way of give evidences for a method to prove or confirm its effectiveness and efficiency. In this study, Bailintou Monastery is selected as a case study to validate the proposed method. This project meets three requirements of validation case for the proposed method as following: Firstly, this project is designed by our team and all the data can be approached on its own. Secondly, this project faces the main issues that the proposed method deals with, such as complex construction process, terrible onsite hardware conditions onsite and unskilled onsite workers for 3D visualization. Thirdly, the volume of this project is not too much, which has a short lifecycle for the research process while remains the effectiveness of the results.

3. BACKGROUND

3.1 BIM

Building Information Modeling (BIM), originated from Building Description System (BDS), which was proposed by Eastman (1974), was first documented by G. A. van Nederveen (1992). A white paper entitled "Building Information Modeling" was released by Autodesk Inc. (AutodeskInc., 2002) which introduces the concept of BIM with its definitions, characters, benefits, road maps for better building projects. Wang (2016) researched the relationship between BIM and VR to keep the sharing and transformation of building information in the whole process of construction. Thus, taking advantage of BIM platform, the proposed method obtains a high-accuracy model full of information in a visual environment.

3.2 VR

VR can assist construction project stakeholders to complete their projects successfully, VR has the potential to enhance the effectiveness and efficiency during the project lifecycle, from initial conceptual design through planning, preparation and detailed design, to construction completion (Thabet et al., 2002). Shi et al. (2016) indicated that VR enables real-time interactions of remote stakeholders in the same environment, with a shared immersive walkthrough experience, which can largely increase the design intent's understanding, improve the project's constructability, and minimize changes and abortive work that can be detected prior to construction's start. Based on a BIM model, the creation of a VR environment could be easier as the 3D model will be available as soon as the BIM-based design is done.

3.3 Mobile cloud streaming

With the fast development of the mobile communication technology, video streaming over phones has become a hot topic among researchers (Banerjee and Bhatnagar, 2014). It opens up new interactive mobile opportunities, including high-performance games and video-related applications (Lawton, 2012). However, the need of resources on mobile devices for multimedia application's increases and Patil et al. (2015) proposed to use cloud resources for mobile multimedia application. Banerjee and Bhatnagar (2014) designed and implemented an adaptive video streaming and effective sharing of video framework for mobile users by using cloud assistance. Thus, mobile cloud streaming is becoming an important computing paradigm to support mobile media services for providing data and control between the cloud and mobile devices through wireless networks, including 3G and Wi-Fi (D.Londhe et al., 2015).

3.4 IPD

Since the 1960s, construction projects have experienced issues with adversarial relationships, low rates of productivity, high rates of inefficiency and rework, frequent disputes, and lack of innovation. These issues result in the increase of construction cost and duration of the project as well as the decrease of construction quality and safety. IPD is structured to address these basic problems (Thomsen and Darrington, 2010). IPD is a delivery system that utilizes a team-based method to combine integrated practices. Therefore, with the fast development of BIM technologies, the adoption of BIM and VR in IPD is urgency needed (Serginson et al., 2013).

4. THE CASE STUDY: BAILINTOU MONASTERY PROJECT

4.1 General description

Bailintou Monastery is located in Yuci District, Shanxi Provence of China. With a total area of 5000 m^2 in a mountain valley terrain, the client has a high expectation on the quality of both design and construction. Due to previous construction project experience the client is very cautious concerning the amount of time and money invested into this Monastery project; therefore, BIM and VR were used to show the client how effectively the money could be managed and display the aesthetics of the building.

4.2 Issues to be faced

This project faced three main issues as below:

a) This project adopts numbers of types of Luban Lock joints for the joint design of the external walls. Luban Lock is a traditional Chinese fabrication method with a complex structure. This increased the difficulty of fabrication and installation process. Meanwhile, as this was an IPD project, the interior decoration was also included in the project scope. The combination of building design and interior decoration was needed. Due to the complex processes above, this project needed more visual methods to coordinate onsite for IPD. Conventional 2D method would not successfully show the construction workers how to work onsite. In addition, onsite workers might not have enough 3D software skills. Thus, the first issue was the 3D visualization for the construction processes.

b) Facing the complex construction process indicated in the first issue, this project needed to involve BIM method to coordinate onsite. BIM can provide a nD model that can involve rich information including installation and fabrication processes data, however the traditional BIM platform do not have mobile devices that can achieve VR-level applications for it. Conventional popular mobile BIM platforms such as BIM 360 GLUE, BIMx only present the roaming of a building in shade mode, which cannot make the users feel like onstage. Thus, the creation of VR environment onsite was the second issue.

c) As mentioned above, this project needed to involve video streaming to make the users feel onstage. However, the hardware requirement for it is much too high. The technology for stereoscopic videos is in common use in recent while a simple stereoscopic video would take large amounts of hardware input from the devices. It is not feasible to install the output file in the mobile phone due to the very nature of the complexity of the BIM model and texture. Moreover, video streaming normally has two screens for both eyes, which means it requires twice the amount of pipelines than the traditional graphic card. On this condition, the mobile devices might not have the power to run the calculations that such compute-intensive programs (Lawton, 2012). Thus, the work redundancy and hardware requirements while promoting the visualization of VR-based project presentations and user mobility adaptions became the third issue.

4.3 Implementation

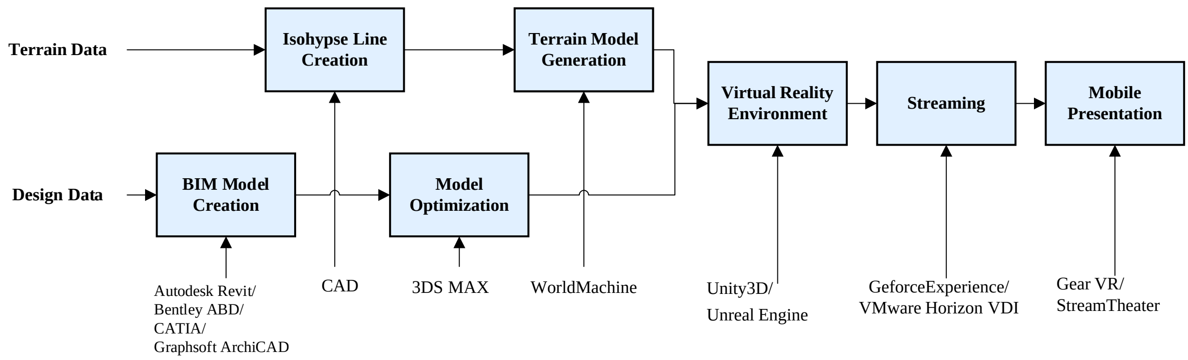


Fig 1. The process of real-time virtual reality streaming mobile devices

This proposed method is to deal with two kinds of models, including terrain models and building models. The workflow of this project is illustrated in Fig. 1. Firstly, terrain models should be generated. In World Machine, digital point-cloud terrain models from Satellites are transformed into GPS Elevation Fitting Models. Subsequently, GPS Elevation Fitting Models are integrated in Unreal Engine 4 or Unity 3D. In this project, Bailintou Monastry is located on a mountainous region. Digital point-cloud terrain models from Satellites were provided (See in **Fig. 2**) and the project team used World Machine to transform the point-cloud terrain models into GPS Elevation Fitting Models (See in **Fig. 3**). During the fitting process, a grey scale height map was used. The grey scale height map can store geographic information.

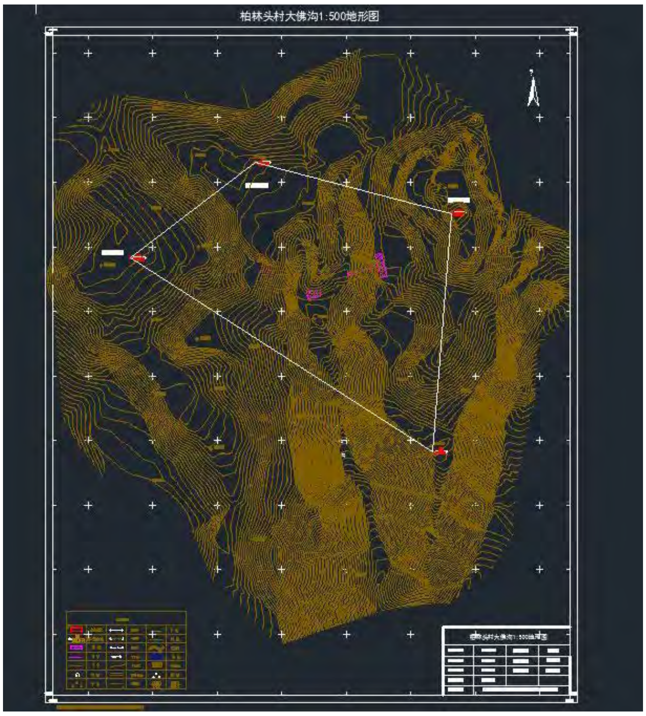


Fig. 2 Isohypse line for Bailintou Monastry project

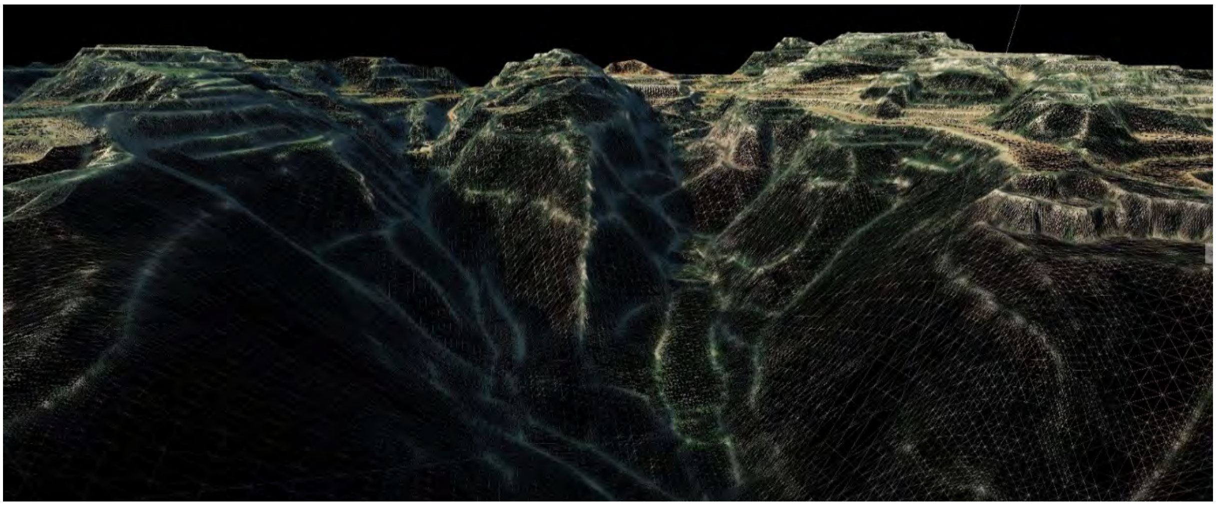


Fig. 3 Fitting terrain for Bailintou Monastry project

Fig 4. BIM model for Bailintou Monastry project

Secondly, BIM models should be created. Initially, BIM models for this research are generated by designers using Autodesk Revit (See in **Fig. 4**). Next, 3DS MAX is used to optimize the models, including decreasing the amount of triangle faces, distinguish different systems and setting light, reflection, texture and camera. Then, BIM models were integrated in Unreal Engine or Unity 3D, aligning with the terrain models (See in **Fig. 5**).

Fig. 5 Integrating BIM model and Fitting terrain for Bailintou Monastry project

Fig 6. 360-degree Stereoscopic video for Bailintou Monastry interior

Thirdly, a series of functional settings should be made in Unreal Engine or Unity 3D. At the outset, the User Interface (UI) of the VR environments should be designed. Following this, the icon, splash image and publishing settings should be set. Then, published the executable file (See in **Fig. 6**).

Fourthly, the Virtual Reality scenes can be projected by mobile cloud streaming. They were then loaded in VMware Horizon VDI with Tridef as a screen divider media. Thus, any mobile phone that connecting the VDI cloud platform can bypass the hardware limitation and enjoy the power of a workstation (See in **Fig. 7**). Despite the bandwidth the internet, VMware uses PCoIP protocol which delivers high compressed H264, aka MPEG-4 stream code of image, however, the experience shown that in order to experience a smooth control over the phone, a high upload bandwidth and reliable internet service provider are preferred. However, it faces challenges such as latency (Lawton, 2012). The mobile users often suffer from disruptions and very long buffering time while receiving video through networks like 3G or 4G due to short bandwidth and link fluctuations (Banerjee and Bhatnagar, 2014). Furthermore, problems such as privacy and reliability are also remained to be solved (Patil et al., 2015).

5. DISCUSSIONS OF THE RESULTS

Our results confirm that real-time VR has a significant impact on IPD. As IPD is expected to combine integrated practice of all stakeholders, the coordination among each stakeholder cannot be emphasized more (Thomsen and Darrington, 2010). During onsite coordination, 2D method cannot fully show the design intents. BIM can provide rich information for the installation and fabrication processes data (Wang, 2016)

The adoption of real-time VR has largely increased the project's constructability, and minimized design changes and abortive work. Due to the expensive mobile devices and small effects of mobile visualization, conventional onsite workers prefer to use interphones to communicate. Although the development of technologies has met with the requirements of mobile applications onsite, the low adoption rate of BIM and VR onsite leave the effects only conceptual. This project adopts the proposed method to integrate cloud computing in the mobile environment and overcomes these obstacles. Onsite workers without 3D visualization skills provided good feedbacks on the effectiveness of this method that they neither need to hold expensive devices, nor receive 3D complex visualization trainings. Thus, this method can largely facilitate the adoption of BIM and VR onsite. Moreover, the improvement of the networks environment is needed. The proposed method currently can only be used onsite with a good network environment, which still largely limits the adoption of it.

Fig. 7 Cloud-based VR in mobile devices

6. CONCLUSIONS

The promotion of real-time VR in IPD has been proposed and applied in Bailintou project, while the mobile cloud streaming has been used to minimize the hardware requirements. With the development of IT technologies, the utilization of highly-efficient computer-based cloud servers is available, which means the hardware requirement of wearable devices is already set free. By applying the proposed approach, the results of the case study reflect a highly visualized coordination onsite.

The proposed approach merges BIM, VR, and mobile cloud streaming in an IPD process. Initially, BIM models are created on BIM platform such as Autodesk Revit, outputted for optimizations and imported into VR environment along with GPS Elevation Fitting Models. Next, VR environment should be created, including UI design and publish settings. After that, mobile cloud streaming can be made through VMware Horizon Client. Finally, the users login to the cloud platform in VMware and use Tridef 3D to enjoy the real-time coordination with all the stakeholders.

The proposed approach provides a simple and useful technique for IPD. Firstly, by adoption of BIM, the work redundancy of remodel has been avoided. The building models created in BIM platform can be utilized with minor optimizations and do not need to remodel. Meanwhile, BIM platform can integrate multiple dimensional building information, which largely facilitate the visualization of VR-based project presentations. Secondly, mobile streaming provides a mobile visualization for the construction process while onsite workers are always on the construction site instead of staying in the office along with the computers. It is expected to significantly promoting the user mobility adaptions. Thirdly, the use of mobile cloud streaming can largely decrease the requirements of hardware while the hardware onsite is usually not satisfied with the requirements of VR.

However, due to the current condition, the proposed approach still faces limitations such as latency, privacy and reliability. Although this method can largely decrease the hardware requirements of onsite environment, the bandwidth and the workload of the networks could limit the effectiveness of the operations of mobile cloud streaming. Meanwhile, the network safety should be guaranteed, because this method significantly rely on networks rather than stand-alone solutions.

Thus, the futuristic research would focus on these limitations. Wide-broad Internet access and reliable network environment solution should be normalized. Otherwise, research on local area network for this topic should be adopted to avoid network troubles.

REFERENCES

AOUAD, G., WU, S., LEE, A. & ONYENOBI, T. 2013. *Computer aided design guide for architecture, engineering and construction*, Routledge.

AUTODESKINC. 2002. Building Information Modeling. *In:* INC., A. (ed.) *Autodesk Building Industry Solutions*

BANERJEE, S. & BHATNAGAR, R. Adaptive and Efficient Video Streaming and Sharing for Mobile Users Using Cloud Assistance. SARC-IRF International Conference, 12th April-2014, 2014 New Delhi, India.

CORY, C. A. 2001. Utilization of 2D, 3D, or 4D CAD in construction communication documentation. *Fifth International Conference on Information Visualisation.* IEEE.

D.LONDHE, R., SHEREKAR, S. S. & THAKARE, V. M. 2015. Cloud-based Mobile Video Streaming Techniques. *International Journal of Computer Applications***,** 0975-8887.

EASTMAN, C. F., DAVID; LAFUE, GILLES; LIVIDINI, JOSEPH; STOKER, DOUGLAS; YESSIOS, CHRISTOS 1974. An Outline of the Building Description System.

G. A. VAN NEDERVEEN, F. T. 1992. Modelling multiple views on buildings. *Automation in Construction,* 1**,** p215-224.

GOULDING, J. S., RAHIMIAN, F. P. & WANG, X. 2014. Virtual reality-based cloud BIM platform for integrated AEC projects. *Electronic Journal of Information Technology in Construction,* 19**,** 308-325.

KOUTSABASIS, P., VOSINAKIS, S., MALISOVA, K. & PAPAROUNAS, N. 2012. On the value of Virtual

Worlds for collaborative design. *Design Studies,* 33**,** 357-390.

LAWTON, G. 2012. Cloud Streaming Brings Video to Mobile Devices. *Computer,* 45**,** 14-16.

MARC, B. 2014. Exploring the impact of virtual reality in design review processes.

PATIL, N., PATIL, N., BAGAL, A., DESAI, M. & BHOSALE, A. 2015. Development of Android Mobile Application for Cloud Video Streaming using Mobile Cloud Computing. *International Journal of Computer Science and Information Technologies,* 6**,** 1990-1993.

SCHANTZ, H. 1989. Banking, information, and imaging standards from a users' perspective.

SERGINSON, M., MOKHTAR, G. & KELLY, G. 2013. A Theoretical Comparison of Traditional and Integrated Project Delivery Design Processes on International BIM Competitions. *International Journal of 3-D Information Modeling,* 2**,** 52-64.

SHI, Y., DU, J., LAVY, S. & ZHAO, D. 2016. A Multiuser Shared Virtual Environment for Facility Management ☆. *Procedia Engineering,* 145**,** 120-127.

SHIRATUDDIN, F. 2015. A comparative study of Virtual Reality displays for construction education. *Jundishapur Journal of Microbiology,* (8).

THABET, W., SHIRATUDDIN, M. F. & BOWMAN, D. 2002. Virtual Reality in Construction. *Engineering Computational Technology.* Saxe-Coburg Publications.

THOMSEN, C. & DARRINGTON, J. 2010. Managing integrated project delivery.

TIAN, C., GUO, H. P., ZHANG, J. & XU, X. T. The Design of Hydraulic Virtual Roaming System Based on Virtual Reality Technology. International Conference on Fluid Power and Mechatronics, 2011. 775 - 778.

WANG, S. S. 2016. Research on Data Conversion of BIM Building Model in VR System. *Value Engineering*.

WATSON, A. & ANUMBA, C. 1991. The need for an integrated 2D/3D cad system in structural engineering. *Computers & structures,* 41**,** 1175-1182.

WOKSEPP, S. & OLOFSSON, T. 2008. Credibility and applicability of virtual reality models in design and construction. *Advanced Engineering Informatics,* 22**,** 520-528.

Part VIII: Laser Scanning and Photogrammetry

SEMI-AUTOMATIC CORRELATION FOR INTEGRATING DATA PRODUCED BY LASER SCANNING AND SFM

Kazuki Fujisato, Hiroshige Dan, and Yoshihiro Yasumuro

Faculty of Environmental and Urban Engineering, Kansai University, Japan

ABSTRACT: *The applicability of three-dimensional (3D) laser scanners, which are capable of capturing the surface shapes of objects as "point cloud" sets, has recently been expanded to include examining, re-designing, and preserving existing constructions, as well as collecting on-site information for building information modeling (BIM). However, one of the difficulties involved when collecting complete scans of outdoor constructions is avoiding occlusions. This means, in order to cover the entire surface of a construction, it is normally necessary to scan it from multiple viewpoints. On the other hand, structure from motion (SFM) is a powerful image-based modeling technique that can be used to recover camera parameters, pose estimates, and create sparse 3D scene geometry from image sequences. Utilizing the mobility of unmanned aerial vehicles (UAVs) equipped with high-resolution cameras, it is possible to compensate for unscanned regions in an outdoor target site and combine the obtained information with multi-view stereo (MVS) process data in order to produce dense surface meshes from the SFM output. In this research, we propose a method for correlating laser scanner point cloud data and SFM data in order to integrate them. Herein, we employ SFM data obtained using UAV-mounted digital camera imagery, as well as an images taken by the laser scanner. Usually, laser scanners are equipped and calibrated with color digital cameras in order to capture color information corresponding to scanned points. This feature allows the scanner viewpoint to be integrated into the 3D geometry reconstructed by SFM. More specifically, the 3D geometry produced by the SFM and the laser-scanned data from scanner position viewpoints are overlaid upon each other, after which, selecting the proper number of points from the scanner view via random sample consensus (RANSAC) permits the proper corresponding points to be found and fit in place automatically. In this study, we conducted an experiment using a UAV (DJI Phantom II) and a laser scanner (Riegl LMS-Z420i) equipped with a high-resolution camera, and found that the resultant 3D data set consisting of complementarily scanner point cloud data and SFM process data covered the entire surface shape of the scene.*

KEYWORDS: *Laser scanner, Structure from motion, Point cloud, 3D integration*

1. INTRODUCTION

Laser range scanners are three-dimensional (3D) surface imaging systems that can be used to produce consistent and accurate assessments of the vast spatial conditions required by various kinds of construction applications. These include investigations into construction process management (Shih et al. 2004, 2006), monitoring as-built infrastructures (Miller et al. 2008), and so forth. Since most of these applications require timely spatial information delivery, collecting the needed information within a limited amount of time is critical for numerous field applications.

Furthermore, as developments of both long-range and vehicle-mounted laser scanners advance, such precise active 3D recording has also come to be effectively used in post-disaster reconstruction work (Watson et al. 2011). On the other hand, due to adverse field conditions at disaster sites, physical access and scanner setup is often limited and difficult. In such cases, scanning the entire shape of a scene is often labor intensive, or may even be impossible because multiple scanning from different viewpoints is often necessary to complement the limited or line-of-sight visibility available from each viewpoint. In such cases, using an unmanned aerial vehicle (UAV), often called a drone, equipped with a digital camera provides an effective alternate strategy for meeting these challenges, particularly since drone flight performance levels and digital cameras image resolution levels have advanced remarkably in recent years.

Additionally, in the computer vision field, 3D reconstruction techniques that use enhanced structure from motion (SFM) techniques can now be easily carried out in combination with those downsized UAVs with small-sized camera. Recently, SFM based on large unorganized photo collections has been successfully used to facilitate 3D reconstruction work. For example, VisualSFM (Wu 2012) achieves $O(n)$ computation cost in practice for n images, while the most commonly known cost for incremental SFM was $O(n^4)$ (Snavely 2006). Since the use of very large photo collections is now acceptable even in chaotic post-disaster situations, small UAVs can examine damaged areas from various distances and viewpoints and gather useful images and/or video footage, not only for reviewing the recorded imagery but also for reconstructing the pre-disaster 3D geometry of the site.

Such 3D information can then be used to facilitate emergency disaster control measures and disaster recovery efforts. However, unlike laser scanner data, SFM data are based on a passive type of 3D imaging measurement

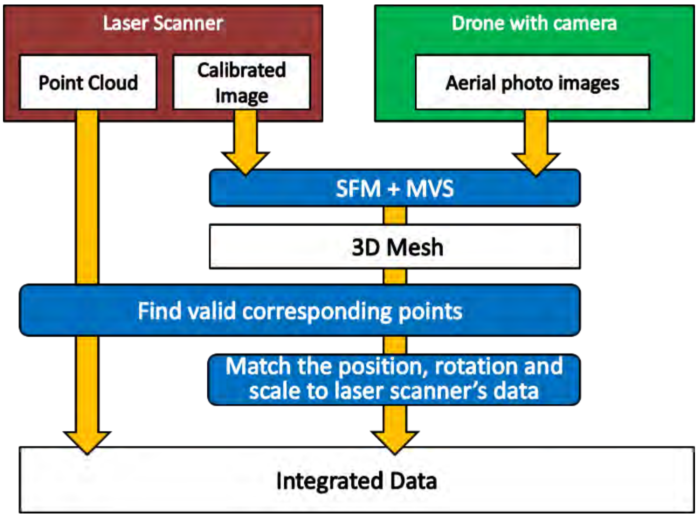


Fig. 1: Diagram depicting the proposed method. A Photo taken by the laser scanner's calibrated camera is combined with photos taken by a UAV for SFM. The generated 3D mesh contains the laser scanner camera viewpoint, which allows valid corresponding points between two data sets to be found easily.

that does not guarantee the absolute scale in nature, and instead depends on the distribution of the natural feature points in the appearance of a scene, which cannot be controlled. As a result, the reconstruction sometimes contains only sparse data points and poor natural features may produce unexpected artifacts, distortions, and noise.

2. METHOD

Conventional methods for registering multiple point cloud data sets are commonly based in the iterative closest point (ICP) algorithm (Besl et al. 1992) and are available for 3D data and designing post-processing in numerous software applications. This algorithm performs difference minimization between point cloud pairs comprising the reference target and the source to be transformed in order to best match the reference. Essentially, the algorithm solves unconstrained optimization problems whose results are sensitive to the initial state, thereby facilitating the iteration start needed to find correspondences between point sets and transform the source points until the best fit is obtained for all points.

When applying simple ICP-based registration to our problem, the initial state is determined by selecting points or mesh vertices as initial correspondences, or by placing the source data set close to the reference data set. This setup is basically manual work, and must take into consideration the acquisition process and characteristic differences between the 3D data sets. More specifically, one is from a laser scanner whose points are aligned on the scan lines, while the other is from an SFM whose points are totally unorganized and may contain huge distortions, noise, and sparse regions. Without this consideration, registration does not work well, even when manual setup is used. This paper addresses this issue by focusing on the reconstructed camera view by SFM.

As shown in Fig. 1, we present a method that can be used to integrate point cloud data from a laser scanner with mesh data generated from SFM. The key idea here is to utilize the photo image taken by the color camera incorporated into many of the laser scanners currently in production. Such cameras are intended to produce pre-calibrated colored point cloud data that allow the 3D coordinates of the measured point data obtained by the laser ranging sensor to be associated with the captured color pixels. This calibration is done by determining the intrinsic camera parameters used to project 3D coordinates onto a two-dimensional (2D) image plane and using extrinsic camera parameters to perform the scaling, translation, and rotation needed transform the 3D coordinates between the laser scanner and the camera image sensor data.

SFM reconstructs 3D geometry by identifying corresponding natural feature points in multiple photo images based on their shooting positions and orientations. More specifically, in the SFM process, photo imagery taken by the camera incorporated into the laser scanner is applied to the SFM input image collection, which consists of numerous images taken by a UAV equipped with a digital camera. From that point, the shooting positions and orientations of both the laser scanner and UAV cameras can be reconstructed in an identical 3D coordinate system determined by SFM.

Since the scanner camera can view both the reconstructed SFM output 3D scene and the point cloud scanned by the laser scanner on an identical image plane, re-projecting the 3D points reconstructed by SFM onto the scanner's camera image permits the pixel position corresponding to 3D points in the scanner coordinates to be identified. Although SFM reconstructs only sparse 3D points, based on which the further multi-view stereo (MVS) process is able to generate dense vertices and meshes, using MVS output facilitates the identification of numerous corresponding pairs of 3D coordinates between the SFM and the laser scanner.

Moussa et al. (2014) proposed a registration method for non-overlapping laser scanned data sets using SFM reconstruction that assumes the reconstructed camera parameters produced by SFM are accurate and useful for the determination of 3D-to-3D correspondences when registering non-overlapping laser scanned data. However, in practice, the SFM reconstruction precision depends significantly on the characteristics of the input image collection. Accordingly, we only use the SFM result for finding candidate correspondences of point pairs between the scanned point cloud and the reconstructed points produced by SFM. Re-projecting both 3D point sets on an identical image plane enables 3D-to-3D pair correspondences for different point set types to be determined in a stable manner.

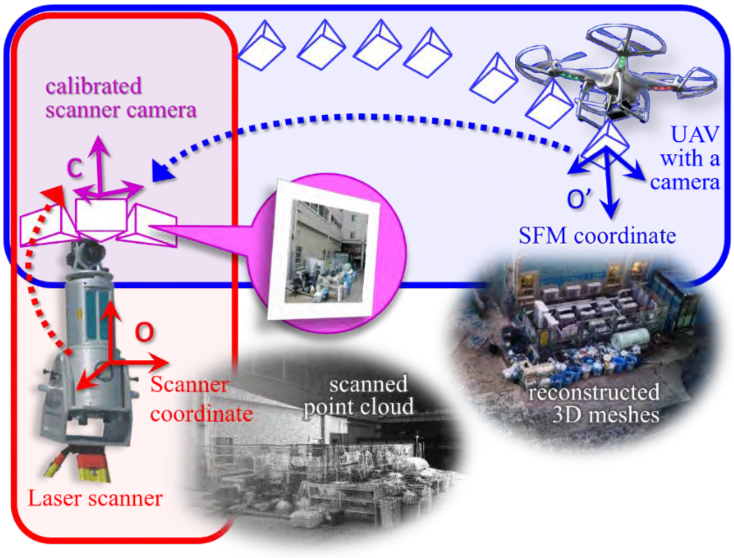


Fig. 2: Schematic concept of the proposed method. Pre-calibrated scanner camera imagery can be used as a medium for transforming SFM and laser scanner coordinate data by incorporating the imagery into the SFM process.

3. Implementation

3.1 Target scene

Assuming that real-world target sites would often have adverse field conditions and complicated structures with numerous visual occlusions, we chose a 20-30-meter-square junkyard on the campus of Kansai University as a test site for our proposed method. In our experiments, we used an LMS-Z420i (Riegl Inc.) laser scanner, and a Phantom2 (DJI Inc.) UAV equipped with a GoPro HERO4 (Woodman Labs Inc.) digital camera. We began by scanning the site from two viewpoints with the laser scanner placed on the ground, and then flew the UAV at a comparatively low height of about 20 meters at the highest in a manner that ensured the aerial view would cover the entire site.

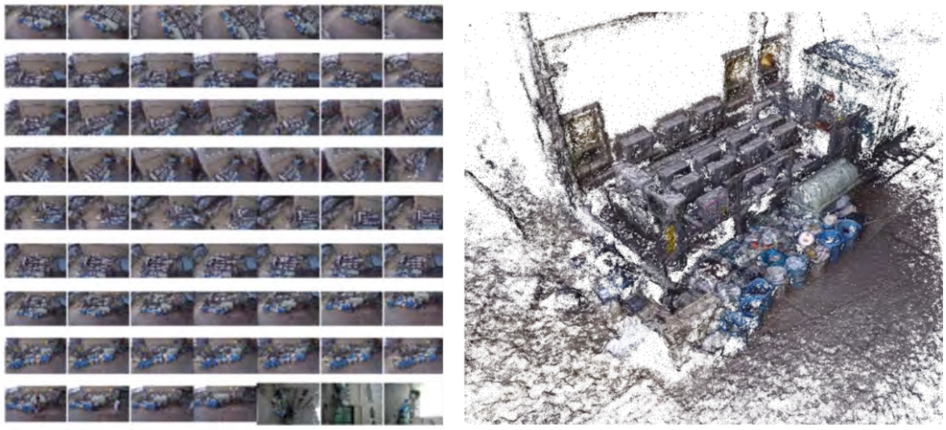


Fig. 3: Portion of the photo collection, including photos taken by both the UAV and laser scanner cameras (left), and the result of the SFM process (right).

3.2 Applying SFM

A total of 133 images were selected for the SFM process. This image collection includes those taken by the scanner camera and captured frames from 4 minutes of video footage taken by the UAV camera. The SFM was produced using VisualSFM, and a further MVS process for creating dense mesh data was performed by CMP-MVS (Jancosek et al. 2012). From these results, 200 million vertices were generated. Moussa addresses the registration of non-overlapping laser scanned data sets using SFM reconstruction (Moussa et al. 2014).

3.3 Selecting Corresponding Points

The scanner camera image plane is associated with the 3D coordinates of the scanned point cloud by using pre-calibrated intrinsic and extrinsic camera parameters. The same image is used in the SFM process, and its estimated viewpoint and orientation results can be used as the extrinsic camera parameters in the SFM coordinate system. From these results, as shown in Fig. 4, corresponding points can be specified in both the scanner point cloud and the SFM reconstructed meshes for each pixel on the image plane. At this point, because the points or reconstructed mesh vertices are unorganized, and thus not aligned on the image plain pixel grid, we use mouse picking to select interest points on the mesh surface produced by SFM.

Mouse picking calculates the ray trajectory from the camera viewpoint toward the mesh surface via pixel selected by mouse, based on the camera parameters. Next, the intersection between the ray and the closest surface from the camera viewpoint is found. Since the intersection point on the mesh polygon surface will be picked up even if the ray does not hit any vertices, it is supposed that point sampling with linear interpolation has been achieved. The laser scanned point counterpart is then associated with the mouse-picked point.

Fig. 4: Point cloud data view (left) and reconstructed meshes view produced by a SFM and MVS process from an identical viewpoint obtained via the scanner camera. Corresponding points can be found at the same pixel position on the image.

3.4 Registration

Since scan data have precise dimensions and organized points, we set the scan data as the reference and the reconstructed data produced by SFM as the source data. Registration is accomplished by finding a scaling, translation, and rotation transform that can match the source data to the reference data. By mouse picking *n* times, candidate corresponding points set in the source data are given as $\mathrm{X} = \{x_i\}_{i=1}^{n}$, and in the reference data as $\mathrm{Y} = \{y_i\}_{i=1}^{n} \subset R^3$. Using unknown rotation and translation parameters $(R, t) \in \mathrm{SE}(3)$ and scaling parameter s gives the following relation:

$$y_i = sRx_i + t.$$

In order to estimate the best parameters $\mathrm{R, t, s}$ from given matrices $\mathrm{X, Y} \in R^{3\times n}$, we minimize the objective function

$$\min_{(R,t)\in SE(3)} \sum_{i=1}^{n} \|y_i - (sRx_i + t)\|^2,$$

where x_i, y_i are aligned columns of $\mathrm{X, Y}$, respectively. The optimization can then be expressed as follows:

$$\min_{(R,t)\in SE(3)} \sum_{i=1}^{5} \|Y_i - (sRX_i + tI^T)\|_F^2,$$

where $I = (1, 1, \cdots, 1)^T \in R^n$ and $\|\cdot\|_F$ denotes the Frobenius norm, which is defined $\|A\|_F = \sum_{ij} a_{ij}{}^2$ for a matrix $A = (a_{ij})$. If we let the centroids (mass centers) of X, Y be $\bar{x} = XI/n, \bar{y} = YI/n$, then following holds:

$$\bar{y} = sR\bar{x} + \mathrm{t}$$

Using $x'_i = x_i - \bar{x},\ y'_i = y_i - \bar{y}$, the translation t can be canceled and the unknown R is the optimal rotation matrix for following problem:

$$\min_{R \in SE(3)} \sum_{i=1}^{5} \|Y' - sRX'\|_F^2$$

where $X' = (x'_1, x'_2, \cdots, x'_5), Y' = (y'_1, y'_2, \cdots, y'_5)$. Using the relation $\|A\|_F = \mathrm{tr}(A^T A)$, the objective function can be written as follows (Arun 1987, Sch**ö**nemann 1996):

$$\|Y' - sRX'\|_F^2$$

$$= tr\left((Y' - sRX')^T (Y' - sRX')\right)$$
$$= \mathrm{tr}(Y'^T Y') + s^2 tr(X'^T X) - 2str(Y'^T RX')$$

Since the first two terms are not related to minimization, the problem can be redefined as the following maximization:

$$\max_R tr(Y'^T RX').$$

Let the singular value decomposition of $X'Y'^T \in R^{3\times 3}$ be $X'Y'^T = U\Sigma V^T$, where Σ is a non-diagonal matrix and $U, V \in O(3)$. Then the objective function can be rewritten as follows:

$$tr\left(Y'^T RX'\right) = tr(RX'V) = tr(RU\Sigma V^T) = tr(V^T RU\Sigma)$$
$$\leq \mathrm{tr}(\Sigma).$$

Eventually, when $V^T RU = I_3$, the objective function is maximized and the rotation is given by $\hat{R} = VU^T$. Then the scaling parameter s is given by the flowing equation:

$$\mathrm{s} = \frac{tr(Y'^T X'\bar{R})}{tr(X'^T X')}.$$

After s and R are obtained, the translation can be calculated as $\mathrm{t} = \bar{y} - sR\bar{x}$.

In our experiment, we implemented a mouse-picking user interface to select ten points (pixels) on the scanner image view without performing any other data operations. Of these, three points are excluded as outliers by random sample consensus (RANSAC). In Fig. 5, the red dots are the selected points and the blue dots are the outliers. The registration result produced by integrating scanned points and SFM reconstructed meshes is shown in Fig. 6. The residual error of the registration was 0.149 m. When compared to the laser scanner root-mean-square (RMS), the residual is large due to noise in the meshes produced by SFM, as show in Fig. 7. This is especially prevalent on the ground surface, where less natural features are found in the image even though many roughly shaped artifacts are visible on the smooth surfaces. Despite this result, we found the correspondences works stably under the same view guarantee.

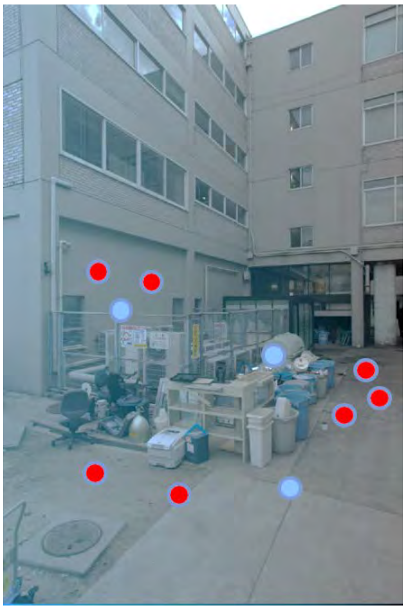


Fig. 5: 3D data view from the scanner image. Both the scanned point cloud and the SFM/MVS reconstructed meshes can be selected from the same pixel section, which permits correspondences to be easily made via mouse picking.

Fig. 6: Registration result. The white dots show the point cloud produced by the scanner and the colored dots are the SFM/MVS reconstruction.

4. CONCLUSIONS

This paper proposed a method for correlating the point cloud data obtained from a laser scanner and UAV camera imagery in order to integrate them together via SFM. More specifically, using a laser scanner equipped with a calibrated color digital camera, the scanner viewpoint is integrated into the 3D geometry reconstructed from UAV collected images via SFM. Then, the 3D geometry of both the SFM and the laser-scanned data are viewed from the scanner position viewpoints, which allows them to be overlaid upon each other. In the next step, selecting the proper number of points on the scanner view by using the RANSAC algorithm facilitates finding the proper corresponding points in order to fit them automatically. Our case study showed effective results based on actual data collected by laser scanner and a UAV-mounted camera that were within the SFM result data quality error rate. Our next step will focus on a fully automatic registration scheme instead of user mouse picking operations.

Fig. 7: Artifacts in the reconstructed SFM and MVS meshes. Reducing the number of image features may cause more unevenly shaped artifacts on originally smooth surfaces.

ACKNOWLEDGMENT

This work was supported by Japan Society for Promotion of Science (JSPS) Grants-in-Aid for Scientific Research (15H02983, 15K02977, 16H05000).

REFERENCES

Shih, N. and Huang, S. (2006). 3D Scan Information Management System for Construction Management, *Journal of Construction Engineering and Management,* 132 (2), 134-142.

Shih, N. and Wang, P. (2004). Point-Cloud-Based Comparison between Construction Schedule and As-Built Progress: Long-Range Three-Dimensional Laser Scanner's Approach, *Journal of Architectural Engineering,* 10(3), 98-102.

Miller P. E., Mills J. P., Barr S. L., Lim M., Barber D., Parkin G. and ClarkeB., Glendinning S. and Hall J. (2008), Ter-restrial laser scanning for assessing the risk of slope in-stability along transport corridors, XXIst ISPRS Con-gress:Commission V, WG 3, Beijing, pp.495-500.

Watson, C., Chen, S., Bian, H., and Hauser, E. (2011). LiDAR Scan for Blasting Impact Evaluation on a Culvert

Structure, *Journal of Performance of Constructed Facilities,* doi: 10.1061/(ASCE) CF.1943-5509.0000318.

Wu, C. (2013). Towards linear-time incremental structure from motion, *International Conference on 3DTV*, pp. 127-134.

Wassim Moussa and Dieter Fritsch, (2014), Automatic Registration of Non-overlapping Laser Scans Based on a Combination of Generated Images from Laser Data and Digital Images in One Bundle, EuroMed 2014, LNCS 8740, pp. 1-10.

Snavely, N., Seitz, S. M., and Szeliski, R. D. (2006). Photo tourism: Exploring photo collections in 3D, *ACM Transactions on Graphics (SIGGRAPH Proceedings)*, 25 (3), 835-846.

Jancosek M. et al., (2011), Multi-View Recon-struction Preserving Weakly-Supported Surfaces, CVPR 2011, pp.3121-3128.

P. J. Besl and N. D. McKay, (1992), A Method for Registration of 3-D Shapes, IEEE Trans. Pattern Anal. Machine Intell, vol. 14, NO. 2, pp. 239-256.

K. S. Arun, T. S. Huang, and S. D. Blostein. (1987), Least-squares fitting of two 3-D point sets. IEEE Trans. on Pattern Analysis and Machine Intelligence, Vol. 9, No. 5, pp. 698–700.

Peter H. Sch**ö**nemann, (1996), A generalized solution of the orthogonal procrustes problem. Psychometrika, Vol. 31, No. 1, pp. 1–10.

REALITY CAPTURE FOR BIM – APPLICATION, EVALUATION AND INTEGRATION WITHIN AN ARCHITECTURAL PLAN OF WORKS

David Craggs

DKS Architects, The Design Studio, Ellerbeck Court, Stokesley Business Park, Middlesbrough, Teesside TS9 5PT, United Kingdom

Michael Crilly

Studio UrbanArea LLP, 31-39 High Bridge, Newcastle upon Tyne, Tyne & Wear, NE1 EW2

Nashwan Dawood

Technology Futures Institute, Teesside University, Middlesbrough, Tees Valley, TS1 3BA

ABSTRACT: *The paper explores the use of reality capture and building information modelling for collaborative retrofitting projects within an architectural SME. Through the use of a series of 'live' case studies, mixed and multiple methods of data and reality capture are tested for speed, cost, accuracy, interoperability and level of detail suitable for concept / detail designs, outline costing, options testing, energy modelling and visualisation tasks. The paper demonstrates an approach to reverse engineering from the perspectives of the different technical and non-expert stakeholders involved within a multi-disciplinary design team to ensure reality capture is appropriately specified and fit for purpose. Specific tasks / activities for (i) data / reality capture, (ii) data integration / editing and (iii) data analysis within a retrofitting architectural and construction project are described using the IDEF0 process mapping methodology and integrated within a standard RIBA architectural 'plan of works'. Examples include measured building survey, photo-matching, structured photogrammetry survey, thermal imagery and both ground level and aerial LiDar survey, combining primary and secondary data sets and utilising a mix of software packages. A comparative evaluation of these reality capture methods sets out the appropriate operational requirements and specifications for a BIM Level 2 project within an SME. The paper explains the benefits of process mapping to understand the interactions between different disciplines and the important role that BIM has in supporting collaboration between SMEs within the AEC sector. The authors also discuss the benefits of utilizing hybrid models as part of a collaborative and unpredictable design process and make recommendations for cost-effective reality capture.*

KEYWORDS: *Process Mapping, Retrofitting, Reality Capture, Drone Survey, Building Information Modelling.*

1. STANDARD ARCHITECTURAL PLAN OF WORKS

This paper is an exploration of a range of reality capture methods and techniques arising out a series of redevelopment and retrofitting projects within a small UK based architectural practice. In common with most architectural practices, this firm followed their own interpretation of a standard work plan and series of specific tasks for individual design jobs. Yet this industry standard processes or 'plan of works' has a particular emphasis on new-build construction rather than refurbishment and didn't provide any specific guidance on initial survey and recent innovations in reality capture processes. There are reasons for this omission. In part it is because within the design industry, standard ‘plan of works’ and business practices originally grew out of the need for legal contract documents within the construction industry. They began as standardised forms of consultancy and contractor services and have since evolved into more complex, state of the art management procedures aimed at addressing each individual stage within the design, construction and development process (Cooper 2008).

A review of BIM policy and practice within the UK house-building industry (HM Government 2012) has indicated how important such a standardised and staged method of working is and how BIM processes need to be fully integrated and embedded in this working method. This is consistent with the policy theme underlying many procedural changes within the UK planning and development professions over the last decade. This has been the idea of a ‘common language’ (Egan 2004) that reflects common aspects of a project brief or specification, a common set of project stages and a common understanding of measurable outcomes. For the design and development industry, this common language is most evident in the wide application and use of the architectural ‘plan of works’ (RIBA 2013) and an adaptation of this framework is the basis for this paper. Within this standard ‘plan of works’ and contract management processes, we aim to identify how project specific requirements for reality capture, as a key task within retrofitting and refurbishment projects, can be integrated with BIM protocols within such a common working process.

This area of applied-research has, in part, grown out of the increasing interest in large-scale retrofitting projects aiming at addressing energy efficiency and fuel poverty within the existing building stock, albeit it is as applicable to other non-domestic building sectors. This is aligned with the absence of any current standard approach to building survey / reality capture within the ‘plan of works’ or accompanying BIM overlay (Sinclair 2012). The lack of an agreed reality capture or survey process from the outset of a project gives rise to complicating issues later into the work stream and potentially negating many of the time and efficiency saving promised by the implementation of a BIM strategy. By understanding the client / employer information requirements, the best approach to reality capture can be specified and related to an overall BIM execution plan. This will avoid duplication of efforts, additional surveys being undertaken, appropriate levels of detail and information, avoid over-specification and ultimately be more efficient.

1.1 BIM overlay for an architectural ‘plan of works’

> “BIM is a process that improves the efficiency of organising and distributing data ... (and) ... many working within house-building do not yet have an awareness of the potential benefits for their sector.” (Nick Raynsford quoted p1 in; NHBC Trust and BSRIA, 2013).

Within the UK there are clear messages from both research and industry reviews that the current housing and retrofitting market “… is not capable of delivering sufficient housing to prevent a serious shortfall …” and that part of the solution is to “… (r)aise awareness and support the training and integration of BIM across *all segments* of the market, providing support and encouragement to the self-builder, the small to medium size house builder, the largest private house-builders, RSLs, LAs and other client organisations” (Miles and Whitehouse 2013, p33). In this context, BIM is understood, by central government at least, as the basis for economic growth in the housing and retrofitting market and the wider construction industry (Saxon 2013).

Yet, while there are an increasing number of retrofitting and refurbishment projects, the BIM 'industry stakeholders' have tended to omit the relative significance of the retrofitting market and instead concentrate on the production of execution plans suitable for new design and construction projects. This is, in part, due to the relationship of a BIM execution plan and industry standard plan of works.

1.2 Process mapping applied to an architectural 'plan of work'

In order to understand the relationship between the RIBA 'Plan of work' (2013), the requirements for project specific BIM Execution Plan(s) and retrofitting tasks or activities that currently fall outside of both of these procedural and project management tools, we based our approach on the use of a process mapping methodology that could effectively incorporate architectural, digital modelling, energy analysis and multiple survey methods in a single approach.

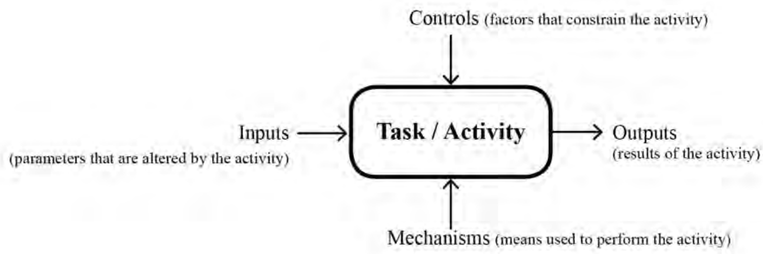


Fig. 1: Structure of IDEF0 process mapping for a specific task or activity.

Reviewing advice on choosing the most appropriate process modelling pointed us toward the Integrated Definition for Function Modeling (IDEF) as a family of hierarchical models (Aguilar-Savén 2004) that provides a comprehensive and common understanding of complex processes. IDEF0 (IDEF level zero) is a modelling technique used for developing structural graphical representations of processes or complex systems. It is used to specify function models, which are "what do I do?" models. These show the high-level activities of a process indicating major activities and the input, control, output, and mechanisms associated with each major activity. Although the methodology emerged from the operations of the US Airforce in the 1960s onwards; as the significance of ICT in the manufacturing operations and practice began to become more prominent and thus the operations correspondingly more complex and involving more stakeholders and actors; it has increasingly been utilised within the design and construction industry sectors.

There are well-documented advantages to using IDEF0 as a standardised, widely accepted and recognised process-mapping technique (Colquhoun *et al.* 1993) within both academia and industry. Firstly, is the imposition of formality for every individual user. Secondly, there is the ability to integrate individual tasks and operations into a much larger model and complex design and development process. There is the potential for 'partitioned' models to be generated for individual stages and / or tasks. Starting at a high level in the development of 'parent' process diagrams that are suitable for non-expert involvement but also the ability to examine and deconstruct any design and development process into much more specific tasks for many different technical specialists. Recognition of hierarchal nature of the processes (Zugal *et al.* 2015) (in the parent diagram) and the sub-processes (in the ‘child diagram) and recognition of common patterns (Bergener *et al* 2015) in the hierarchy. This hierarchical structure of tasks in IDEF0 closely reflects the hierarchy of stages, tasks and sub-tasks within the architectural ‘plan of works’ and the development of BIM overlay and supporting tools (NBS 2016). It is the closest thing to an industry standard that presently exists. This level of recognition is important to support external review, comparison and analysis of design and / or manufacturing practices and processes (Melao and Pidd, 2000).

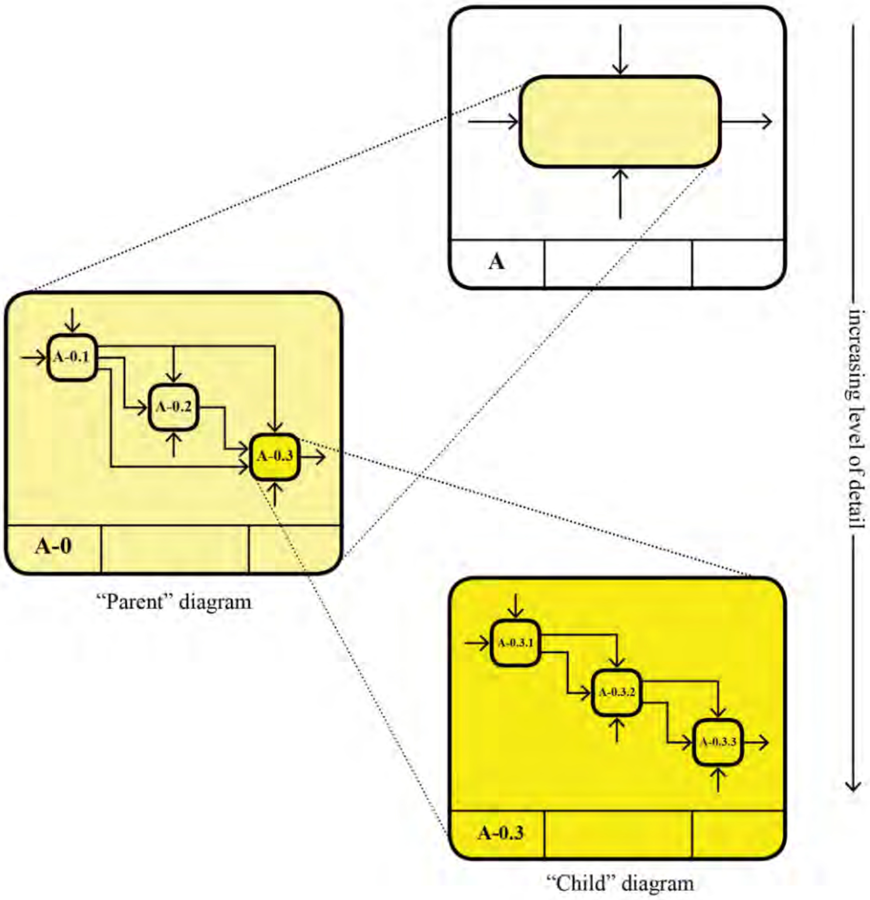


Fig. 2: Hierarchy of IDEF0 process mapping tasks.

We recognize that there are limitations around the IDEF0 model (Billo *et al.* 1994), specifically that it is a static description of any process or series of tasks, and that it is not quantitative in a manner that can provide any empirical aspects around the different weighting and relationships between the tasks that in certain engineering tasks can be limiting (Kusiak *et al.* 1994). Yet it is the core strengths of the method to create consistent multiple models that can be integrated that led to us choosing it as the most appropriate methodology for understanding the mixed and multi-disciplinary processes. As a methodology, it has proven application regarding collaboration with professional, supply-chain and construction stakeholders and partners.

There is significant published evidence to show how the IDEF0 methodology can assist in fully understanding workflows within a manufacturing process (Kim and Jang 2002), including the architecture and construction industry. It has proved useful for identifying redundancies and repetition within any design and development process (Busby and Williams 1993), highlighting missing controls or other inputs into the specified task to improve overall efficiencies. IDEF0 process mapping tools have been applied to comparative task based (and sub-task) analysis for collaboration within industry supply chain (Barratt and Oliveira 2001). One of several techniques and process mapping tools; increasingly becoming ICT based; supporting collaboration between vendors, fabricators, assemblers and distributors within any industry supply chain (Fliedner 2003). This supply chain behaviour is in part driven by the client / stakeholder pressure (Worthington *et al*. 2008) as much as the statutory legal requirements, and ultimately the realisation that these can provide a clear economic imperative to follow ethical and sustainable business practices (Walker and Brammer 2009b).

Similar architectural design processes have been previously addressed using the same methodology, albeit for a Finish construction context (Karhu *et al*. 1997). This case study analysis demonstrated IDEF0 process mapping can be an important framework for all parties / stakeholders understanding the overall process of which they play a part, and the significant aspects of exchange of information as the output from one task as the input into another task. It is structured and has graphical strengths through its strict 'standardised' rules make it suitable for implementation as computer software. Indeed, as a method for analysis its' application has brought about many process improvements suitable for both high level and sub processes (Zellner 2011).

In short, it is simple, quick and economical to use by non-experts, easily interpreted and understandable by all stakeholders, easy to add to and undertake analysis (Cantamessa and Paolucci 1998).

1.3 Aligning an architectural 'plan of work' and BIM using IDEF0 process mapping

While there has be some limited application of the RIBA 'plan of work' (2013) to wider design and construction tasks; for example, in the linking the plan of work to the tasks undertaken by structural engineers (Davies 2015); this remains a weakness for many non-standard tasks that fall outside of the remit of an architectural practice. And non-standard tasks with the use of multiple professionals are more dominant in refurbishment and retrofitting projects compared to new-build construction. In this context, it is specifically a concern in many early-stage tasks (RIBA pre-stage 0) relating to site and / or property survey for both geometry and associated performance parameters, including current energy performance. This emphasis on standard architectural tasks has been at the expense of collaboration with other built environment professionals ranging from planners, surveyors, engineers and facility managers.

Yet collaboration around a 'common language' is one of the important critical factors in the successful and efficient delivery of any design and construction project. ICT systems and BIM tools are growing in recognition as the most important 'mechanisms' in making such improvements in collaboration a reality (Xue *et al.* 2012). For example, many current examples of energy performance models increasingly see the ICT side of BIM as a means for effective integration (Schlueter and Thesseling 2009) with architectural / geometric building models as well as the means for effective integration through the requirements for environmental management systems and performance standards (Walker and Brammer 2009a) as a pre-requisite for an extended supply chain, in effect adding building specification and performance parameters to architectural / geometric building models. This support for professional collaboration is the policy intention within the current UK government, where the current requirement for compliance with BIM level 2 operations allow earlier stage collaboration with better integration between the multiple disciplines (House of Lords 2016).

This pressure for improvement in BIM standards, protocols and processes in the UK is extending to the domestic sector and the growing importance of the retrofitting industry. In this context, current British Standards (BSI 2013) establish the requirements for a suitable common data environment (CDE), interoperability standards; including file and layer naming conventions; and issues around the Levels of Detail and Definition (LoD) as they relate to geometric information and associated data. These are based on earlier attempts at developing a ‘common language’ or consistent set of standards (VICS 2000) within a multi-disciplinary that provided the most appropriate balance between accuracy, realism and simplicity in use. Yet, there remains a limited alignment between BIM and other design and development strategies, including sustainability, statutory planning and architects ‘plan of work’, and gaps that remain around the use and implementation of BIM protocols (Kassem *et al.* 2014). This is due in part to the complexity; and thus bespoke nature; of many planning, architectural and construction projects where there are multiple design decisions being made. For example, one recent study identified 35 design stages decisions / tasks from a series of over 90 design decisions made at all stages of work (Lam *et al* 2010), and this may well be an underestimation of identifiable discrete tasks within any work programme. Yet, within these complex processes there has been the development of tools to simplify the process or tasks associated with energy assessment in the early design stages (Hall and Purchase 2006) beginning to address overlay of sustainability implications on procedures within business (Kleindorfer *et al*. 2005) and construction practice. We have begun to apply IDEF0 process mapping to many of these early-stage design and project management tasks.

Table 1: Example section of a generic plan of works within the architectural and construction industry tabulated for IDEF0 process mapping as a series of hierarchical tasks and activities.

	task(‘parent’ diagram)		sub tasks 1 (‘child’ diagram)		sub tasks 2
A-0	Strategic Definition	A-0.1	Identify Business Case		
		A-0.2	Project Programme	A-0.2.1	Risk Assessment
				A-0.2.2	Establish Project Team / Project Board with Management Decision-Making Responsibilities
				A-0.2.3	Pre-BEP / Draft Project or Building Execution Plan
		A-0.3	Strategic brief	A-0.3.1	Pre-application Planning Discussions
				A-0.3.2	Regional Design Review

				A-0.3.3	Precedent Project Review & Feedback
				A-0.3.4	Core Project Requirements
				A-0.3.5	Sustainability requirements
		A-0.4	EIR (Employer Information Requirements)	A-0.4.1	OIR (Organizational Information Requirements)
				A-0.4.2	AIR (Asset Information Requirements)
A-1	Initial Project Brief	A-1.1	Project Execution Plan	A-1.1.1	Technology & Communication Strategy
				A-1.1.2	Interoperability & Common Standards
				A-1.1.3	Define Common Data Environment
				A-1.1.4	(BEP) Building Execution Plan
		A-1.2	Design Roles & Responsibility Matrix / Project Roles Table	A-1.2.1	Contractual Tree / Schedule of Services
				A-1.2.2	Information Exchange Requirements
		A-1.3	Project Objectives / Success Criteria	A-1.3.1	Quality Objectives
				A-1.3.2	Sustainability Aspirations
				A-1.3.3	Project Outcomes
		A-1.4	Project Budget		
		A-1.5	Handover Strategy		
		A-1.6	Feasibility Studies		
		A-1.7	Due Diligence / Review of site Information	A-1.7.1	Ownership & restrictions
				A-1.7.2	Statutory Constraints
		A-1.8	Review Project Programme	A-1.8.1	Risk Assessment

Within the national UK context, the *Bonfield Review* (DECC 2015) has ‘Terms of Reference’ for retrofitting standards that are looking at elements of design stage advice, standards framework and compliance checking. There is a clear decision in emerging policy to be grounded in an agreed process that has common stages, tasks, work streams. On a similar basis, the characteristics for an effective architectural ‘plan of work’ is a clear and coherent programme of tasks and sub tasks and activities.

Yet, there is discrepancy between accepting the need for a common language / common process and the day-to-day practice within the industry. There is currently no statutory requirement to apply a ‘plan of work’ in work practices and the running of contracts, or a requirement for adoption of BIM protocols. Without such a legal mandate, the promotion of advisory standards and best practices will not be sufficient to support wide take-up within the architecture and construction sectors (Samuelson and Björk 2013). This is particularly acute within a retrofitting project where the significance of site survey and reality capture tasks are largely ignored or assumed to be within the remit of non-architectural professionals.

1.4 Aligning reality capture tasks to an architectural 'plan of works'

Our challenge was to find the appropriate means for aligning site survey and reality capture activities within a plan of works or process that could be project specific and used by a range of different professionals. These activities should include a range of possible options (Table 2) for survey methodology that allowed for the appropriate accuracy and / or format of the survey data based on the end-user applications.

Table 2: Hierarchical reality capture activities.

	task('parent' diagram)		sub tasks 1 ('child' diagram)		sub tasks 2
A-S	Reality capture	A-S.1	Measured survey		
		A-S.2	Photographic / photo matching survey		
		A-S.3	Photogrammetry survey		
		A-S.4	LiDAR survey	A-S.4.1	Ground level survey
				A-S.4.2	External conservation survey
				A-S.4.3	Combined external and internal survey
				A-S.4.4	Complex services survey
		A-S.5	Aerial survey	A-S.5.1	Photographic / Photogrammetry survey
				A-S.5.2	Thermographic survey
				A-S.5.3	LiDAR survey

In the application of the IDEF methodology, the most effective application of process mapping within practice is to tabularize the individual tasks or component processes in the form of an activity table (Damij 2007) as the starting point for understanding the overall business process. This then becomes suitable form linking and integration into a standardised flowchart. Thus, in short the simplified process we followed is as follows; (1) tabulate the high levels tasks and stages, (2) IDEF0 diagram produced for each of the 'parent' tasks, (3) breakdown high-level tasks and processes into any additional sub-processes, (4) IDEF0 diagram produced for each of the 'child' tasks, and (5) integrate and link these tasks into a flow chart.

2. REALITY CAPTURE

In undertaking a series of process mapping exercises and experiments, we have based our research on a number of ‘live’ architectural projects being undertaken within a small to medium sized practice in North Yorkshire. As a result of this pragmatism, these are opportunistic projects as much as selected case studies. However, they begin to illustrate how heuristic knowledge can be used to provide standardization and structure for a range of possible survey techniques. In each case study we begin by describing the input and output requirements needed for the particular application. In most cases this related to the employer information requirements (EIR) and the detail from the project execution plan when they actually existed. Added to this was a review of controlling factors; typically, these related to national regulations, professional standards and local planning conditions; and the particular mechanisms; such as equipment, materials, software, skills; needed to undertake the task / activity. This record formed the basis of the IDEF ‘parent’ diagram. Below this hierarchical level, details for each sub-task / activity was broken down into sequential actions as the basis for the ‘child’ diagram. In practice, these sub-tasks and sequencing are a set of instructions. In setting out the sequence of sub-tasks and creating a visual record, they have proven to be useful as the basis for knowledge transfer and supporting in-house / stakeholder training.

2.1 Measured survey

As part of the entrance remodeling of a Georgian theatre in Stockton-on-Tees, we tested the approach to process mapping a standard approach to undertaking a measured survey. The record is based on collaboration with the surveyor as part of the primary survey process. It describes the measurement of the building façade and significant physical features against a fixed measuring control point.

Table 3: Tabulation of IDEF0 process mapping requirements for undertaking a measured survey.

Task / Activity	Input	Controls	Mechanisms	Outputs
Measured survey	Employer Information Requirements; Project Execution Plan	RICS Method (Code of measuring practice 6th edition)	Measuring equipment (Disto, laser measure); Total station / Theodolite (GPS logger / autolevel); Qualified professional (RICS / RIBA)	Field notes, annotated drawings

photogrammetry

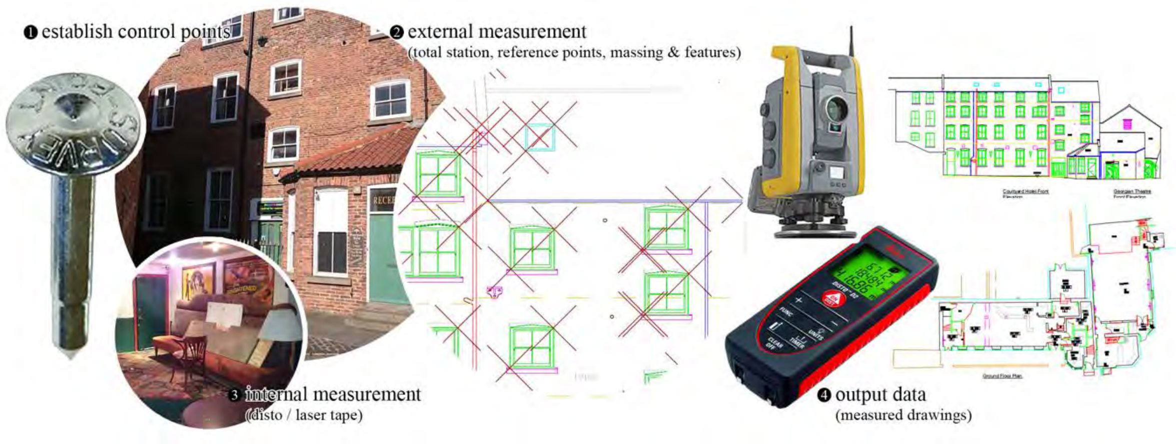


Fig. 3: Sequence of tasks for undertaking measured survey.

The output requirements were a simple set of measured drawings provided in a suitable digital format. The output itself was limited to two dimensions but became the basis for a three dimensional geometric model. Key reference points in the survey were typically the changes in materials, junction points and corners of windows and doors. The entire survey was limited to dimensions and held no parametric data, although annotations and field notes were included as part of the survey record.

2.2 Photographic / photo matching survey

A basic three-dimensional model was created for a North Yorkshire school block based on an historic set of design drawings. The intention was to undertake a simple energy assessment prior to and following refurbishment and the addition of insulation, new glazing and external cladding.

Table 4: Tabulation of IDEF0 process mapping requirements for undertaking a photographic survey.

Task / Activity	Input	Controls	Mechanisms	Outputs
Photographic survey	Project Execution Plan; Field Notes (annotated drawings)	Employer Information Requirements (specification)	Camera (colour / lens); Open source images (*StreetView*); Photomatching software (*Sketchup*, *Photoshop*, *3D Max*)	Rectified images (matched images and / or textures)

A photo-matching survey was undertaken with the intention of checking the accuracy of the provided set of drawings and highlight differences between the design and as-built project. The requirement was for a single rectified image with a clear visible reference point against which we could align the digital model. For simplicity, we used the corner and building vertices. With the geometric digital model superimposed over the reference image within suitable software, we were able to and manipulate the simple model geometry. To this basis model we were able to add some performance parameters relating to materials and thermal characteristics. The output model became the input data for an energy assessment.

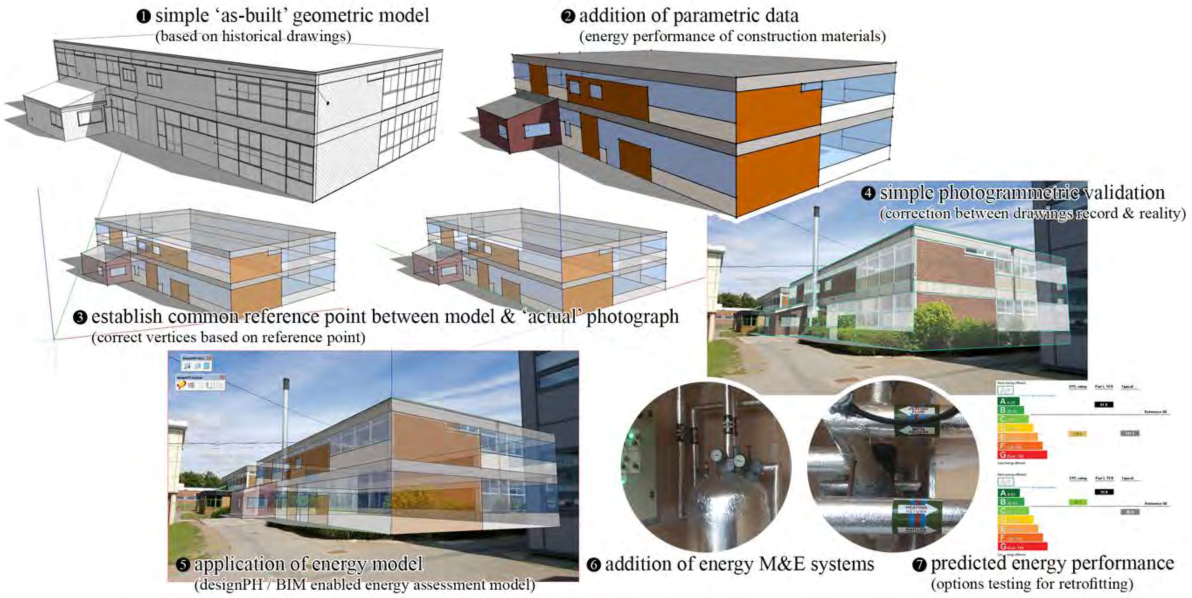


Fig. 4: Sequence of tasks for photo matching to adapt a geometric model for energy performance calculation.

2.3 Photogrammetry survey

We re-examined the Georgian theatre using a structured photographic survey with the intention of using the set of photographs to construct the building geometry in three dimensions. Photogrammetry is increasingly being used as a low-cost approach to survey and model generation in the architecture and construction sector and the practice was interested in exploiting this new technology. Like the other visual survey methods above, the use of photogrammetry uses 'line of sight' technologies and thus requires a structured approach to survey to ensure complete coverage of the site, building or object modelled.

Table 5: Tabulation of IDEF0 process mapping requirements for undertaking a photogrammetry survey.

Activity A-3.1.3	Input	Controls	Mechanisms	Outputs
Photogrammetry survey	Employer Information Requirements; Project Execution Plan	Best practice method statement (Autodesk)	Camera (specification requirements for colour / resolution / lens); GPS (in-built geo referencing system within scanning equipment); Aerial (manned and / or	Digital images with associated metadata

	unmanned airborne vehicle); Qualified professionals (RICS, RIBA, RTPI)	

Central to this structured survey is the linking of embedded GPS data with high-resolution cameras, particularly via the growth in number and functionality of smartphones. The fact that the key ‘mechanism’s for the workflow have become integrated in a single technology has, in part, simplified the stage of image capture. However, we found there is still the need for semi-skilled professionals, who understand the approach needed for structured data acquisition using a photographic survey and 3D data reconstruction. Often it will be the same professional undertaking the survey who will be processing the data collected. Thus, perhaps the core control for this specific activity is the actual specification and selection of the camera and geo-referencing systems to ensure the output model is suitable for the intended process and manipulation software. In this instance, multiple view images have been used (Po-Han *et al*. 2012) in the creation of sparse point cloud models, which itself becomes the basis for the generation of a mesh and solid model object.

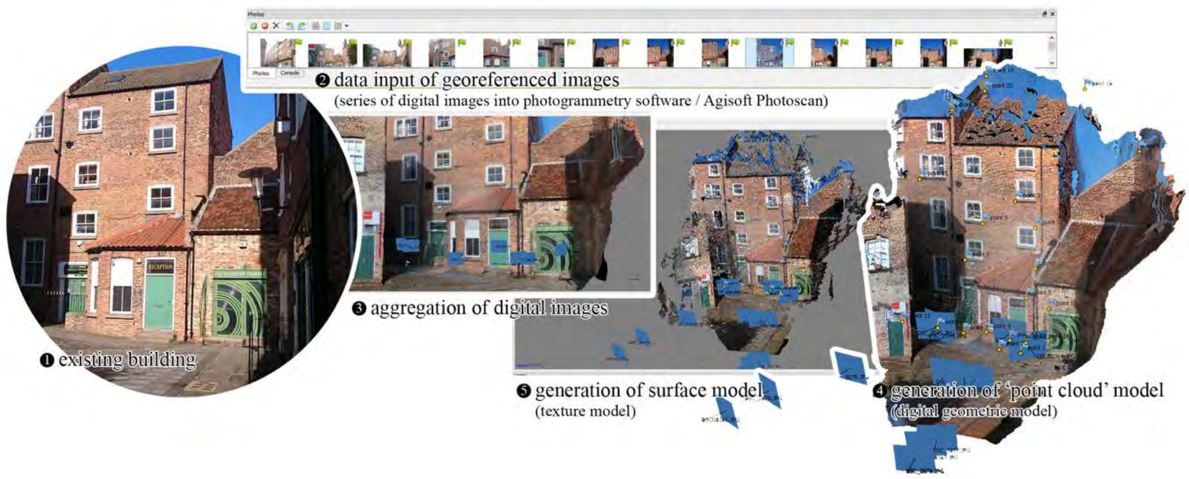


Fig. 5: Sequence of tasks for undertaking ground level photogrammetry survey.

Recent comparative workflow, software analysis and evaluation on the application of terrestrial photogrammetry (Niederheise *et al*. 2016) suggests the choices between different applications is one around the need for customisation versus the user-friendly interface. Similar comparative analysis (McCoy 2014) of the different technical (hardware and software) options have been explored for wider reality capture applications and the generation of useful 3D computer models for other stages within any construction workflow and / or ‘plan of work’ such as design / refurbishment / reconstruction, options modelling through to construction monitoring. Thus, in practice, it will be the availability of processing software with the supporting skills in the use of the software that will determine the accuracy of the resultant geometric model.

2.4 LiDAR survey

We then explored the process of undertaking a terrestrial LiDAR survey as part of the remodeling and extension of an industrial pharmaceutical plant in North Yorkshire. In this instance, we required external consultants to undertake the actual survey but observed and informed by staff from the architectural practice. This had much in common with a simple terrestrial measured survey in requiring reference / control points and a structured approach to covering the entirety of the property.

Table 6: Tabulation of IDEF0 process mapping requirements for undertaking a LiDAR survey.

Task / Activity	Input	Controls	Mechanisms	Outputs
LiDAR survey	Project Execution Plan	Employer Information Requirements (specification)	Laser Scanner; Control points (checkerboard and / or prominent geometry); GPS (in-built into scanning equipment)	Digital point cloud

We found that the approach was informed by the end-use of the data and the level of accuracy needed. It thus benefited from members of the design team being more closely engaged with the survey specification, even if this was not set out explicitly within the initial EIR. Having prior knowledge of the BIM environment used for the design stages helped with data exchange and interoperability (and consequently better accuracy by avoiding unnecessary data conversion stages). It could also help with over-specification and the reduction in time and resultant costs on the project. Indeed, it was questionable if the level of detail and accuracy required actually needed a LiDAR survey whenever the data for the existing structure was external, largely contextual and of a level more appropriate for a photogrammetry survey.

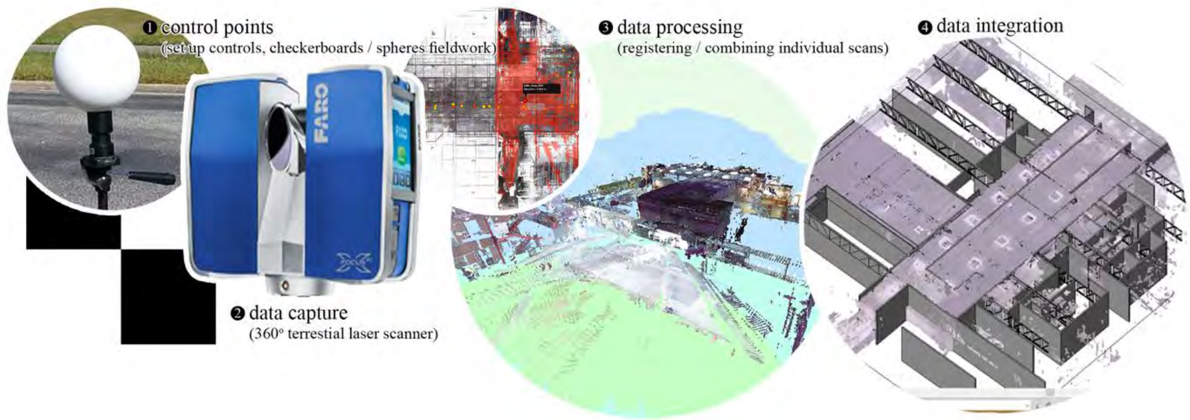


Fig. 6: Sequence of tasks for undertaking ground level LiDAR survey.

2.4.1 LiDAR External conservation survey

In comparison to a similar survey process undertaken for a conservation project on Durham Cathedral, the controls and mechanisms were constant, as were the limitations of a ground level survey. However, the inability to view the roof structures via line of sight became a restricting factor whenever there was a requirement to convert the LiDAR dense point cloud into an object orientated model. Certain assumptions had to be made in the tracing or conversion of the LiDAR point cloud to an object and resulted in potential errors and inaccuracies being introduced.

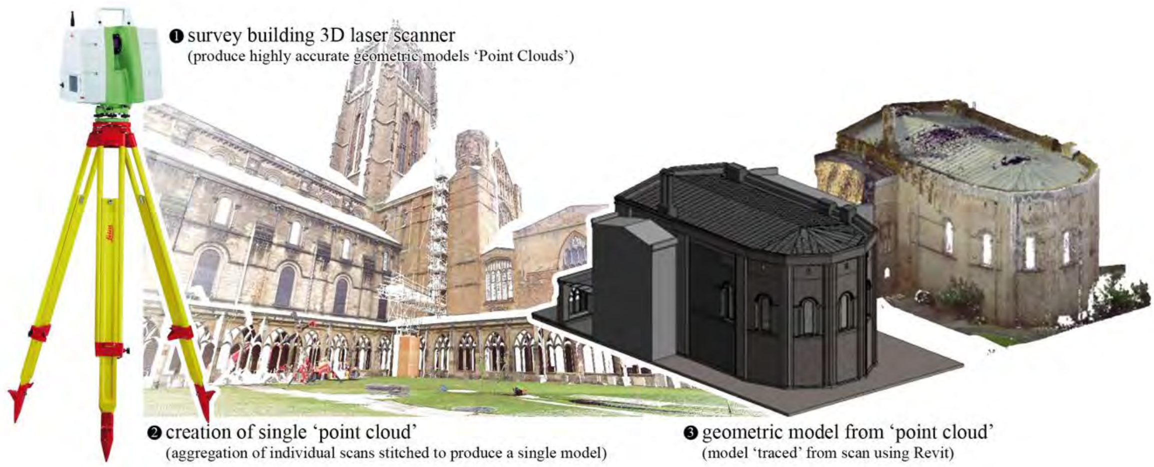


Fig. 7: Application of LiDAR survey process for external ground level building conservation survey.

2.4.2 LiDAR External and internal survey

The need for an object-orientated model to be produced from the survey was a common factor in other LiDAR data sets. We explored examples where there was a requirement for parameters to be added to the model for both internal and external applications. For example, interior architecture designs required highly accurate information to meet the EIR / statutory pharmaceutical industry requirements. Reality capture using a mix of internal and external ground level LiDAR allowed for the design team to review the accuracy of an existing object-orientated model. The LiDAR data included additional information regarding materials and textures that were valuable for several design-stage tasks including compliance checking and visualisation.

When the LiDAR survey process was based on a full appreciation of the application in the later project stages it helped with a more intelligent approach to the specification of reality capture together with a more flexible use of the data sets whenever this was appropriate. One example was in the use of variable specification and hybrid models (Figs. 8 & 9) that mixed dense point-cloud data sets with object-orientated models. This was possible for both internal and external data sets when the extension or adaptation was limited to part of the initial structure and where only the new design interventions required parametric data and higher levels of detail. In this instance, the survey process, controls and mechanisms remained constant, but the end-use applications of the data became an important input to undertaking the task. In integrating the survey process to the overall project in this way it helped to approach the survey in a more bespoke manner, avoid over specification in accuracy / detail and save time in data processing, conversion and integration.

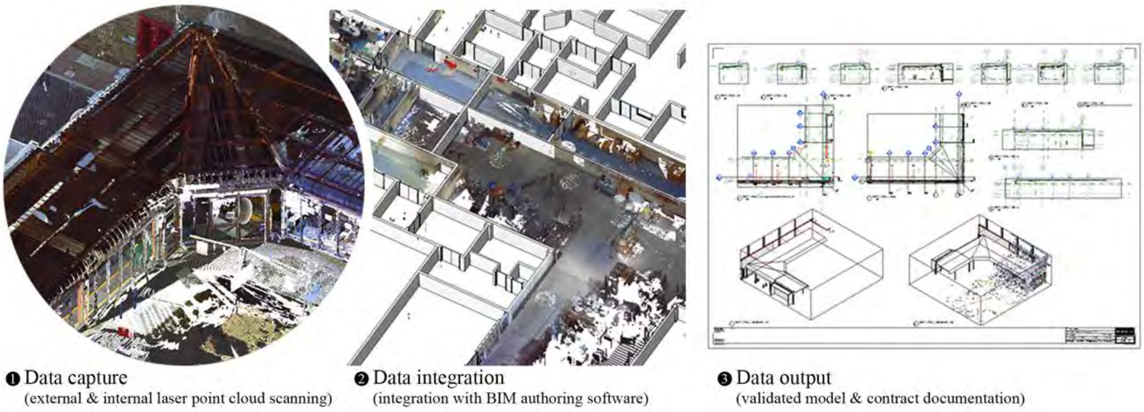


Fig. 8: Sequence of tasks for LiDAR internal / external ground level survey.

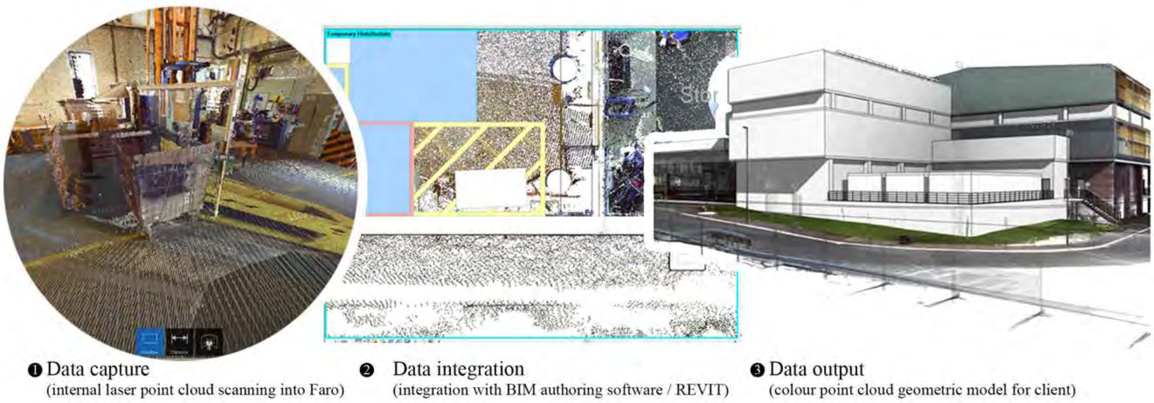


Fig. 9: Direct use of point cloud LiDAR ground level survey.

2.4.3 LiDAR complex services survey

One final application of LiDAR data was in the approach to surveying complex services and structures. Drawing examples from another pharmaceutical building, we explored complex pipework and external structures that had potential risks around clashes that had significant implications for the operation of the facility if they arose.

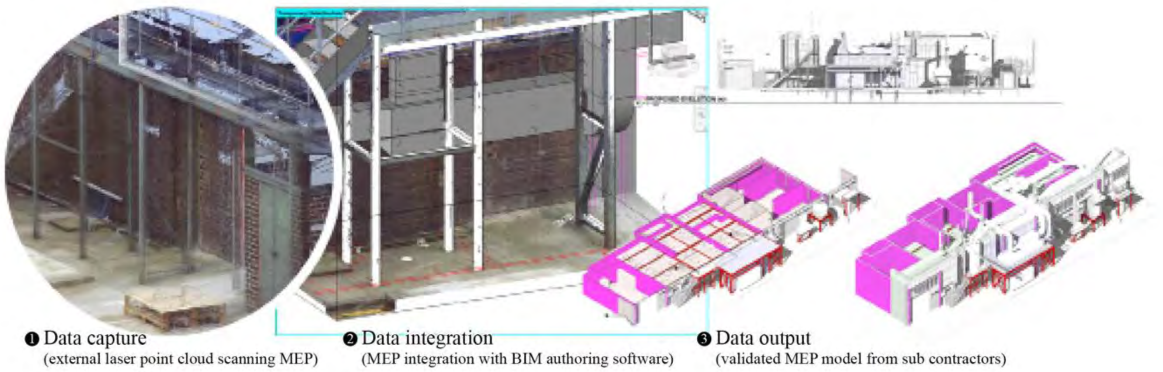


Fig. 10: LiDAR ground level survey of complex services.

Here the specification for the survey in level of detail, accuracy and interoperability of data ensured that clashes between external structures and M&E services were avoided. Indeed, this specific example of high quality survey data based on the appropriate specification reduced the need for on-site construction supervision, increased the speed of the project delivery and consequently reduced the direct project costs compared to similar projects undertaken by the practice for the same client.

3. AERIAL SURVEY OPTIONS

The limitations of terrestrial survey processes led us to explore the options for reality capture using aerial survey methods. In practice this was about supplementing rather than replacing ground level survey data with some form of hybrid model that could use data collected by unmanned drone. Commentators have highlighted the growing importance and application for the use of unmanned drones (Colomina and Molina 2014) to undertake aerial surveys and fill many of the procedural gaps highlighted within the preceding reality capture methods above. The use of drones is cost-effective (Fernández-Hernandez *et al*. 2015) in many instances and examples.

Table 7: Tabulation of IDEF0 process mapping requirements for undertaking an aerial survey.

Task / Activity	Input	Controls	Mechanisms	Outputs
Aerial survey	Safety case / Risk assessment (for one-off flight) Operating manual (permanent approval)	Landowner permission Flight permission, PFAW (Permission for Aerial Work from the CAA) Pilot competence assessment process	Drone with attachments Operating manual NQE training (National Qualified Entities)	Survey photographic data with associated metadata LiDAR data

Operator insurance

Fig. 11: External photogrammetry and thermal imagery survey.

The sequencing of tasks for drone-based aerial survey was significantly more concerned with the safe and efficient operation of the drone equipment. The process required the preparation of a flight plan; a pre-flight check; setting / programming of optimised survey route over the study site (in this example it comprised of a survey grid geolocation / height and size optimised for both 2D and / or 3D output model); undertaking an automated survey flight (following the pre-determined survey grid); an additional manual survey flight (providing supplementary data to ensure total coverage, particularly at lower levels for building façades – potential for additional ground level photographic survey to provided set of survey images form more than one camera).

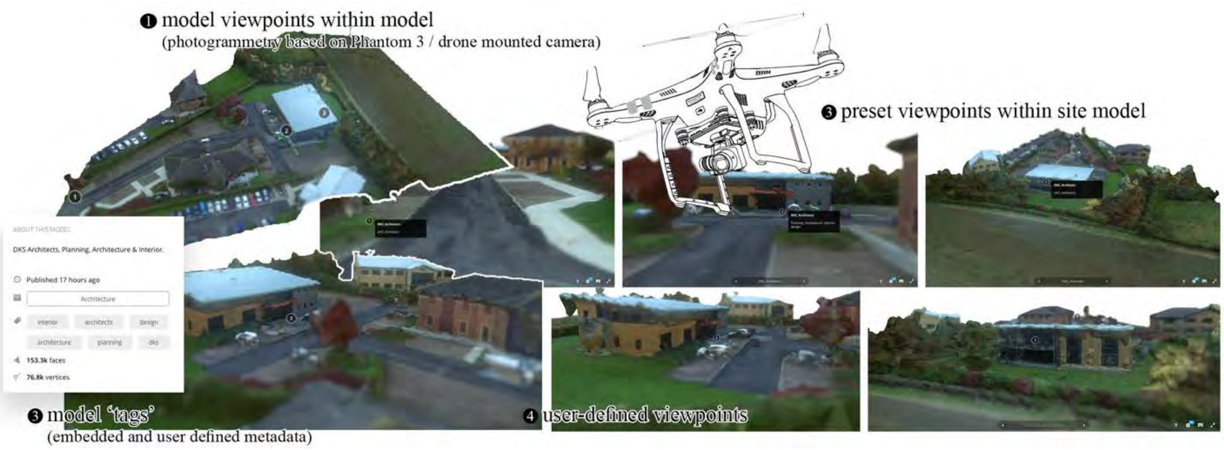


Fig. 12: Initial Drone photogrammetry site survey(s).

4. EVALUTION OF REALITY CAPTURE OPTIONS

This exploration of the different reality capture techniques currently available for a small to medium architectural practice has been undertaken in the context of the development of a practice-wide BIM execution plan. The interest and emphasis on digital survey methods and processes is commercially significant to the practice given the scale of refurbishment and retrofitting projects. Yet understanding how the reality capture processes relates to the overall design process, including many wider professional collaborators has been valuable for many different reasons.

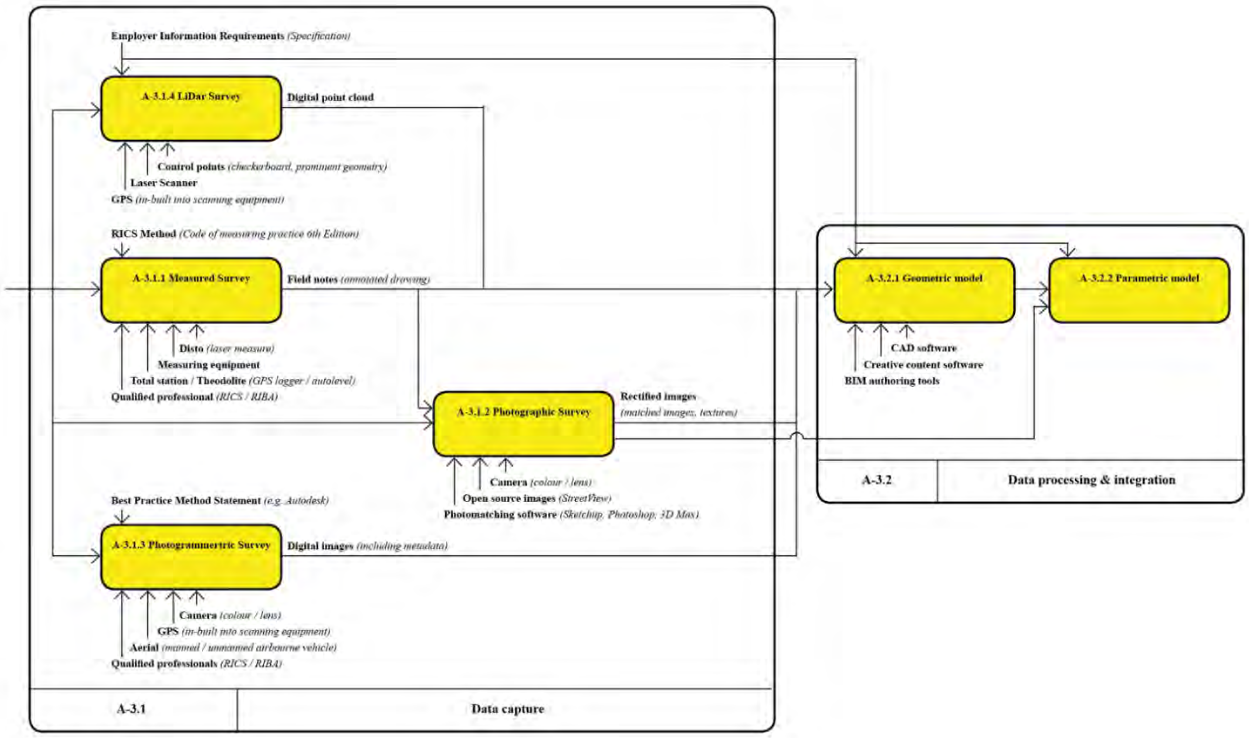


Fig. 14: Development of integrated IDEF0 process map of reality capture methods.

There is more clarity in how reality capture processes fit into current bespoke office procedures and more generic plan of works. IDEF process mapping (fig. 14) has supported the systematic consideration, visualisation and evaluation of specific tasks. Even when the detail around the task is not necessary for the design team, their involvement has allowed for more intelligent choices and technical specifications in initial survey work. Historical practices have been challenged from this learning process. Many of the procedural options are within reach of the practice and they are less reliant on other consultants to undertake survey activities. The relationship between the data management, modelling and integration is more clearly understood with regard the initial survey requirements. There is added-value for the practice in getting involved in the initial survey specification, even when they are unable to undertake it directly.

Ultimately the practice can see how reality capture fits into a wider BIM and information strategy with the resultant efficiency and cost benefits. While the work is not comprehensive, the approach to process mapping can continue to be utilised and extended as the work develops. Each of the specific processes and sequencing of tasks is adds value to in-house training and client communication as the BIM execution plan is prepared.

5. REFERENCES

Aguilar-Savén, R.S. (2004). "Business proves modeling: Review and framework". *International Journal of Production Economics* **90**(2) 129-149.

Barratt, B. and Oliveira, A. (2001). "Exploring the experiences of collaborative planning initiatives". *International Journal of Physical Distribution & Logistics Management* **31**(4) 266-289.

Bergener, P., Delfmann, P. and Weiss, B. (2015). "Detecting potential weaknesses in business processes: An exploration of semantic pattern matching in process models". *Business Process Management Journal* **21**(1) 25-54.

Billo, R.E., Rucker, R. and Paul, B.K. (1994). "Three rapid and effective requirements definition modeling tools: evolving technology for manufacturing system investigations". *International Journal of Computer Integrated Manufacturing* **7** 186-199.

BSI (2013). *PAS 1192-2:2013* Specification for information management for the capital / delivery phase of construction projects using building information modelling (British Standards Institution, London).

Busby, J.S. and Williams, G.M. (1993). "Value and limitations of using process models to describe the manufacturing organization". *International Journal of Production Research* **31**(9) 2179-2194.

Cantamessa, M., Paolucci, E. (1998). "Using organizational analysis and IDEF0 for enterprise modeling in SMEs". *International Journal of Computer Integrated Manufacturing* **11**(5) 416-429.

Colomina, I., Molina, P. (2014) "Unmanned aerial systems for photogrammetry and remote sensing: A review". *ISPRS Journal of Photogrammetry and remote sensing* **92** 79-97.

Colquhoun, G.J., Baines, R.W. and Crossley, R. (1993). "A State of the Art Review of IDEF0". *International Journal of Computer Integrated Manufacturing* **6** 252-264.

Cooper, R. (2008). *Process Management in Design and Construction* (Wiley-Blackwell, Oxford).

Damij, N. (2007). "Business process modeling using diagrammatic and tabular techniques". *Business Process Management Journal* **13**(1) 70-90.

Davies, I. (2015). "A guide to the new RIBA Building Contracts". *Structural Engineer* **93**(3) 26-27.

Department of Energy and Climate Change. (2015). Independent Review of Consumer Advice, Protection, Standards and Enforcement: Terms of Reference (Department of Energy and Climate Change and Department for Communities and Local Government, London). https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/465119/150721_Independent_Review_-_short_ToR_-_REV.pdf [accessed 13th June 2016].

Egan, J. (2004). *The Egan Review: Skills for Sustainable Communities* (Office of the Deputy Prime Minister, London).

Fernández-Hernandez, J., González-Aquiklera, D., Rodríquez-González, P., Mancera-Taboada, J. (2015). "Image-based modelling from unmanned aerial vehicle (UAV) photogrammetry: An effective, low-cost tool for archaeological applications".*Archaeometry* **57**(1) 128-145.

Fliedner, G. (2003). "CPFR: an emerging supply chain tool". *Industry Management & Data Systems* **103**(1) 14-21.

Hall, M., Purchase, D. (2006). "Building or bodging? Attitudes to sustainability in UK public sector housing construction development". *Sustainable Development* **14**(3) 205-218.

HM Government. (2012). *Industrial strategy: government and industry in partnership - Building Information Modelling* (Department of Business, Innovation & Skills, London).

HOUSE OF LORDS Select Committee on National Policy for the Built Environment Report of Session 2015–16 (2016). *Building Better Places* (The Stationery Office, London). http://www.publications.parliament.uk/pa/ld201516/ldselect/ldbuilt/100/100.pdf [accessed 18th April 2016]

Karhu, V., Keitilä, M., Lahdenperä, P. (1997). "Construction process model: Generic present-state systematization by IDEF0". *VTT Tiedotteita – Valtion Teknillinen Tutkimuskeskus* **1845** X-38.

Kassem, M., Iqbal, N., Kelly, G., Lockley, S., Dawood, N. (2014). "Building Information Modelling: Protocols for collaborative design processes". *Journal of Information Technology in Construction* **19** 126-149.

Kim, S. and Jang, K. (2002). "Designing performance analysis and IDEF0 for enterprise modeling in BPR". *International Journal of Production Economics* **76**(2) 121-133.

Kleindorfer, P., Singhal, K., Van Wassenhove, L. (2005). "Sustainable Operations Management". *Production and Operations Management* **14**(4) 482-492.

Kusiak, A., Larson, T.N. and Wang, J. (1994). "Reengineering of design and manufacturing processes". *Computers and Industrial Engineering* **26**(3) 521-536.

Lam, P., Chan, A., and Wong, F. (2010). "A study of key design decisions at the scheme design stage of building projects in Hong Kong Star with a view to buildability enhancement". *15th Annual Symposium on Advancement of Construction Management and Real Estate: Towards Sustainable Development of International Metropolis, CRIOCM* Johor Bahru Malaysia; 6th-7th August.

McCoy, A. (2014). “Reducing barriers to remote project planning: Comparison of Low-Tech site capture approaches and image-based 3D reconstruction”. *Journal of architectural engineering* **20**(1) 5013002.

Melao, N. and Pidd, M. (2000). “A conceptual framework for understanding business processes and business process modeling”. *Information Systems Journal* **10** 105-129.

Miles, J. and Whitehouse, N. (2013). *Offsite Housing Review* (Construction Industry Council, London).

NBS (2016). *NBS BIM Toolkit* [online] https://toolkit.thenbs.com [accessed 10th November 2016].

NHBC Trust and BSRIA. (2013). *Building Information Modelling: An introduction for house builders - Informing the debate* (NHBC Foundation, Milton Keynes).

Niederheise, R., Mokron, M., Lang, J., Petschko, H., Prasicek, G., Elberink, S. (2016). “Deriving 3D point clouds from terrestrial photographs – Comparison of different sensors and software”. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences - ISPRS Archives* **41** 685-692.

Po-Han, L., Jui-Wen, H., Huei-Yung, L. (2012). “3D model reconstruction based on multiple view image capture”. *ISPACS 2012 - IEEE International Symposium on Intelligent Signal Processing and Communications Systems*, 58-63.

Samuelson, O., Björk, B. (2013). “Adoption processes for EDM, EDI and BIM technologies in the construction industry”. *Journal of Civil Engineering and Management* **19**(1) 172-187.

Saxon, R.G. (2013). *Growth through BIM* (Construction Industry Council, London).

Schlueter, A., Thesseling, F (2009). “Building information model based energy/exergy performance assessment in early design stages”. *Automation in Construction* **18**(2) 153-163.

Sinclair, D. (Ed.) (2012). *BIM Overlay to the RIBA Outline Plan of Work* (RIBA Publishing, London).

VICS (2000). CPFR Guidelines (Voluntary Inter-industry Commerce Standards).

Walker, H., Brammer, S (2009a). "Use the supply relationship to develop lean and green suppliers". *Supply Chain Management: An International Journal* **10**(1) 60-68.

Walker, H. and Brammer, S. (2009b). "Sustainable procurement in the United Kingdom public sector". *Supply Chain Management: An International Journal* **14**(2) 128-137.

Worthington, I., Monder, R., Harvinder, B. and Mayank, S. (2008). “Researching the Drivers of Socially Responsible Purchasing: A Cross-National Study of Supply Chain Initiatives”. *Journal of Business Ethics* **79**(3) 319-331.

Xue, X., Shen, Q., Fan, H., Li, H., Fan, S. (2012). “IT supported collaborative work in A/E/C projects: A ten-year review”. *Automation in Construction* **21** 1-9.

Zellner, G. (2011). “A structured evaluation of business process improvement approaches”. *Business Process*

Management Journal **17**(2) 203-237.

Zugal, S., Soffer, P., Haisjackkl, C., Reichert, M. and Weber, B. (2015). "Investigating expressiveness and understandability of hierarchy in declarative business process models". *Software & Systems Modeling* **14**(3) 1081-1103.

DIMENSIONAL QUALITY ASSESSMENT OF CONCRETE SLABS USING 3D LASER SCAN POINT CLOUDS

Nisha Puri & Yelda Turkan

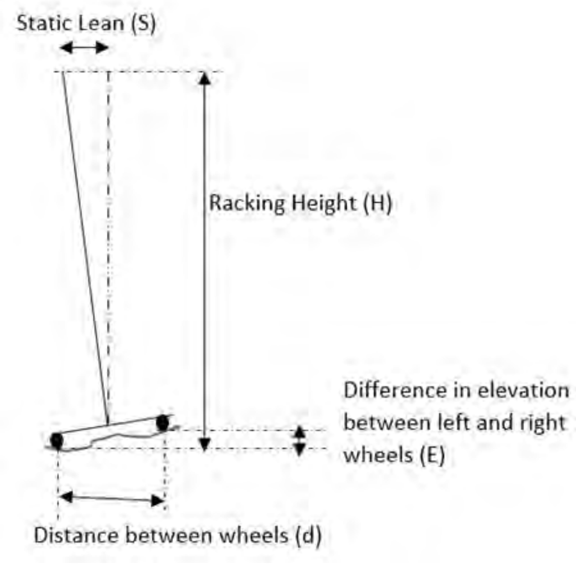
Iowa State University, USA

ABSTRACT: *Terrestrial Laser Scanning (TLS) has revolutionized the process of capturing as-built data from construction sites for project monitoring and dimensional quality control purposes through the acquisition of very accurate and dense three dimensional (3D) point clouds. Surface characterization of constructed surfaces is an essential feature that renders useful information for identifying possible defects and diagnosing potential detriments to the functionality of the element being considered. Traditional dimensional quality control methods, surface waviness measurement methods in particular, depend on manual measurements and calculations that are time consuming and error prone. In an effort to devise an effective, accurate and timely approach for measuring surface waviness of concrete elements and performing dimensional tolerance analysis, a framework based on continuous wavelet transform that relies upon LiDAR data for accurate representation of surface geometry is presented. Two-dimensional continuous wavelet analysis (2D CWT) provides both the characteristic period of undulation and the its location for characterizing the surface waviness. The existing method of using 1D CWT was extended to implement 2D wavelet transform to perform a more comprehensive analysis of surface profiles.*

KEYWORDS: *Laser Scanning, Computer Vision, Quality Control.*

1. INTRODUCTION

Dimensional quality control in the construction industry plays an important role in identifying defects in as-built concrete elements and helps in making necessary changes in the geometry of such elements. Quality control inspectors need to be updated with the geometric information of newly constructed elements in order to ensure that the quality of such elements will not affect the construction of the subsequent elements. Consequently, it is



essential to monitor the quality of finished surfaces in order to obtain accurate geometric information and make timely decisions for any corrections that are necessary. Surface flatness of concrete slabs is a very important attribute that needs proper control not only for aesthetic reasons, but also for ensuring proper functionality of the surface being evaluated. It is especially important in industrial settings, where deviations from specified tolerances or incorrect levels of flatness and levelness can affect operational activities (Bosché & Biotteau 2015). Flatness of the floor can be a good indication of how good vehicles can operate across the surface. Efficient operations of vehicles such as lift trucks can be ensured when such machines are operating at maximum speeds, which can only be achieved on flat surfaces. While operating very narrow aisle (VNA) trucks, the variations in elevation across the aisle between the load wheel tracks affect the height of the storage rack, as evident from Figure 1. When the vehicle is operating under such conditions, there is a potential of three-fold increase in static lean (Neal 2002).

During the construction of slabs, correct placement and finishing procedures should be carefully regulated based on the specifications provided in order to meet the specified level of tolerance for flatness and levelness. Depending upon how properly the procedures are followed during construction, the slab surface will exhibit different levels of flatness and levelness (Bimel et al. 1997). Periodic (preferably daily) measurements should be carried out as soon as the poured concrete surface is ready for foot traffic or before the curing compound is applied, so that existing problems can be identified and corrected in a timely manner. If the specified tolerances are not met upon evaluation, the area with defects have to either be repaired upon approval, or the entire element has to be removed and replaced (Gillette et al. 1913). Otherwise, it may lead to extra cost in rework, sometimes as much as 12% of the construction cost (Tang et al. 2009).

Existing practices for assessing waviness or smoothness of concrete surfaces in the industry rely on 10-ft straightedge method (Ballast 2007), F-number method (as described in ASTM E1155) and Waviness Index method (as described in ASTM 1486). Currently practiced methods (straightedge, string line, profilograph and F-meter) rely on contact-based measurement devices for quality assessment, which are laborious, prone to human error and are time consuming. Some of the disadvantages of using the straightedge method include the inaccuracies of measured data resulting from manual measurements, large time investment required for carrying out measurements over large surface areas (e.g. warehouse floors) and obtaining results that only define deviations of measured points in the as-built structure compared to the as-designed surface (Bosché & Biotteau 2015). F-numbers, FF (floor flatness) and FL (floor levelness) define the bumpiness of the surface and the slope of the surface respectively (Gupton 2009). F-numbers method, although introduced to minimize the inefficiencies associated with using straightedges and profilographs, has its own shortcomings in terms of sparseness and speed of measurements. The disadvantages associated with the above mentioned methods are the possible inaccuracies and sparsity in the measurements since they are carried out only along spaced survey lines instead of the entire surface. The principle behind all of these techniques is to carry out point measurements recorded at fixed intervals along fixed survey lines, which fails to characterize the surface waviness of slabs. Therefore, it can be concluded that the current dimensional quality control methods are inefficient and labor-intensive, especially when testing large surface areas of concrete to provide information about the waviness of the surface. The industry is in need of a methodology that enables the assessment of concrete surface geometry while delivering results that are easily interpretable real-time. This paper attempts to address this need by presenting a methodology that is based on the application of two-dimensional (2D) Continuous Wavelet Transformation on laser scan point cloud data for assessing the quality of concrete surfaces.

One of the key features that requires special attention in dimensional quality control is the ability of the measuring device to accurately collect geometric information from the surface being tested. The measurements obtained may vary when different methods are adopted depending upon the instrument and the technique used. Terrestrial Laser Scanning (TLS) (commonly referred to as LiDAR (Light Detection and Ranging)) is a revolutionary technology that can be used for surveying purposes as it enables fast acquisition of dense 3D geometric data from concrete elements with millimeter level accuracy. TLS technology outputs data in the form of 3D dense point clouds within minutes of scanning and can help overcome the problems of sparsity and inaccuracies in measured data associated with manual measurements.

2. RELATED WORK

The application of 3D imaging technologies, including TLS and photogrammetry, for progress and quality control in the Architectural, Engineering, Construction and Facilities Management industry (AEC&FM) has gained increased interest in recent years. This real-time assessment technique can also be used in the assessment of areas that limit human interactions with the environment (Cheok et al. 2000). In the field of dimensional quality control, several algorithms based on detecting deviations of laser scanned points from a reference surface have been developed (Fuchs et al. 2004) (Schafer & Weber 2004). Turkan et al. (2012) presented a system that enables progress tracking using as-built data from TLS and as-planned information from 3D CAD combined with schedule information (4D model). Golparvar-Fard et al. (2011) used photogrammetry and computer vision (SIFT algorithms) techniques to develop 3D point clouds from 2D photographs, and they compared these 3D point clouds (as-built data) with 4D BIM to automatically infer project progress. Bosche (2010) presented an approach for project monitoring using TLS and 3D CAD modeling. Kalyan et al. (2016) used Project Tango to acquire as-built information and compared it with as-designed BIM models to perform quality control assessments. Wang et al. (2016) proposed a framework for quality control of precast concrete elements by comparing as-built data collected using a TLS and as-designed data obtained from Building Information Modelling (BIM). Bosche and Guenet (2014) proposed a method that uses the combination of TLS and BIM to test whether the geometry of point clouds associated with the concrete surface adhere to the specified tolerances. Israel and Pileggi (2016) used TLS to evaluate the flatness of multi-story building facades and the financial consequences of placing a mortar layer that is thicker than required in critical areas. Shih and Wang (2004) used two different 3D scanning based methods to analyze surface smoothness of finished walls. The method used in this study used a height map of the surface and different colors for each height interval, which gave a general idea of the height of each point with respect to a reference plane, however it did not impart much information about the waviness. Tang et al. (2011) developed three algorithms that quantify the degree of deviation of laser scan points with respect to a reference plane obtained from CAD models or a user specified plane. These algorithms assisted with surface quality control by localizing the defects, but failed to characterize the waviness at a global level.

Several works have adopted wavelet transformation for characterizing surface texture. Chen et al. (1995) introduced a technique that applied one-dimensional wavelet transform to characterize engineering surfaces. This leads to one of the drawbacks discussed earlier regarding the sparseness of measurements. The multi-scale decomposition process was performed in 2D using images instead of profiles in (Josso et al. 2002). 2D wavelet transform was applied to analyze deviations of cylindrical surfaces in (Stępień & Makieła 2013) but the variability of basic input parameters that characterize a profile during profile decomposition requires further investigation. The concepts of lifting wavelets and diffusion wavelets for surface filtering are relatively new and have been described in (Jiang et al. 2001), (Hussein et al. 2012), and (Coifman & Maggioni 2006). Abdul-Rahman et al. (2013) applied lifting wavelets to triangular meshes to filter freeform complex surfaces.

For concrete surfaces, the surface profile can be broken down into roughness and waviness components. Although several works to date applied wavelet transformation to characterize surfaces, a very few of them used TLS data. Wavelet transform was used in (Ge et al. 2015), (Bitenc et al. 2015) and (Khoshelham & Altundag 1998) to denoise the data obtained from TLS and quantify rock surface roughness. Bosche and Biotteau (2015) proposed a method that integrates TLS data and continuous wavelength transformation (CWT), which helped mitigate one of the shortcomings of the previously suggested approach: the surface waviness would now be characterized by considering five surface undulation periods. However, both approaches failed to address the concerns of carrying out measurements along two dimensional (2D) surfaces instead of one dimensional (1D) lines.

In order to overcome the above mentioned shortcomings, this study uses applies 2D CWT on TLS data to develop a surface profile of the scanned surface. Detailed information about wavelet analysis can be found in (Polikar, 1994) and (Addison, 2002). The fact that waves or “signals” present on the surface can be decomposed as the summation of sinusoidal functions with different amplitudes and frequencies inspired the idea of using wavelet transform for characterizing surface waviness. The idea that sets the point of departure for this research is that the wavelet transformation can be applied not just to 1D signals but to multi-dimensional signals as well (Bosché & Biotteau, 2015).

3. METHODOLOGY

Figure 2 summarizes the methodology proposed in this paper. Upon acquisition of the point cloud, the challenge is to identify a proper tool for assessing the flatness of the surface based on the data. The flatness or waviness associated with a surface can be assessed with the help of wavelet digital filters. After processing the data using wavelet filters, the waviness component of the surface can be analyzed and this information can be used to assess whether repair work is needed or not.

3.1 Data Preprocessing

Three-dimensional (3D) point cloud of the surface of a precast concrete slab was acquired using Trimble TX5 Scanner, a high-speed 3D terrestrial laser scanner that is able to measure at speeds up to 976,000 pts / sec and a range of 120 m. The raw point cloud data included approximately 1.5 million points, which was exported to ASCII format, and then imported into MATLAB for further processing. The point cloud data was de-noised using the K-nearest neighbor algorithm (Morales et al. 2010). The raw point cloud data represents the local x, y and z coordinates of measured points relative to the scanner's position. Using Singular Value Decomposition (SVD), the direction with the most variance was identified and the point cloud is aligned to the z=0 plane. The new coordinates give the actual deviation of each point with respect to the z=0 plane. This helps create a discrete 2D 'signal' from the raw point cloud data.

The frequency domain helps in analyzing the different frequencies present in the signal; such information cannot be readily extracted from the spatial domain. In order to transfer the obtained signal from spatial to frequency domain, it is necessary to retrieve a 2D signal on a regular grid (Kunis 2007). After generating equally spaced rows

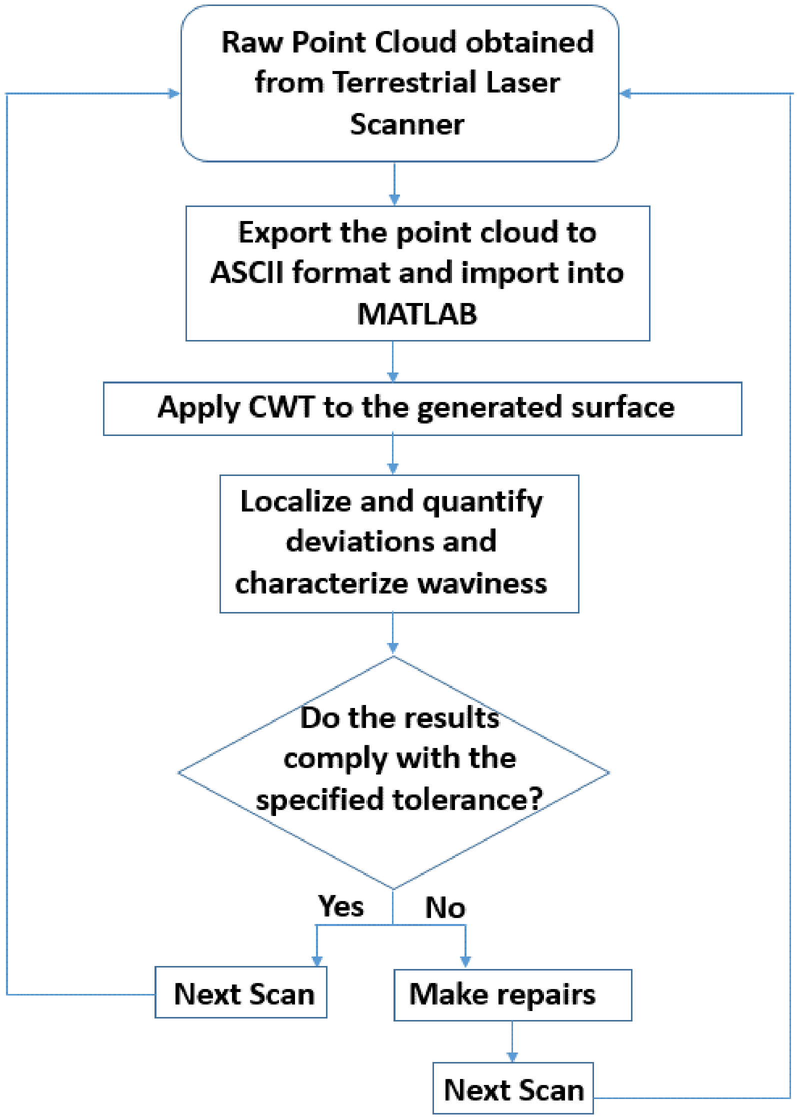


Fig. 2: Research Methodology

along the x and y axes, the rows were meshed into a grid. A window size of 25mm x 25mm was considered and the average of the z-values of all the co-ordinates that falls into the same window was taken. This process helped in generating a color coded deviation map as shown in Figure 3, which serves as a visual reference for assessing the variation in surface height with respect to a reference plane z=0 and helps in defining the surface levelness. The information about the surface deviation from z=0 can also be represented with the help of a contour map (Figure 4) generated from the height values obtained for each point (x, y). The contour map provides a better separation of boundaries between the zones that carry deviations from the z=0 surface. Both of these maps provide a significant advantage over the straight-edge, F-number and Waviness index method as they overcome the

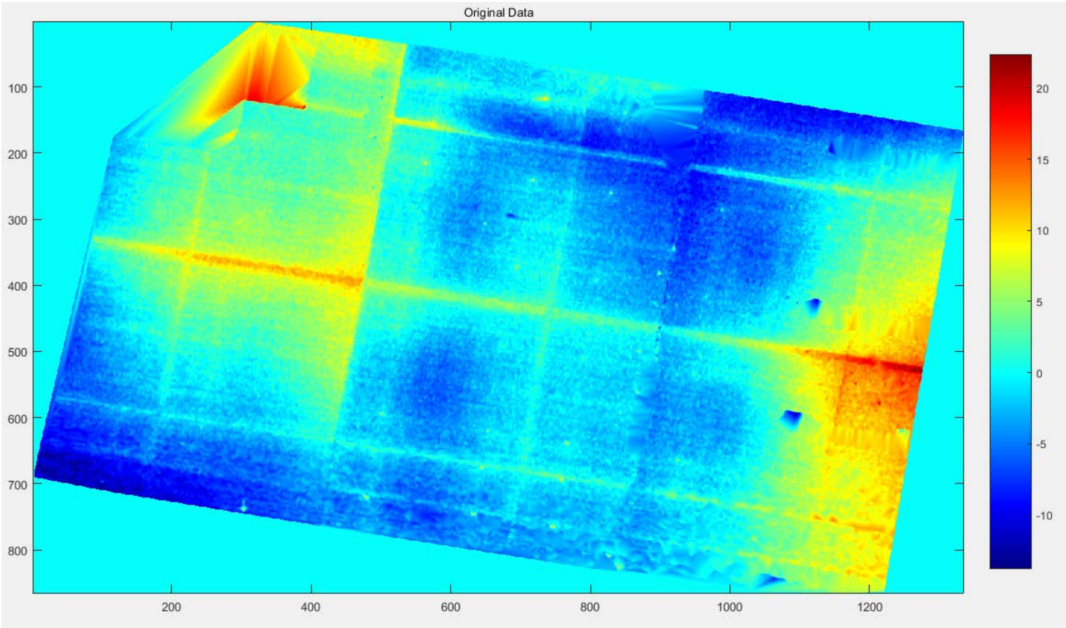


Fig. 3: Color coded deviation map in mm

problem of measuring deviations along straight lines in fixed intervals for the entire surface.

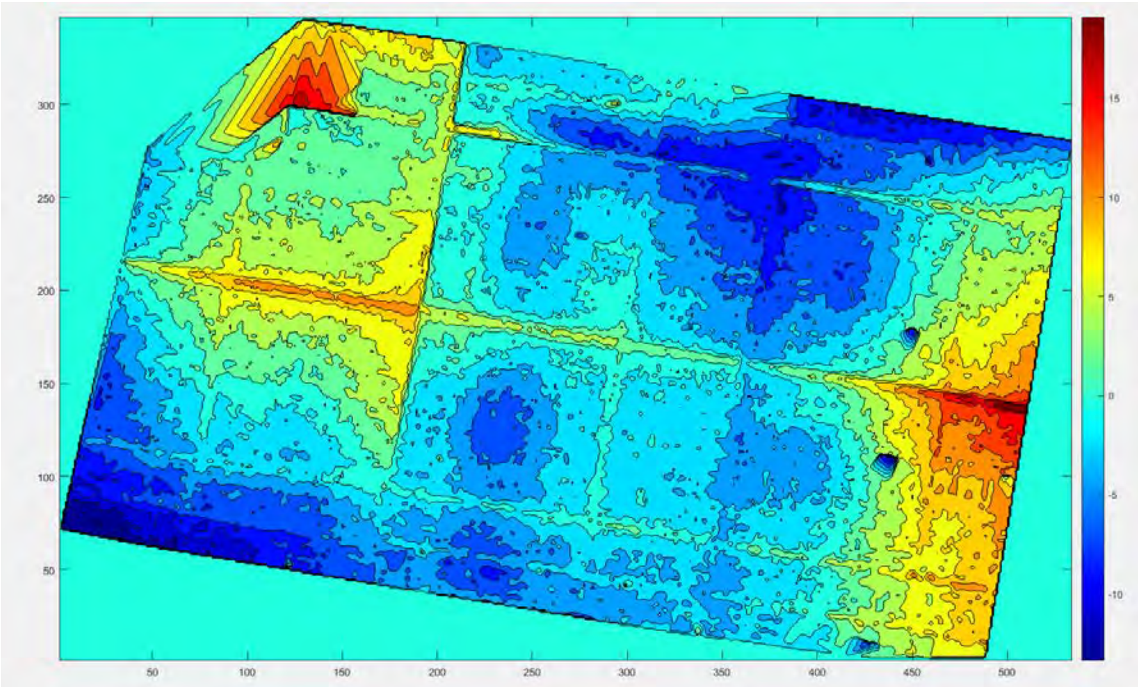


Fig. 4: Contour map showing the undulations present in the surface

3.2 Wavelet Analysis

The first step in performing wavelet analysis is the selection of the wavelet type. Mexican hat wavelet is a real and isotropic wavelet that is good for detecting edge and contour features. The high frequency and low frequency components that make up the surface texture can be observed by manipulating the translating and dilating parameters of the mother wavelet (Leach 2013). For smaller scales, the higher frequency components are highlighted, and for larger scales the lower frequency components are highlighted as shown in Figure 5. The 2D-CWT thus detects the oscillations or waviness of the surface profile for different scales. The wavelet analysis is performed on the matrix with heights with respect to the z=0 plane.

While examining the wavelets at different scales, it was found that the regions with the highest correlation are reflected by the higher values of the coefficients obtained after the transform. Figure 5 (a) shows that there are almost no regions where frequencies or periods (high frequencies) corresponding to scale 15 exist. Figure 5 (b), (c), (d) and (e) show a few regions where frequencies or periods corresponding to scales 30, 45, 60 and 75 exist. The regions showing periods at the corresponding scales are marked with circles. Figure 5 (d) shows two regions where the periods corresponding to scale 60 are dominant. From Figure 3, it is evident that in these two regions, there are changes in elevation approximately from 5mm to 20 mm (left) and from 10 mm to 20 mm (right). The location-frequency map in Figure 5 (d) helps us understand that the characteristic period corresponding to this deviation is represented by scale 60. These analysis was performed at scales of 15, 30, 45, 60 and 75, but in actual practice, it can be performed at any scale, based on the parameters described in Equation 1. The relationship between the time period and the scale is determined by this equation (Addison, 2002):

$$a = \frac{fc}{f * \delta p} = \frac{T * fc}{\delta p} \tag{1}$$

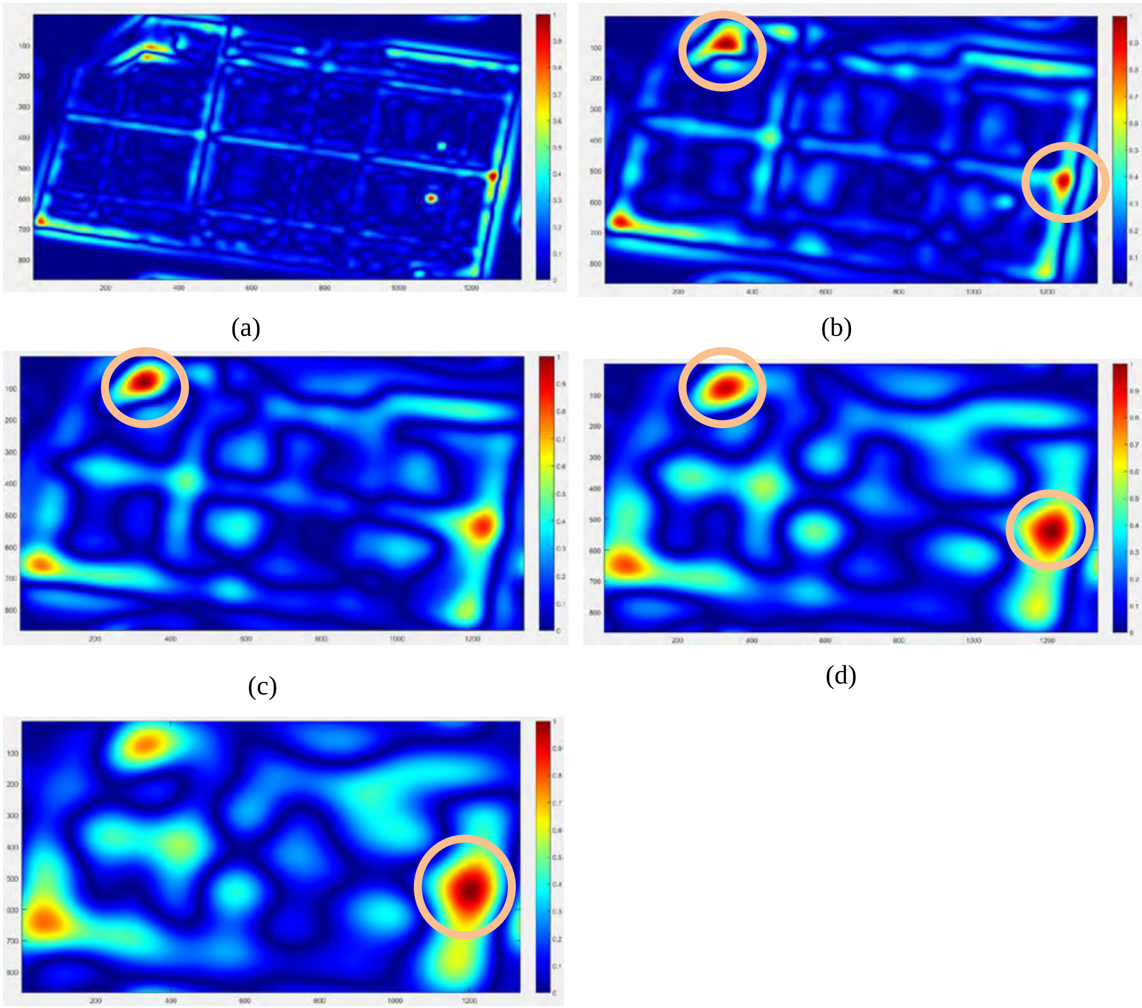
where f_c is the main frequency component of the Fourier transform of the mother wavelet. For Mexican hat wavelet, it is 0.252 cm^{-1}. δ_p is the sampling period along the signal, which in our case is 1 cm. f is the frequency of undulation and T is the characteristic period of the signal.

Another way of verifying the validity of 2D CWT results can be done by comparing the coefficients obtained from 2D CWT along a certain profile with the coefficients obtained by performing 1D CWT along the same profile from the original laser scan. In order to obtain the correlation coefficients for analyzing such a relationship, 1D profiles of the original scan were taken along the y- axis randomly as shown in Figure 6. After performing 1D CWT of these profiles at scales 15, 30, 45, 60 and 75, the correlation between these coefficients and the coefficients obtained for these regions from the 2D CWT analysis were compared. The correlation coefficients at different scales show satisfactory results apart from profile 1 at scale 15 (0.57), profile 2 at scale 75 (0.71) and profile 3 at scale 45 (0.70). As shown in Table 1, the results show that there is a strong correlation between 1D CWT and 2D CWT analysis results. The results of the CWT analysis obtained at different scales can be compared to the characteristic period (T) or Waviness Index (WI) results (see Table 2). This comparison would help inspectors assess whether the examined area of the concrete slab requires repair or not.

The 2D CWT results can be made comparable to the results obtained by using the Waviness Index method. It was shown earlier by Bosche and Biotteau (2015) that the results of 1D CWT and WI methods are strongly correlated. Thus, in order to make the results of 2D CWT comparable to the WI method, the correlation between the 2D CWT results and the 1D CWT were analyzed. If strong correlation between 2D CWT and 1D CWT results are obtained, it can be inferred that the 2D CWT and WI results are strongly correlated as well. The results of 1D CWT were made comparable to the results of the Waviness Index method with the help of Table 2 as shown by Bosche and Biotteau (2015). A proposed revision at ACI 117R-90 gives correlation between different measurement systems, presented in Table 3. Based on the working principle of the Waviness Index method, a WI of value 1 represents a chord length (characteristic period) of 2 ft (or 60 cm) (Bosche and Biotteau 2015). Using equation 1, the corresponding CWT scale *a* can be determined and in this case, the characteristic period of 60 cm corresponds to a scale of 15.

Table 1. Correlation coefficients generated by comparing the coefficients of the 1D CWT along four profiles and 2D CWT along the same profiles

	Scales				
	15	30	45	60	75
Profile 1	0.57	0.70	0.73	0.81	0.76
Profile 2	0.82	0.83	0.78	0.79	0.71
Profile 3	0.76	0.80	0.70	0.74	0.79
Profile 4	0.86	0.77	0.81	0.91	0.92



(a) (b) (c) (d) (e)

Fig. 5: Plot of the coefficients obtained from the wavelet transformation corresponding to scales 15 (a), 30 (b), 45 (c), 60 (d) and 75 (e)

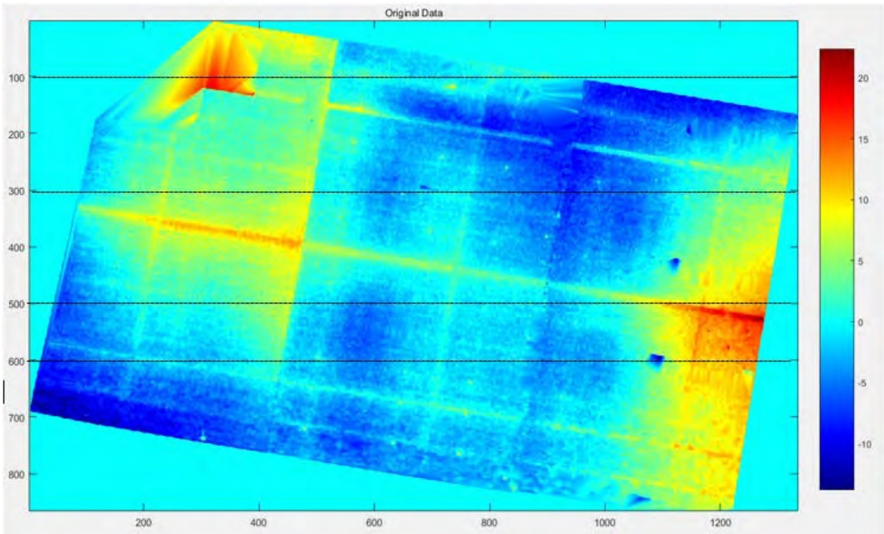


Fig. 6: 1D surface profiles taken from the original scan along randomly selected locations along the y-axis

Table 2. Continuous Wavelet Tranform scales and equivalent Waviness Index obtained by assuming 1 cm spacing for CWT and 1ft for Waviness Index (Bosche and Biotteau 2015)

Characteristic Period (T)	CWT Scale (a)	Waviness Index (k values)
60	15	1
120	30	2
180	45	3
240	60	4
300	75	5

Table 3. Floor flatness tolerances for three conventional methods from the proposed revision at ACI 117R-90

Floor Classification	WI [inches]	Gap under 10-ft straightedge [inches]	F_F [dimensionless]
Conventional	0.31	1/2	12
Moderately Flat	0.2	5/16	20
Flat	0.12	1/4	25
Very Flat	0.08	3/16	32
Super Flat	0.05	1/8	50

4. CONCLUSIONS

The method described in this paper helped in deriving information about the undulations present in concrete surfaces using terrestrial laser scanning technology. The raw laser scan data obtained from a concrete slab was processed in Matlab environment using 2D Continuous Wavelet Transform (CWT). The results obtained from the experiments show that processing TLS data using 2D CWT is an efficient way of assessing the waviness characteristics of concrete slabs. Since it provides the frequency information together with the location information, the 2D-CWT has a significant advantage over other methods such as Fourier transform. The plot of the coefficients at different scales reflect the waviness characteristics of the surface. Additionally, the color coded deviation map and contour map complement the results obtained from CWT analysis. Based on the plots, it is possible to determine whether the existing characteristics of the floor comply with the specified tolerances and consequently help make decisions whether a repair is necessary or not.

5. REFERENCES

Abdul-Rahman, H.S., Jiang, X.J. and Scott, P.J. (2013). Freeform surface filtering using the lifting wavelet transform. *Precision Engineering*, Vol 37, No. 1, 187–202.

Addison P.S. (2002). The Illustrated Wavelet Transform Handbook: Introductory Theory and Applications in Science, Engineering, Medicine and Finance, 1st Ed., CRC Press.

Azernikov S. and Fischer A. (2003). Surface reconstruction of freeform objects based on hierarchical space decomposition, *International Journal of Shape Modeling*, Vol. 9, No. 2,177–190.

Ballast D.K. (2007). Handbook of Construction Tolerances Second, John Wiley & Sons.

Bimel C., Anderson R. B., Ault C. M., Ayers C. M., Beaudoin K. L., Colasanti A. E., Epifano R. A., Face S. A., Finkel E. B., Foreman B. E., Fricks T. J., Hill E. D., Holland J. A., Mckinney A. W., Munday J. P., Nussmeier R. W., Panarese W. C., Phelan W. S., Phillips D.W., Rohrer J. W., Scott M. L., Tatnall P. C. and Taylor R. G. (1997). Guide for Concrete Floor and Slab Construction Reported by ACI Committee 302.

Bitenc M., Kieffer D.S. and Khoshelham K. (2015). Evaluation of Wavelet Denoising Methods for Small-Scale Joint Roughness Estimation Using Terrestrial Laser Scanning, *ISPRS Annuals of Photogrammetry, Remote Sensing and Spatial Information Sciences*, Vol. 3, No. 5, 81–88.

Bosché F. (2010). Automated recognition of 3D CAD model objects in laser scans and calculation of as-built dimensions for dimensional compliance control in construction, *Advanced Engineering Informatics*, Vol. 24, No. 1, 107–118.

Bosché F. and Biotteau B. (2015). Terrestrial laser scanning and continuous wavelet transform for controlling surface flatness in construction – A first investigation, *Advanced Engineering Informatics*, Vol 29, No. 3, 591–601.

Bosché F. and Guenet, E. (2014). Automating surface flatness control using terrestrial laser scanning and building information models, *Automation in Construction*, Vol .44, 212–226.

Chen X., Raja J. and Simanapalli S. (1995). Multi-Scale Analysis of Engineering Surfaces, *International Journal of Machine Tools and Manufacture*, Vol. 35, No. 2, 231–238.

Cheok G.S., Stone W. C., Lipman R. R. and Witzgall C. (2000). Ladars for construction assessment and update, *Journal of Automation in Construction*, Vol. 9, No. 5, 463–477.

Coifman R.R. and Maggioni M. (2006). Diffusion wavelets, *Applied and Computational Harmonic Analysis*, Vol. 21, No. 1, 53–94.

Fuchs P. A., Washer G. A., Chase S. B. and Moore M. (2004). *Applications of Laser-Based Instrumentation for Highway Bridges. Journal of Bridge Engineering*, Vol. 9, No. 6, 541–549.

Ge Y., Tang H., Eldin M., Chen P., Wang L., Wang J. (2015). A Description for Rock Joint Roughness Based on Terrestrial Laser Scanner and Image Analysis, *Nature Publishing Group*, 1–10.

Gillette H.P., Hill C.S., Murray C.T., Kirkland H.B. and Hadden S.C. (1913). Engineering and Contracting, Gillette Publishing Company. URL: https://books.google.com/books?id=VKjmAAAAMAAJ.

Golparvar-Fard M., Bohn J., Teizer J., Savarese S**.,** Peña-Mora F. (2011). Evaluation of image-based modeling and laser scanning accuracy for emerging automated performance monitoring techniques, *Automation in Construction*, Vol. 20, No. 8, 1143–1155.

Gupton P.W. (2009). F-Numbers - Concrete Floor Slab Flatness and Levelness, *TTL*, 100.

Hussein S., Paul J., Abdul-Rahman H. S., Jiang X. J. and Scott P. J. (2012). Freeform Surface Filtering Using the Lifting Wavelet Transform.

Israel M.C. and Pileggi, R.G. (2016). Use of 3D laser scanning for flatness and volumetric analysis of mortar in facades, *Rev. IBRACON Estrut. Mater.*, Vol. 9, No. 1, 91–106.

Jiang X.Q., Blunt L. and Stout K.J. (2001). Lifting wavelet for three-dimensional surface analysis, *International Journal of Machine Tools and Manufacture*, Vol. 41, No. 13-14, 2163–2169.

Josso B., Burton D.R. and Lalor M.J. (2002). Frequency normalised wavelet transform for surface roughness analysis and characterization, Vol. 252, 491–500.

Kalyan T.S., Zadeh P. A., Staub-French S. and Froese T.M. (2016). Construction Quality Assessment Using 3D as-built Models Generated with Project Tango, *Procedia Engineering*, Vol. 145, 1416–1423.

Khoshelham K. and Altundag D. (1998). Wavelet De-Noising of Terrestrial Laser Scanner Data for the Characterization of Rock Surface Roughness, Vol. 38, 373–378.

Morales R., Wang Y. and Zhang Z. (2010). Unstructured Point Cloud Surface Denoising and Decimation Using Distance RBF K-Nearest Neighbor Kernel, *Advances in Multimedia Information Processing - PCM 2010: 11th Pacific Rim Conference on Multimedia, Shanghai, China, September 2010, Proceedings, Part II. Berlin, Heidelberg: Springer Berlin Heidelberg,* 214–225.

Neal F.R. (2002). Concrete Industrial Ground Floors, Thomas Telford. URL:

https://books.google.com/books?id=QxuofcwjR8gC.

Polikar, R. (1994). The Wavelet Tutorial, URL: http://users.rowan.edu/~polikar/wavelets/wttutorial.html.

Schafer T. and Weber T. (2004). Deformation measurement using terrestrial laser scanning at the hydropower station of Gabcikovo, *In INGEO 2004 and FIG Regional Central and Eastern European Conference on Engineering Surveying, FIG, Copenhagen, Denmark.*

Shih N.J. and Wang P.H. (2004). Using point cloud to inspect the construction quality of wall finish, *Proceedings of the 22nd eCAADe Conference*, 573–578.

Stępień K. and Makieła W. (2013). An analysis of deviations of cylindrical surfaces with the use of wavelet transform, Vol 20, No. 1, 139–150.

Tang P., Akinci B. and Huber D. (2009). Characterization of three algorithms for detecting surface flatness defects from dense point clouds, *IS&T/SPIE Electronic Imaging*, Vol. 7239, 72390N–72390N.

Tang P., Huber D. and Akinci B. (2011). Characterization of Laser Scanners and Algorithms for Detecting Flatness Defects on Concrete Surfaces, *Journal of Computing in Civil Engineering*, Vol 25, No. 1, 31–42.

Turkan Y., Bosche F., Haas C. T. and Haas R. (2012). Automated progress tracking using 4D schedule and 3D sensing technologies, *Automation in Construction*, Vol. 22, 414–421.

Wang Q., Kim M., Cheng J. C. P. and Sohn H. (2016). Automated quality assessment of precast concrete elements with geometry irregularities using terrestrial laser scanning, *Automation in Construction*, Vol. 68,170-182

Ytterberg C.N. (1996). Using the Waviness Index to Improve Floor Flatness

POLYGONIZATION OF POINT CLOUD OF ELONGATED CIVIL INFRASTRUCTURES USING LOFTING OPERATION

Nao Hidaka

Osaka University, Japan

Takashi Michikawa

Photonics Control Technology Team, RIKEN Center for Advanced Photonics, RIKEN, Japan

Ali Motamedi, Nobuyoshi Yabuki, and Tomohiro Fukuda

Osaka University, Japan

ABSTRACT: *This paper proposes a novel method for polygonizing swept structures from scanned point cloud data. The proposed method uses 2D profile curves of structures and polygonizes them by a lofting operation. In order to extract profile curves from the input point cloud, center lines of the point cloud are extracted using local symmetry analysis and a set of profile curves is found by computing cross-sections of the orthogonal planes to the center line. This approach is efficient for the swept objects such as tunnels and monorails, since the method can create polygonal meshes with regular connectivity. In addition, incomplete parts with low density or defects can be recovered from other similar profiles. This paper also shows the results for road and train tunnels and discusses the advantages and limitations of the proposed method.*

KEYWORDS: *Point Cloud, Polygonization, Center line extraction, Lofting, BIM for infrastructure, CIM*

1. INTRODUCTION

The maintenance of existing civil infrastructures is a critical issue for the government in order to prolong their service lives. Building Information Modeling (BIM) for infrastructure, which is referred as CIM (Civil Information Modeling) (Yabuki, 2012), consolidates all life-cycle information of structures into 3D models; and can be used to improve the maintenance management. However, it is mainly used for new infrastructures. In order to use it for existing infrastructures, their 3D models must be prepared using scanning devices. Since the scanned data is provided as a set of points (i.e. point cloud), converting them to meaningful polygons is required. Many approaches have been proposed for such conversion (See a survey by Burger et al. (2014)); and some research projects specifically focused on polygonization of civil infrastructures, e.g. (Hidaka et al., 2015 and 2016).

This research focuses on creating product models of swept and elongated civil infrastructures such as tunnels and monorails. These infrastructures are usually elongated, and data acquisition is usually difficult for most of scanning devices other than car-equipped LiDAR (a.k.a. mobile mapping system). In addition, acquired point clouds may lack many features due to bad scanning conditions, noise, and occlusions by obstacles (e.g. cars and pedestrians). There are two major issues when applying conventional polygonization methods to point clouds of such infrastructures. First issue is that the point clouds of these infrastructures often lack important features and the quality of their polygonization is not sufficient. State-of-the-art methods (Kazhdan et al., 2006 and Kazhdan and

Hoppe, 2013) may fill missing regions, however, the polygonization accuracy of that region is not guaranteed although the missing region of elongated objects can be estimated. The other issue is that it is difficult to polygonize the point clouds of these infrastructure directly due to the requirements for heavy computation. This may be resolved by using grid-based clustering, however, fragmented polygons must be aggregated in the final step, and additional operations are usually involved. The use of shape matching techniques may reduce the memory usage (Hidaka et al., 2015 and 2016), however, these methods work well for infrastructures with multiple distinct parts and, cannot handle swept features.

This paper presents a polygonization method for unorganized point cloud of elongated objects. Basic idea of this method is to extract cross-section curves of the elongated objects. In order to extract accurate cross-sections, center lines of the point clouds are firstly found by computing local geometric symmetry of the objects (Mitra et al., 2006). Once the center lines are computed, cross-section planes can be defined so that they are perpendicular to the identified center lines, and profile curves are computed from them. Polygonal meshes of the point clouds is then computed by the lofting operation or connecting cross-sections. This approach generates simple and accurate polygonization of elongated structures. In addition, missing parts of the point clouds can be completed by using other profile curves. This paper also validates the proposed method by using scanned point cloud data.

2. PROPOSED METHOD

The proposed polygonization method is specialized for civil infrastructures with specific elongated features such as sweep and loft. In order to create such polygon data, profile curves or cross-sections of the structures are extracted, and are connected by lofting operations. A similar idea for the building data can be found in Michikawa et al. (2015), however, their method assumes the input data comes from a man-made BIM data, whereas our method supposes that a scanned point cloud without explicit topological structure is used. Fig. 1 shows an overview of the proposed method consisting of four major steps: (a) as-is point cloud is input to the system, (b) the center line (Fig. 1 (b)) is created, (c) cross-section points are computed for orthogonal planes perpendicular to the center line, and are translated into polyline (Fig. 1 (c)), (d) a polygon data is created from the polylines by lofting operations (Fig. 1 (d)). Details of the above-mentioned steps are explained in the following subsections.

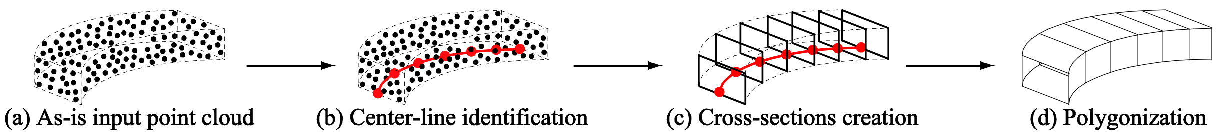


Fig. 1: Overview of the proposed method

2.1 Center line computation based on geometric symmetry

The first step is to detect the center line of the elongated object. This problem is related to Medial Axis Transform

(MAT) of the solid objects (e.g. Blum (1967)). However, our input point cloud sometimes includes large defects, and conventional methods (e.g. (Tagliasacchi et al., 2009 and Vanna et al., 2012)) do not fit to our problem. Whereas our approach uses local symmetry (Mitra et al., 2006) of the geometric objects to extract the center line of the objects, and it works particularly well for incomplete point data, which are main subjects of polygonization for civil infrastructures, and are the main focus of this research. The detection of the center line has three steps: (1) detection of silhouette points, (2) selection of candidate center line points, and (3) identification of the center line. Note that this is computed in 2D space for faster computation, and the points are projected onto XY plane prior to the computation.

Silhouette points are outermost points of the input point cloud (Fig. 2). In our proposed method, these points are extracted from the projected points to be used for a robust identification of center lines. There are techniques to extract these points by convex hull (Preparata and Hong, 1977) or alpha shapes (Edelsbrunner and Mücke, 1994), however, convex hull fails to capture concave features and alpha shapes may extract inside points. Our method applies a simplified version of approximate convex decomposition (Lien and Amato, 2004) to the projected point. First, a separation plane is found by Principal Component Analysis (PCA) so that the plane is perpendicular to the first principal component vector (Fig. 2 (a)), and the points are decomposed into two sub regions. This step is recursively applied until all sub regions are approximately convex (Fig. 2 (b)), and finally points are extracted as silhouette points if distance between the point and the convex hull is less than a user-defined threshold d_{sil} (drawn in red in Fig. 2 (c)).

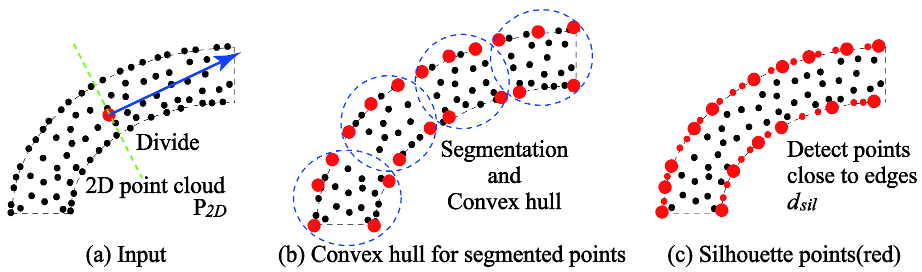


Fig. 2: Detection of silhouette points

The next step finds candidate points of the center line P_c using the silhouette points based on the symmetry detection from geometric models (Mitra et al., 2006). This step uses generalized Hough transform (Ballard, 1981) that votes the distance and angles with X-axis of each point pair (Fig. 3 (a)). The pairs that fall inside the high density area of resulting histogram (Fig. 3 (b)) are shortlisted and the midpoints of the point pairs are selected as center points P_c (Fig. 3 (c)).

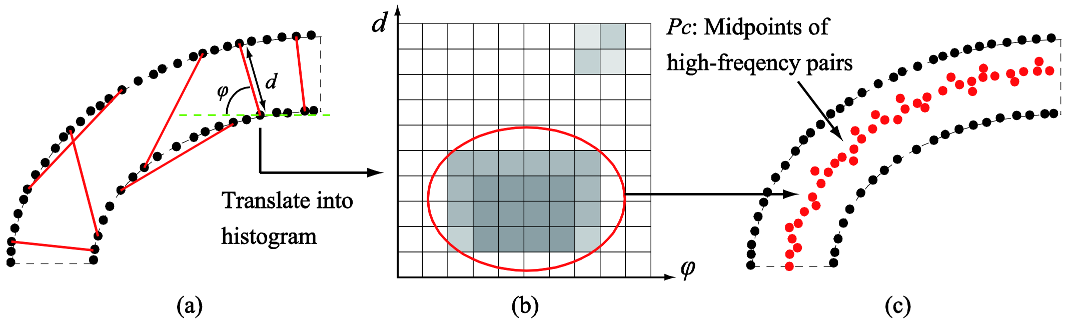


Fig. 3: Determining candidate points of a center line based on symmetry

The center line points may involve noises due to low threshold in the previous step (Fig. 4 (a)). Next, the smoothing method introduced in Vanna et al. (2012) is applied to the center line points (Fig. 4). Prior to the smoothing, isolated outlier points are removed (Fig. 4 (a)). Smoothing is then applied to the points by Laplacian smoothing (Fig. 4 (b)) and PCA projection using the plane defined by first principal component (Fig. 4 (c)) with user-defined radii r_{lap} and r_{PCA}, respectively. Since the points are dense, the number of points is reduced by sub-sampling. Fig. 5 shows the result of center line computation by using a point cloud of a monorail. The result shows that the center line is successfully obtained, although the data contains many defects that may cause failure of extraction.

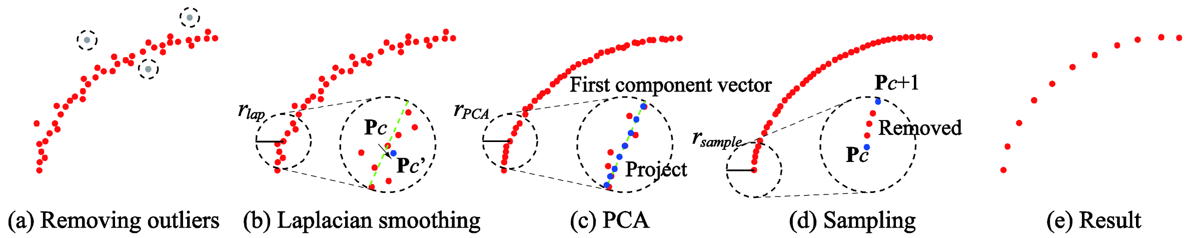


Fig. 4: Simplifying candidate points of a center line

(a) Center points after PCA

(b) Center points final result

Fig. 5: Result of center line computation by using a point cloud of monorail

2.2 Creating polylines of cross-sections

This step computes profile curves from cross-sections of the input point cloud using the center line. In order to compute cross-sections of the points, orthogonal plane s_c is defined so that it is perpendicular to the center line and sampled center line point p_c is included (Fig. 6 (a)). Then, cross-section points $P_{sc} = \{p_i\}$ are extracted so that Equation 1 is satisfied:

$$P_{sc} = \{p_i | d(p_i, s_c) < d_{sc}\}, \tag{1}$$

where $d(p, s)$ denotes Euclidean distance between p and a plane s, and p_i is then projected onto s_c (Fig. 6 (b)).

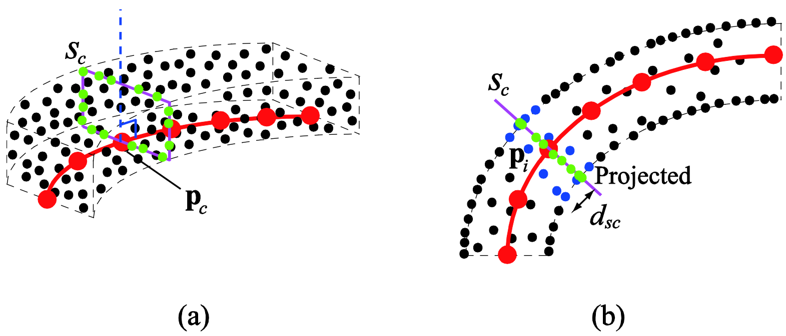


Fig. 6: Detecting cross-section points

Next, polylines are computed from P_{sc} in 2D space defined by s_c. First, the convex hull of P_{sc} is computed in order to compute a rough closed polyline (Fig. 7 (a)); Next, the polyline is refined based on Ramer-Douglas-Peucker algorithm (Ramer, 1972; Douglas and Peucker, 1973). In this step, all points are classified by their closest line segment and the distance between the point and the line segment is evaluated as error (Fig. 7 (b)). Our refinement step finds the line segments with maximum approximation error (segment $(C_h,\ C_{h+1})$ in Fig. 7 (b)), and subdivide it so that the created vertex moves to the farthest point of the segment (Fig. 7 (c)). This step is iterated until the approximation error is lower than a user-defined threshold d_h (Fig. 7 (d)).

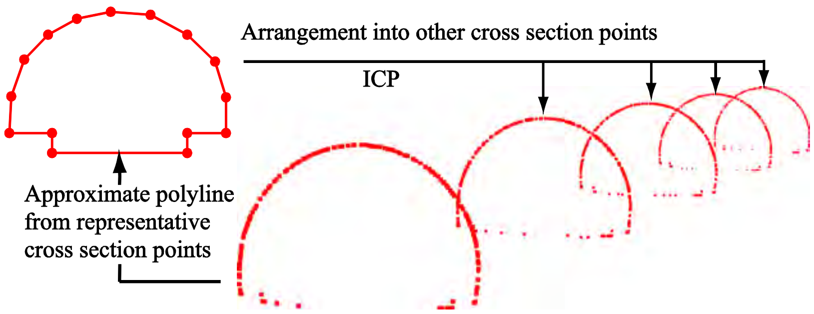


Fig. 7: Polyline fitting to projected points.

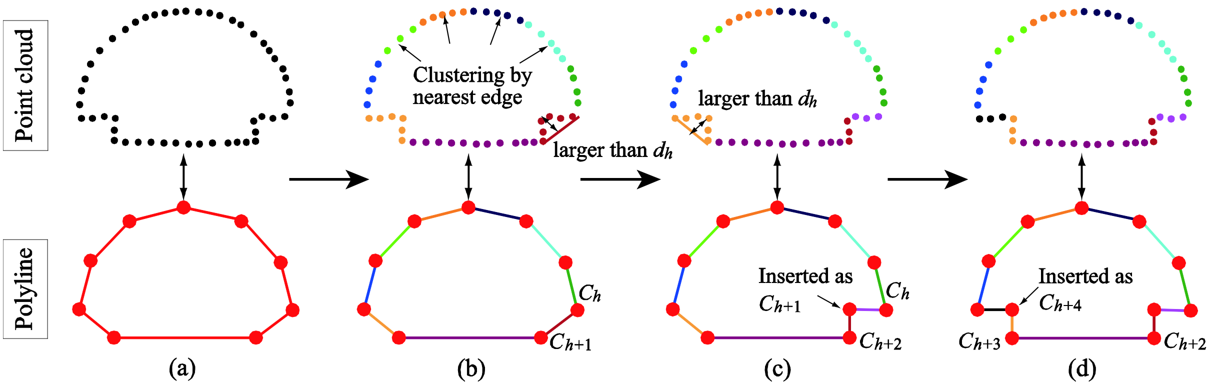
Although the geometries of profile curves are similar, their number of points are usually different from each other. This sometimes causes low quality of polygonization. Representative polygons can be fitted to the profile curves to maintain the topological structure of the resulting surface. In order to find similar curves, similarity metric (e.g. Mori, et al. (2006)) can be used, and Iterative Closest Point (ICP) (Besl and McKay, 1992) is used for the registration of curves (Fig. 8).

Fig. 8: Representative polygons fitted to the profile curve

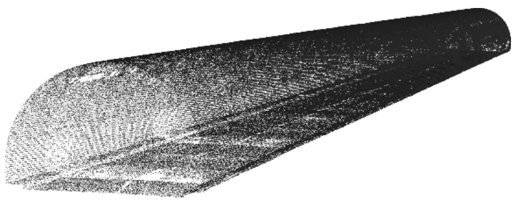
3. RESULTS AND DISCUSSION

3.1 Results

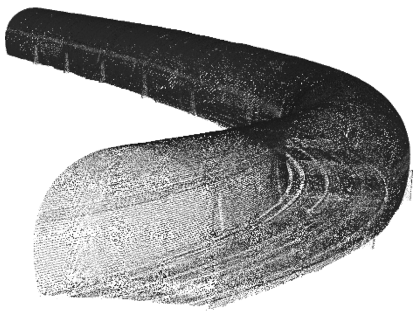
The proposed method was implemented using the Point Cloud Library (PCL) (Rusu and Cousins, 2011), and we applied this to point cloud data of existing tunnels (Straight road tunnel (Figs. 9 (a) and (c)) and curved train tunnel (Figs. 9 (b) and (d))) and a monorail (Figs. 9 (e) and (f)). Point cloud data of both tunnels are acquired by stationary



laser scanners, and monorail data is acquired by a mobile mapping system. Figs. 10 and 11 show the extracted center line points and the resulting polygons. The parameters used in these experiments are summarized in Table 1.



(a) Straight tunnel (side view)



(b) Curved tunnel (side view)

(c) Straight tunnel (top view)

(d) Curved tunnel (top view)

(e) Rail (side view)

(f) Rail (top view)

Fig. 9: Point clouds of the tunnels

Table 1: Parameters

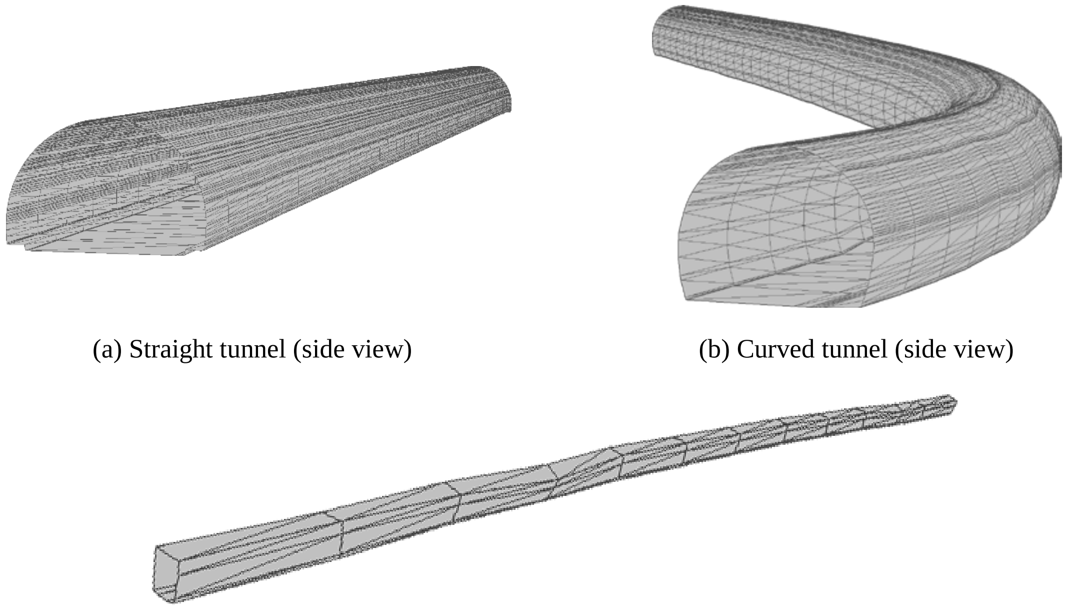
	d_{sil}(m)	r_{lap}(m)	r_{PCA}(m)	d_{sc}(m)	d_h(m)
Straight tunnel	0.2	0.5	0.5	0.5	0.2
Curved tunnel	0.2	0.05	0.1	0.5	2.0
Rail	0.05	0.5	0.1	0.5	0.2

(a) Straight tunnel

(b) Curved tunnel

(c) Rail

Fig. 10: Center lines ($r_{\text{sample}} = 9.0$)



(a) Straight tunnel (side view)

(b) Curved tunnel (side view)

(c) Rail (side view)

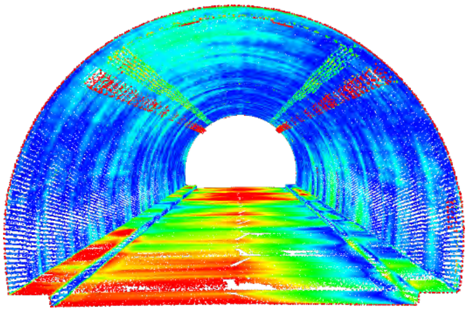
Fig. 11: Results of polygonization ($r_{\text{sample}} = 9.0$)

Table 2: Comparison of results

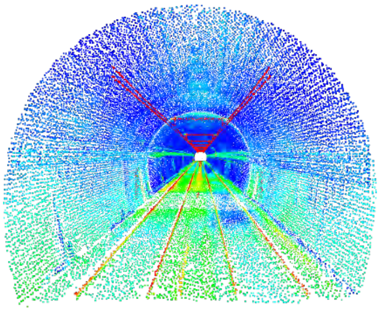
	r_{sample}(m)	Time(s)	Vertices	Faces	Error(m)
Straight tunnel (1,046,899 points)	9.0	10.989	6,273	12,240	0.045
	4.5	22.544	12,382	24,462	0.027
	3.0	43.088	16,560	32,844	0.039
Curved tunnel (1,163,924 points)	9.0	17.115	3,619	7,084	0.134
	4.5	33.565	12,160	24,064	0.068
	3.0	59.567	15,336	30,456	0.072
Rail (8,096 points)	18	8.666	56	96	0.241
	9	8.604	117	216	0.236
	4.5	9.694	297	572	0.089

3.2 Discussion

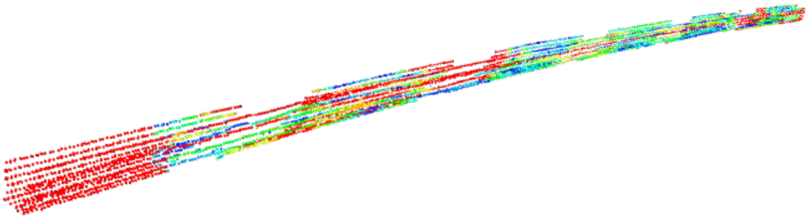
All polygonization results were well-approximated to the input point clouds, and the Hausdorff-distance between the point clouds and the polygons were 0.106 m in average (Fig. 12). A lower accuracy can be seen in the areas that have facilities such as rails and lights. Since these objects were ignored in our polygonization, large error is detected. In addition, in the case of the rail point cloud, when r_{sample} is large, the point cloud of the whole rail was not polygonized, which creates high Hausdorff-distance. Additionally, the resulting polygons have regular connectivity, and the number of triangles can be reduced. Table 2 shows that the number of vertices of the resulting polygons makes it about 1~2% of that of the original points. Moreover, regular connectivity of polygons makes it easy to unfold surfaces onto 2D space. This property will help to create various types of maps (e.g. crack and degradations).



(a) Straight tunnel (min. = 0, max. = 0.1)



(b) Curved tunnel (min. = 0, max. = 0.3)



(c) Rail (min. = 0, max. = 0.1)

Fig. 12: Hausdorff-distance between the point cloud and the polygon (red: max. and blue: min.)

The processing time durations for the experiments are summarized in Table 2. The main processing bottleneck of the proposed method can be found in the symmetry detection step and the performance of this step directly depends on the number of points. In our implementation, number of points were reduced for improving performance. In the case of calculating the center line, it is not necessary to have high-density points. Hence, it is efficient to sample points in order to reduce the computation time. On the other hand, accuracy of the polygonization depends on the density of point cloud of cross-sections. When point cloud of the straight tunnel was sampled 20% points at random and validated with same parameter, one sidewalk was not polygonized. The number of representative cross-section points was 534. It may depend on d_{sc} and d_h. It is considered that such density is required in order to polygonize complex structures.

Our method has three major limitations. First limitation is that polygonization may fail when the input data contains large defects. In such case, the quality of cross-sections may be low (Fig. 13) even though the center line is robustly computed. Since the proposed method selects an average of cross-sections, when many low-quality cross-sections are detected due to large defects, the quality of average becomes worse. Therefore, a method to obtain good cross-sections from an incomplete data should be considered. The second limitation is that elongated parts must be decomposed from the input point clouds prior to polygonization, because center lines are computed in the projected plane. For the automatic computation, we need to develop an automatic method to extract elongated objects from dense point cloud data. The last limitation is that our method does not consider the torsion of center line curves. For instance, the proposed method cannot extract polygons of a roller coaster.

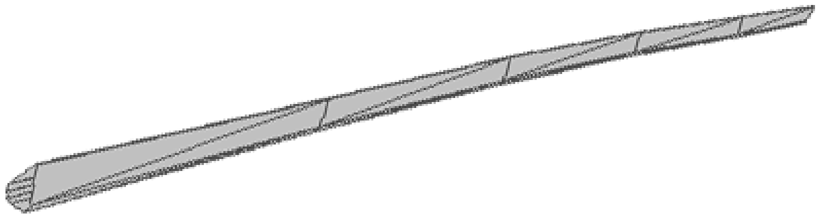


Fig. 13: Example of polygonization by using worse cross-sections

4. CONCLUSIONS AND FUTURE WORK

This paper presented a novel method to create a polygon model of elongated structures. The proposed method polygonizes the point cloud data by the lofting operation of cross-section profile curves of the input data. In order to find a set of cross-sections by defining orthogonal planes perpendicular to the center line, a method for computing center lines of the input data based on geometric symmetry was introduced. According to the results of experiments, the method succeeded to polygonize the point clouds with accurate and well-formed and well-connected polygons.

Several future work can be considered for improving our method. First, determination of intervals is an important issue for further applications. For example, tunnels are usually managed by spans (MILT, 2014), and it is better that the interval of tessellation corresponds to boundaries of tunnel spans. The other future work is to combine other polygonization methods to polygonize point cloud data at once, since this method is designed only for elongated structures.

5. ACKNOWLEDGMENT

The point cloud data used in the experiments are courtesy of KUMONOS Corporation Co. Ltd. And this work was supported by JSPS KAKENHI Grant Number JP26-04368 and in part by the Japan Construction Information Center Foundation. Finally, authors would like to thank Professor Amin Hammad for his valuable comments.

6. REFERENCES

Ballard D. H. (1981). Generalizing the Hough Transform to Detect Arbitrary Shapes, *Pattern Recognition*, Vol. 13, No. 2, 111-122.

Berger M., Tagliasacchi A., Seversky L. M., Alliez P., Levine J. A., Sharf A., and Silva C. T. (2014). State of the Art in Surface Reconstruction from Point Clouds, In S. Lefebvre & M. Spagnuolo, eds, *Eurographics 2014 - State of the Art Reports*, The Eurographics Association.

Besl P. J. and McKay H. D. (1992). A Method for Registration of 3-D Shapes, *IEEE Transactions on Pattern*

Analysis and Machine Intelligence, Vol. 14, No. 2, 239-256.

Blum H. (1967). A Transformation for Extracting New Descriptors of Shape, In W. Wathen-Dunn, ed, *Models for the Perception of Speech and Visual Form*, Cambridge, MIT Press, 362-380.

Douglas D. H. and Peucker T. K. (1973). Algorithms for the Reduction of the Number of Points Required to Represent a Digitized Line or Its Caricature, *Cartographica: The International Journal for Geographic Information and Geovisualization*, Vol. 10, No. 2, 112-122.

Edelsbrunner H. and Mücke E. P. (1994). Three-dimensional Alpha Shapes, *ACM Transactions on Graphics*, Vol. 13, No. 1, 43-72.

Hidaka N., Michikawa T., Yabuki N., Fukuda T., and Motamedi A. (2015). Creating Product Models from Point Cloud of Civil Structures based on Geometric Similarity, *ISPRS - International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, XL-4/W5, 137-141. Available at: http://www.int-arch-photogramm-remote-sens-spatial-inf-sci.net/XL-4-W5/137/2015/ (Accessed 27 July 2016).

Hidaka N., Michikawa T., Yabuki N., Fukuda T., and Motamedi A. (2016). Quality Enhancement Technique for Similarity-based Polygonization from Point Cloud, *Proc. of 16th International Conference on Computing in Civil and Building Engineering*, 1152-1159.

Kazhdan M., Bolitho M., and Hoppe, H. (2006). Poisson Surface Reconstruction, In *Proceedings of the Fourth Eurographics Symposium on Geometry Processing*, SGP ’06, Aire-la-Ville, Switzerland, Switzerland: Eurographics Association, 61-70.

Kazhdan M. and Hoppe H. (2013). Screened Poisson Surface Reconstruction, *ACM Transactions on Graphics*, Vol. 32, No. 3, 29:1-29:13.

Lien J. M. and Amato N. M. (2004). Approximate Convex Decomposition of Polygons, In *Proceedings of the Twentieth Annual Symposium on Computational Geometry*, SCG ’04, New York, NY, USA, ACM, 17-26.

Michikawa T., Yabuki N., and Fukuda T. (2015). Lofting-based Shape Simplification of Building Models using Voxelization, In *Proceedings of International Conference on Civil and Building Engineering Informatics (ICCBEI 2015)*, Tokyo.

Ministry of Land, Infrastructure, Transport and Tourism. (2014). Points of Periodic Check for Road and Tunnel (Written in Japanese). Available at: http://www.mlit.go.jp/road/ir/ir-council/pdf/yobo3_1_9.pdf (Accessed 27 July 2016).

Mitra N. J., Guibas L. J., and Pauly M. (2006). Partial and Approximate Symmetry Detection for 3D Geometry, In *ACM SIGGRAPH 2006 Papers*, SIGGRAPH ’06, New York, NY, USA, ACM, 560-568.

Mori G., Belongie S., and Malik J. (2005). Efficient Shape Matching using Shape Contexts, *IEEE Transactions on Pattern Analysis and Machine Intelligence*, Vol. 27, No. 11, 1832-1837.

Preparata F. P. and Hong S. J. (1977). Convex Hulls of Finite Sets of Points in Two and Three Dimensions, *Communications of the ACMÄi0*, Vol. 20, No. 2, 87-93.

Ramer U. (1972). An Iterative Procedure for the Polygonal Approximation of Plane Curves, *Computer Graphics and Image Processing*, Vol. 1, No. 3, 244-256.

Rusu R. B. and Cousins S. (2011). 3D is here: Point Cloud Library (PCL), *IEEE International Conference on Robotics and Automation (ICRA)*. Available at: http://pointclouds.org (Accessed 27 July 2016).

Tagliasacchi A., Zhang H., and Cohen-Or D. (2009). Curve Skeleton Extraction from Incomplete Point Cloud, In *ACM SIGGRAPH 2009 Papers*, SIGGRAPH ’09, New York, NY, USA, ACM, 71:1-71:9.

Vanna S., Kawata H., and Kanai T. (2012). A Robust and Centered Curve Skeleton Extraction from 3D Point Cloud, *Computer-Aided Design and Applications*, Vol. 9, No. 6, 869-879.

Yabuki N. (2012). BIM and Construction Information Modeling (CIM) in Japan, In *Proceedings of the International Conference on Computational Design in Engineering (CODE 2012)*, 325.

POST-DEMOLITION LANDSCAPE ASSESSMENT USING PHOTOGRAMMETRY-BASED DIMINISHED REALITY (DR)

Kazuya Inoue, Tomohiro Fukuda, Nobuyoshi Yabuki, Ali Motamedi, and Takashi Michikawa

Division of Sustainable Energy and Environmental Engineering, Osaka University, Osaka Japan.

ABSTRACT: *Recently, Augmented Reality (AR), which extends a visible scene with virtual objects, has gained popularity for landscape assessment. It is used in urban planning to facilitate reaching consensus on a design. However, existing AR approaches cannot correctly simulate views after the demolition and removal of outdoor buildings. Tanemura et al. (2014) applied Diminished Reality (DR) for this application. DR is a technique for removing an object from a scene by overlaying an appropriate background image on top of the object's area, in real time. They proposed a system that facilitates landscape simulation before removal of outdoor buildings by using point cloud data. Their system creates point cloud data using a 3D laser scanner and registers video camera's position and orientation manually. However, this method is expensive due to the use of laser scanners. Moreover, some parts of acquired point cloud data have low density or low quality. This paper proposes a photogrammetry-based DR system for landscape assessment. It uses photographs to obtain point cloud data of buildings and to calculate the video camera's position and orientation. The proposed system is advantageous to the previous work as it is higher in quality due to the use of polygon data instead of point cloud data to overlay the background image. Additionally, this system is more robust in the augmentation step as the computation of camera's position and orientation is done using automatic image matching, whereas the conventional method uses manual registration between point clouds and real-time video feed. The effectiveness of the proposed method is successfully demonstrated in a case study performed in a real environment.*

KEYWORDS: *Diminished Reality, Augmented Reality, Photogrammetry, Visual simulation for community planning, Construction Planning*

1. INTRODUCTION

Augmented Reality (AR), which extends a visible scene with virtual objects, has gained popularity for exterior construction applications (Klinker et al. 2001). AR can facilitate reaching consensus on a landscape design due to its ability to simulate views of full scale new structures at the design stage. Unlike Virtual Reality (VR) technology, AR does not require 3D virtual models of every object around the desired target, such as buildings, roads, lands, and terrains. Hence, AR has a potential to drastically reduce time and cost required to produce 3D virtual models of the surrounding environment (Fukuda et al. 2014).

However, existing AR approaches cannot correctly simulate the view after the demolition and removal of exterior structures. If simulation of new structures is carried out while old existing structure is still present, a 3D virtual model of the new structure will overlap the existing to-be-renewed structure. As a result, part of it, if not all, will be still visible and displayed. To solve this problem, Diminished Reality (DR) can be employed. DR is a technique that removes the image of an existing object from a scene, replacing it with the background image of the area.

Enomoto and Saito (2007) proposed a DR method for diminishing the occluding objects from each camera's view by employing different cameras that capture the same scene at different viewpoints. This method used AR-Tag markers to calibrate multiple cameras. However, the markers should constantly remain in the camera's viewpoint which makes it impractical for outdoor structures. Cosco et al. (2009) proposed a DR method which simulates a view without using a visuo-haptic device by using Image Based Rendering (Buehler et al. 2001; Debevec et al. 1996). In this method, to-be-removed target objects must be moved freely because the background image was prerecorded without the target objects. If the target objects is movable, this method is effective. However, this method is not effective for fixed objects such as exterior structures.

Tanemura et al. (2014) proposed a DR system by using point cloud data. This system called Point Cloud Diminished Reality Simulation (PCDR) creates point cloud data of a target structure and background structures by using a 3D laser scanner. This system overlays the point cloud data of parts of background structures on the target structure and simulates the view as if the target structure is removed. In this system, a user registers natural feature points of images that the web camera captured to correspond to the point cloud data for the alignment of new structures (Yabuki et al. 2012). However, this system is expensive due to the use of laser scanners which limits its usability. Moreover, some parts of acquired point cloud data have a low density or a low quality. Additionally, this system requires natural feature points to be continuously captured by the web camera. Once natural feature points go out of the view, a user must register the points again.

This research focus on photogrammetry as an alternative measurement technology. Photogrammetry is a technique which computes camera's position and orientation and creates point cloud data of target objects. In comparison with laser scanners, photogrammetry enables creating inexpensive point cloud data. Recently, Sato et al. (2016) proposed a marker-less AR system. Using automatic image matching technology, their system matches camera's position and orientation, computed by Structure from Motion (SfM) method (Hartley and Zisserman 2000), to the web camera's position and orientation. This system does not need special equipment such as GPS and gyroscope sensors, allowing users to move freely when the target structure is visible.

This paper proposes a novel DR method for landscape assessment using photogrammetry. A prototype application called PhotoDR-2015 is also developed, which simulates views after the demolition and removal of exterior structures with a lower cost and a higher quality. Moreover, PhotoDR-2015 automatically computes the web camera's position and orientation based on the method proposed by Sato et al. (2016). This paper evaluates the accuracy of the proposed method and demonstrates its applicability in a case study performed in a real environment.

2. PHOTOGRAMMETRY-BASED DIMINISHED REALITY

Our proposed system creates DR scenes from video images acquired by a camera for the post-demolition landscape assessment. As explained in Section 1, DR is a technique for removing an unwanted object from a scene by overlaying an appropriate background image on the object. DR requires using computational techniques for tasks, such as estimation of the video camera's position and orientation, computation of the background image, and recognition and tracking the object. Our method estimates the video camera's position and orientation based on the method proposed by Sato et al. (2016). Based on the estimated position and orientation, our method computes the background image of the target area and recognizes and tracks the target. Our method has two main phases; preprocessing and the real-time processing (Figure 1).

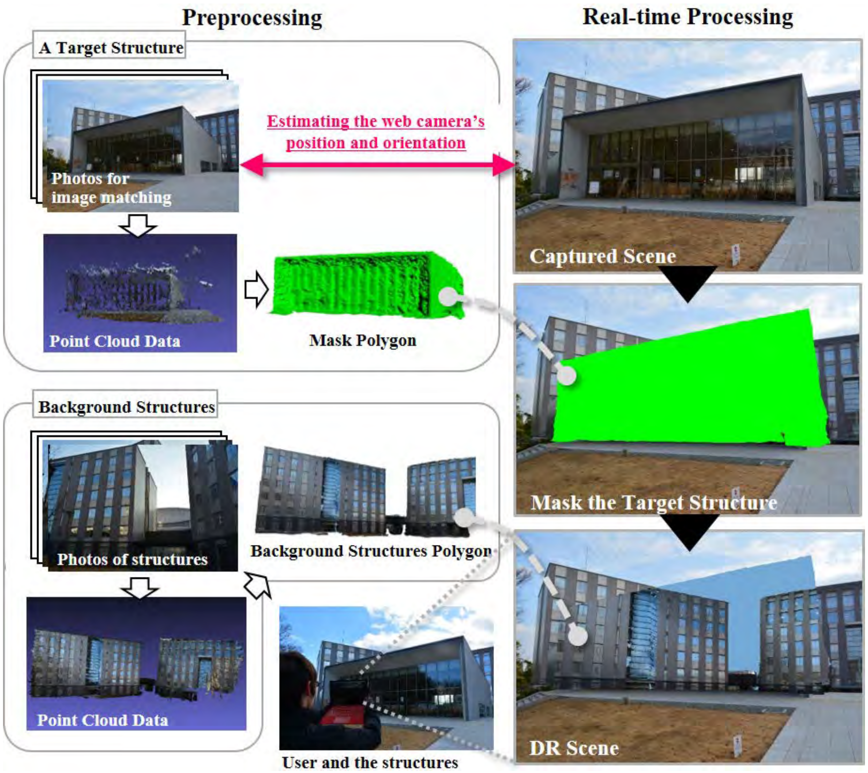


Fig.1: Overview of the proposed method

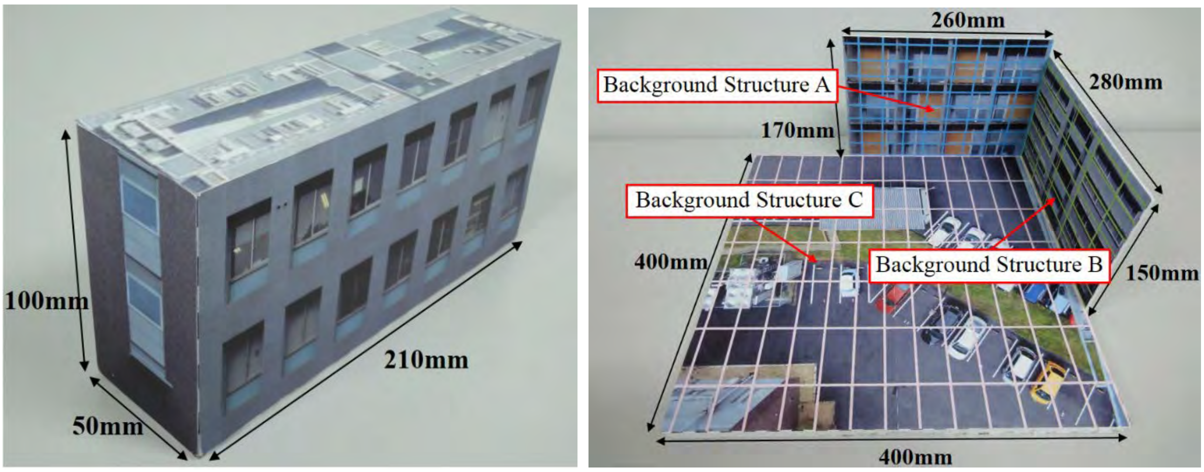
In the preprocessing phase, several photographs of the target structure which is to be diminished and background structures which are hidden behind the target structure are needed as input data. Photographs of the target structure are used for reconstructing point cloud data and estimating the position and orientation of the web camera. Point cloud data of the target structure is reconstructed using SfM method. From its point cloud data, a mask polygon is made, which is used for determining the removal region. The green mesh of the mask polygon (Figure 1) is to distinguish the removal region clearly. Additionally, local features of each photographs of the target structure are extracted to be used for the image matching. Moreover, point cloud data and polygon model of background structures are reconstructed from their photographs by using SfM method.

In the real-time processing phase, local features, mask polygon, and, background structures polygon, which are calculated and created in the preprocessing phase, are used as input data. First, local features of a live video image are extracted. The extracted features are compared with the features of stored images, which are calculated in the preprocessing phase. The automatic image matching method finds the most similar image and the position and orientation of the camera for that image are chosen as the current position and orientation of the web camera. By using the estimated positon and orientation and the web camera, the mask polygon and background structures polygons are rendered. The rendered mask polygon determines the removal area. The area of the rendered background structures polygon is overlaid on top of the live video image. As a result, the target structure on the live video image seems to be diminished.

3. VERIFICATION AND THE CASE STUDY

3.1 Experiment for Verification of System's Accuracy

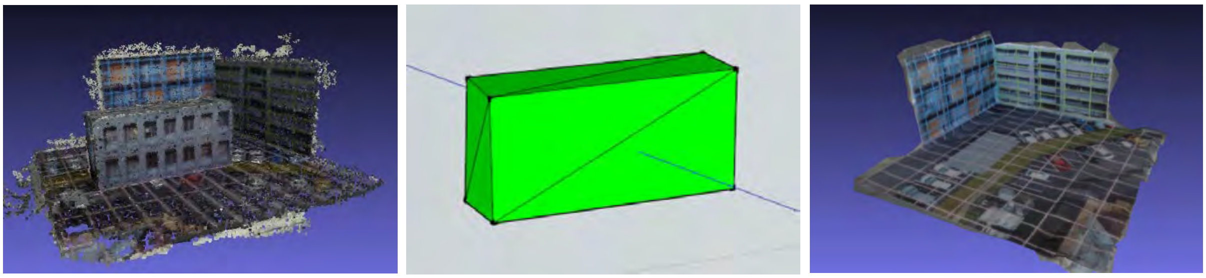
A comparative verification was applied in order to determine the accuracy of the developed system (i.e., PhotoDR-2015). The verification test consists of a physical model made of two sub-models; (1) the target structure (Figure 2 (a)), and (2) background structures (Figure 2(b)). The physical model is modular and each part is removable. Additionally, grid lines are printed on the texture of background structures and on the ground. The accuracy is evaluated using these grid lines. If PhotoDR-2015 accurately diminished the target structure, the DR image should look similar to the ideal image with continuous and matching grid lines.



(a) Model of target structure (b) Model of background structures

Fig.2: Physical model of structures for verifying of the accuracy of PhotoDR-2015

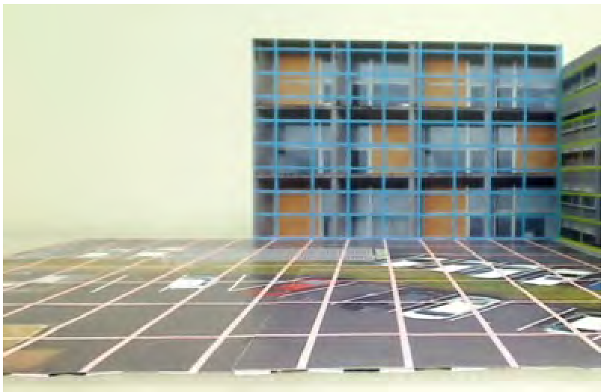
In the preprocessing phase, 42 photos of the model were used to reconstruct point cloud data of the model and for the image matching (Figure 3 (a)). To reconstruct point cloud data, OpenMVG (Open Multiple View Geometry. Ver. 0.7) was used, which is an open source library for SfM. From the point cloud data, the mask polygon was then manually created (Figure 3 (b)). By using SfM, polygons for background structures were made from 40 photos in which only the model of background structures could be seen (by physically removing the model of target structure) (Figure 3 (c)). PhotoScan (by Agisoft LLC ver. 1.2.3) was used, which can reconstruct 3D polygon with photorealistic textures. The orientation, position, and size of both polygons were manually adjusted based on point cloud data of the model.



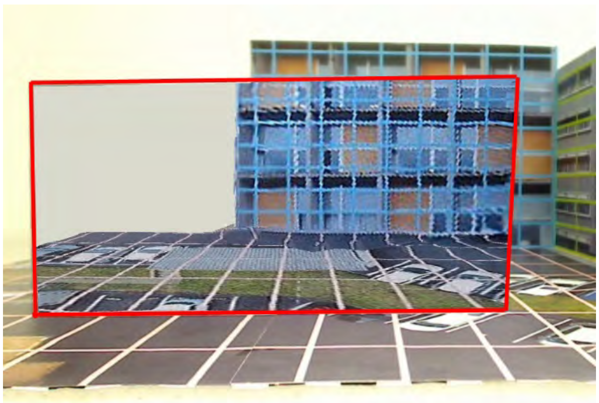
(a) Point cloud data of models (b) mask polygon (c) Background structures polygon

Fig.3: Point cloud data and polygons for the accuracy verification

In the real-time processing phase, the model of the target structure was placed on its position (Figure 4 (a)) and DR operation was carried out with a web camera at three viewpoints. The target structure is then removed from the model and three pictures were taken from the same viewpoints (Figure 4 (b)) for comparison. Figure 4 (c) and (d) show the resulting DR images after placing the target structure back to its position and executing DR.



(a) Captured image (b) Ideal image

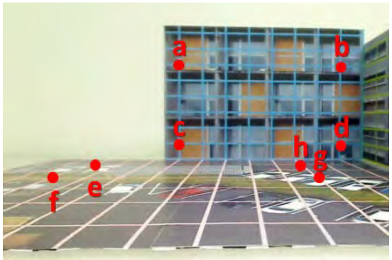
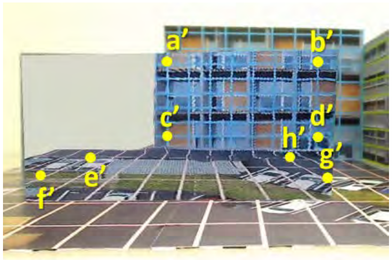
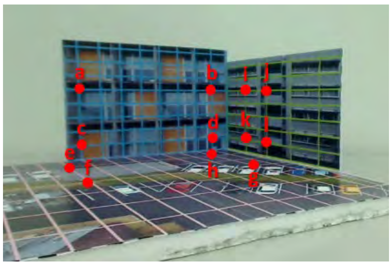
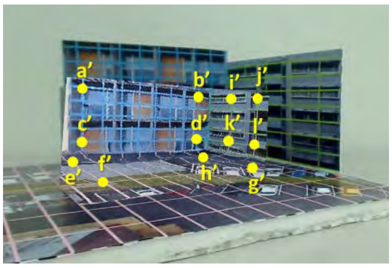
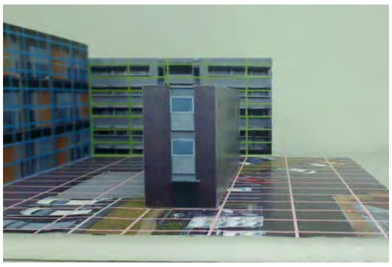
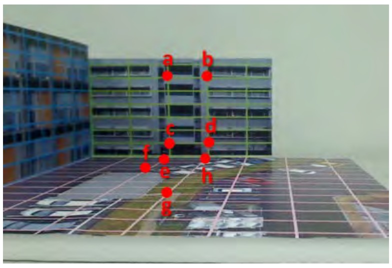
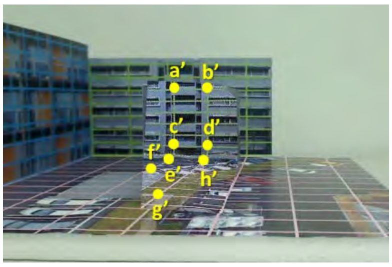


(c) DR image (d) The diminished area on DR image (Inside the red frame)

Fig.4: Results for the verification model (from Viewpoint1)

The accuracy of PhotoDR-2015 was evaluated using a comparative verification method. As shown in Table 1, measuring points on the ideal image and measuring points on a DR image were compared and the horizontal and vertical axis errors were measured.

Table 1: Comparing measuring points from three different viewpoints

	Captured Image	Measuring points on the ideal image	Measuring points on the DR image
Viewpoint 1			
Viewpoint 2			
Viewpoint 3			

Results presented in Table 2 are the average error for all measuring points. They show that the ratios of the average error to the image size were less than 5 %. Background Structure A (Figure 2 (b)), which contains measuring points a, b, c, and d (shown in Table 1), was vertical to the direction of the web camera from viewpoint 1. Therefore, the pixel errors are easily translated to distance errors regarding Background Structure A. Table 3 shows both pixel and distance errors of measuring points a, b, c, d from viewpoint 1. The distance errors of Background Structure A, which is 280 millimeters in height and 170 millimeters in width, is 21.78 millimeters in the horizontal axis, 4.66 millimeters in the vertical axis.

Table 2: The average error for the accuracy verification experiment

	Average Error (pixel)	Error Ratio (%)

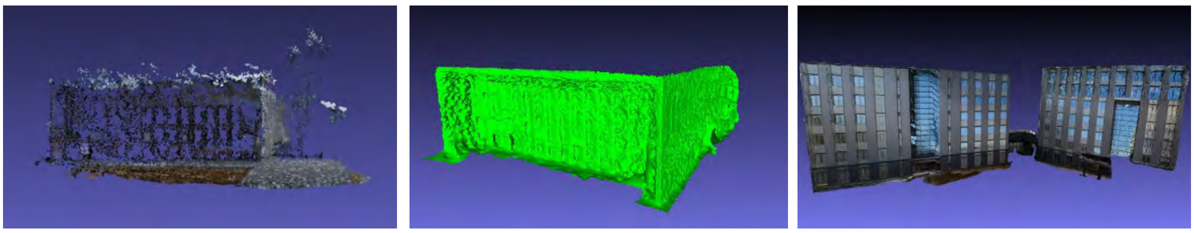
	Horizontal Axis	Vertical Axis	Horizontal Axis	Vertical Axis
Viewpoint 1	30.2	9.25	3.35	1.54
Viewpoint 2	21.5	7.67	2.39	1.28
Viewpoint 3	8.41	11.2	0.93	1.86

Table 3: The pixel and distance error

Pixel Error (pixel)		Distance Error (mm)	
Horizontal Axis	Vertical Axis	Horizontal Axis	Vertical Axis
39.56	8.63	21.78	4.66

3.2 Case Study

To verify the applicability of the proposed method, a verification experiment was conducted in an outdoor environment. Restaurant, 2F, Welfare Bldg., Poplar Street in Osaka University, Suita Campus was selected as a target of the experiment. In the preprocessing phase, 21 photos of the target structure were used to construct point cloud data and for image matching (Figure 5 (a)). The number of photos is less than that of the verification experiment (Subsection 3.1). This is because it was difficult to take photos of the whole target structure due to narrowness of the street. Although the density of the resulting point cloud was not very high, it was possible to create the mask polygon (Figure 5(b)). The polygon of the background structures were made from the point cloud data of 75 photos by using PhotoScan (Figures 5 (c)). The orientation, position and size of both polygons were adjusted based on the point cloud data of the target structure. Table 4 shows the results of PhotoDR-2015 for diminishing the target structure from the scene in the real-time processing phase.



(a) Point cloud of the target structure (b) Mask polygon (c) Background structures polygon

Fig.5: Point cloud data and polygons for case study

Table 4: Results of PhotoDR-2015

	At the start	20 seconds later	40 seconds later
Captured image			
DR image			

Table 4 confirms that PhotoDR-2015 can simulate views after the demolition with high-quality in an outdoor environment. Moreover, it shows that the web camera's positions and orientations were correctly calculated while the web camera was moved during 40 seconds. PhotoDR-2015 was able to maintain the proper position of DR images while changing the viewpoint during this time period.

Additionally, a verification test was designed to verify an AR scenario in which a new structure replaces the target structure. Figure 6 shows the plan plot of the new structure and the camera's position and orientation in preprocessing phase. The red line and arrows (Figure 6 (a)) show the photography route and camera's direction for the target structure. Figure 6 (b) shows the photography route and camera's direction for taking pictures from the background structures. Table 5 shows the result of AR visualization both with PhotoDR-2015 and without PhotoDR-2015. It shows that the 3D virtual model of the AR images of the new structure is overlapped the target structure when DR function was not used (first row of Table 5). Hence, it is hard to assess the landscape of the new structure considering the landscape of the background structures. However, as shown in the second row of Table 5, DR have solved this problem which can and facilitate reaching a consensus on a landscape design more easily. Table 5 also confirms that PhotoDR-2015 can maintain the correct position of DR images while changing the camera's viewpoints.

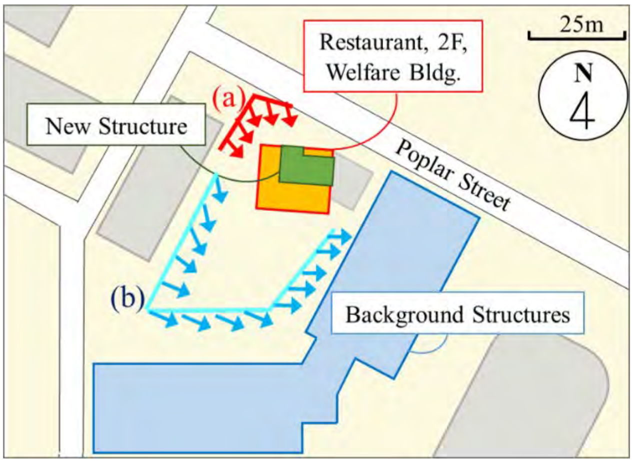


Fig.6: A plan plot of new structure and the camera's position and orientation in preprocessing phase

Table 5: Results of a new structure simulation using PhotoDR-2015

	At the start	20 seconds later	40 seconds later
AR Image without			
AR Image with			

4. CONCLUSIONS AND FUTURE WORK

In this paper, a novel DR method for landscape assessment using photogrammetry and geometric registration methods was proposed. It demonstrated that augmenting the scene with a new structure using the DR function is of higher quality than that of without using the DR function. A prototype application (i.e., PhotoDR-2015) was developed to verify the proposed method. Through the experiments for the verification of the accuracy, the errors of overlaid background image were 21.78 mm in the horizontal axis and 4.66 mm in the vertical axis. In the case study, PhotoDR-2015 proved to be able to simulate views after the demolition with the removal of unwanted target structures. In comparison to the previous study, PhotoDR-2015 can simulate views with a higher quality, it is less costly due to the use of camera instead of a laser scanner, and it doesn't require manual input for inputting the web camera's position and orientation.

It is only possible to use this method on the route in which photos of the target structure are taken, hence, this system has a limitation in simulating from multi-viewpoints. Moreover, this method is sensitive to the light condition. It is not possible to use when there is not enough light or it is raining. Additionally, this system requires having photographs of the background structure in order to create their polygons. If it is not possible to capture photographs that cover the entire building or if the building is occluded by trees, signs or eaves, high-quality polygons cannot be created. The use of UAVs for taking photographs can be considered for certain cases. In the future, it is necessary to adapt image inpainting technique (Bertalmio et.al. 2000; Herling and Broll 2010), which automatically generate semi-realistic textures using information from around the target area, to improve the quality of visualization.

ACKNOWLEDGMENT

This work was supported by JSPS KAKENHI Grant Number JP25350010 and JP26-04368.

REFERENCES

Bertalmio M., Sapiro G., Caselles V., and Ballester C. (2000). Image inpainting, In *Proceedings of the 27th annual conference on Computer graphics and interactive techniques*, 417-424.

Buehler C., Bosse Michael., McMillan L., Gortler S., and Cohen M. (2001). Unstructured lumigraph rendering, In *Proceedings of SIGGRAPH'01*, 425-432.

Cosco F. I., Garre C., Bruno F., Muzzupappa M., and Otabuy M.A. (2009). Augmented touch without visual obtrusion, In *Proceedings of ISMAR2009*, 99-102.

Debevec P. E., Taylor C. J., and Malik J. (1996). Modeling and rendering architecture from photographs: A hybrid geometry- and image-based approach, In *Proceedings of SIGGRAPH'96*, 11-20.

Enomoto A. and Saito H. (2007). Diminished reality using multiple handheld camera, In *Proceedings of ACCV 2007,* 130-150.

Fukuda T., Zhang T., and Yabuki N. (2014). Improvement of registration accuracy of a handheld augmented reality system for urban landscape simulation, *Frontiers of Architectural Research*, Vol. 03, No. 04, 386-397.

Hartley R. and Zisserman A. (2000). Multiple view geometry in computer vision, Cambridge University Press.

Herling J., and Broll W. (2010). Advanced self-contained object removal for realizing real-time diminished reality in unconstrained environments, In *Proceedings of ISMAR 2010*, 207-212.

Klinker G., Stricker D., and Reiners D. (2001). Augmented reality for exterior construction applications, *Augmented Reality and Wearable Computers*, 379-382.

Sato Y., Fukuda T., Yabuki N., Michikawa T., and Motamedi A. (2016). A marker-less augmented reality system using feature-based image registration and structure from motion technologies for building and urban environment, In *Proceedings of the 21st International Conference on Computer-Aided Architectural Design Research in Asia (CAADRIA 2016)*, 713-722.

Tanemura T., Yabuki N., and Fukuda T. (2014). Diminished reality for ar simulation of demolition and removal of urban objects, *Journal of Japan Society of Civil Engineers*, Ser. F3 (Civil Engineering Informatics). Vol. 70, No. 2, I_16-I_25.

Yabuki N., Hamada Y., and Fukuda T. (2012). Development of an accurate registration technique for outdoor augmented reality using point cloud data, In *Proceedings International Conference on Computing in Civil and Building Engineering.*

AUTOMATIC REGISTRATION OF LASER SCANNED COLOR POINT CLOUDS BASED ON COMMON FEATURE EXTRACTION

Pil Eun Kim & Dr. Yong K. Cho

School of Civil and Environmental Engineering, Georgia Institute of Technology, 790 Atlantic Dr. NW., Atlanta, GA 30332-0355, United States

Jingdao Chen

School of Electrical and Computer Engineering, Robotics Institute, Georgia Institute of Technology, 777 Atlantic Dr. NW., Atlanta, GA 30332-0355, United States

ABSTRACT: *Point cloud data acquisition with laser scanners provides an effective way for 3D as-built modeling of a construction site. Due to the limited view of a scan, multiple scans are required to cover the whole scene, and a registration process is needed to merge them together. The aim of this paper is to introduce a novel method that automatically registers colored 3D point cloud sets without using targets or any other manual alignment processes. For fully automated point cloud registration without artificial targets or landmarks, this study uses 1) the Speeded-Up Robust Features (SURF) algorithm to identify geometric features among the series of scans and 2) plane-to-plane matching algorithm to achieve precise registration. For an initial alignment during the registration process, common feature extraction is utilized to perform a 3D rigid-body transformation followed by aligning the view into the reference system. Further alignment is obtained using plane segmentation and matching from the 3D point clouds. The test outcomes show that the method is able to achieve registration accuracy of less than 1^{o} in deviation angle.*

KEYWORDS: *3D LIDAR; Point cloud; Registration; Feature Extraction; RGB image; Plane Segmentation.*

1. INTRODUCTION

A virtual 3D model of a construction site through point cloud construction and registration can foster the understanding of the scene of interest, monitoring construction progress, and recognizing potential safety hazards. The construction site should be scanned from various points of view to get a full reconstruction of the site. This is because some point clouds could be disturbed by obstacles and each scanned point cloud is described by its own local coordinate system. Therefore, the point cloud registration process is necessary to merge several collected point cloud data from many scan positions. Point cloud registration is the process of transforming of each point cloud set from its local coordinate frame to a global coordinate frame.

However, the current methodologies present some limitations. For instance, a manual alignment method, which is known as the simplest method, requires at least three common points between two overlapped point clouds in order to set a 3D rigid-body transformation matrix; due to the simplicity, many pieces of commercial software such as CloudCompare, employ this manual alignment method. It is straightforward, but it is time consuming because it requires to find matching points between point clouds manually. In addition, this manual process can be inaccurate especially when handling huge and complicated data sets, where it is difficult to identify point correspondences with the naked eye. There exists other commercial software for point cloud registration such as Faro Scene and Recap 360 Ultimate. Although these software tools provide functions for automatic point registration, they need a large amount of overlapping area and not robust yet for many cases. Becerik-Gerber et al. (2011) proposed 3D target-based point cloud registration. They experimented with three different types of targets such as fixed paper, paddle, and sphere, and with phased-based, time of flight laser scanners. According to their experiments, the sphere target with time of flight scanner provided the best results with respect to accuracy. However, the target-based point cloud registration requires an extra time for setting up and adjusting the targets at every scan. Also, the use of targets necessitates extra costs and is not desired on a busy construction site.

2. LITERATURE REVIEW

Over the last decade, laser scanning systems have been identified as an effective tool for measuring equipment in various application fields, especially in 3D reconstruction and mapping of the environment for construction fields, due to the fast and non-intrusive scanning process. However, a technique is needed to register and visualize the resulting 3D scans in a common coordinate system. The registration in high accuracy should be done to minimize the errors between the merged point cloud sets to acquire the best 3D reconstruction in visualization.

The most well-known method for point cloud registration is the iterative closest point (ICP) algorithm proposed by Besl et al. (1992) and Chen et al. (1992). ICP is an algorithm that finds common matching points of two point clouds that minimize the difference between them. In the ICP algorithm, one point cloud is used as a reference and the other point cloud is merged to the reference based on the criterion of minimum distance. The algorithm iteratively corrects the transformation parameters required to minimize the distance from the source to the reference point cloud. As an advanced method, the iterative closest compatible point (ICCP) algorithm was proposed by Akca (2003) to diminish the search area of the ICP algorithm. In the ICCP algorithm, the distance minimization is achieved between the pairs of points considered compatible on their viewpoint invariant properties. Men et al. (2011) developed a registration procedure using integrated Hue values to carry out a 4D ICP algorithm. The ICP algorithm with the Hue values can attain advanced accuracy and convergence. However, ICP-based registration methods still arouse issues with computing time because of the heavy calculation load related to the ICP algorithm. Also, the performance is not stable due to its dependence of overlapping area and the initial starting points (Wang et al. 2014).

Common feature-based registration could be achieved without initial alignment because 2D images are employed to aid the recognition of feature points. This method uses 2D intensity images with Scale-invariant feature transform (SIFT) algorithm (Eo et al. 2012). However, it is sensitive to the overlapping size of point cloud data. In addition, a large number of scans are needed to get a good performance result, and the feature extraction is heavily influenced by the environment on behalf of brightness changes. Also, a heavy amount of computation is another disadvantage for common feature-based registration (Gai et al. 2013). To reduce the time during the computation process, Cho et al. (2014) used data fusion to track a certain target of interest. Although their method can rapidly perform the scanning and modeling of the scene, it was limited to track the dynamic target of interest, and thus, its application is suitable for tracking a dynamic object such as equipment and materials.

Geo-referencing based registration is using sensors such as GPS and RFID. Olsen et al. (2011) presented a registration method using GPS information. This method could be used in the outdoor domain, but suffers from a lack of accuracy. Valero et al. (2012) used RFIDs for indoor point cloud registration. This method is only suitable for indoor spaces, and the laser scanner is required to be mounted in close proximity to objects in order to recognize the RFID tags. Thus, geo-referencing based registration is not suitable for large-scale sites due to sensor performance dependence (Mastin et al. 2009).

For the registration of 3D point clouds and 2D image, fusing edge extracted in 2D images and 3D point cloud data using range images is proposed by a simple pixel corresponding mechanism (Wang et al. 2013). Their approach implies edge extraction from 2D images, but there are some flaws in border feature detection. Moreover, Moussa et al. (2012) proposed a procedure for automatic combination and co-registration of digital images and terrestrial laser data. The method used images associated with intensity and RGB values. For the common feature extraction, Bay et al. (2006) proposed Speeded Up Robust Features (SURF) algorithm, which is a local feature detector and descriptor. It can be used for object recognition, image registration, classification or 3D reconstruction. It is developed from the scale-invariant feature transform (SIFT) descriptor, and several times faster than SIFT. For automatic point cloud registration, Kim et al. (2016) presented a framework using feature extraction of RGB panorama images. The experiment result was good but it was performed only in an indoor location.

3. OBJECTIVE

The main objective of this study was to develop a target-free automatic point cloud registration method, based on common features extraction between multiple images. In this paper, the SURF feature extraction algorithm was used, which matches 3D point cloud data automatically by using 2D common features to increase registration speed and accuracy. Following sections will discuss the proposed framework, experimental results, and finally conclusion and future work.

4. METHODOLOGY

To achieve the requirements defined by the objective, a framework for automatic registration method was designed and it consists of four steps as shown in Figure 1. The first step is data acquisition using 2D line scanner and digital camera. The second step is RGB texture mapping, which is merging 3D point clouds with 2D RGB images by kinematics calculation. The third step is transformation based on common features detected and extracted from RGB images which correspond to a 3D point cloud data set for an initial alignment. Lastly, a final adjustment is performed by plane segmentation and fitting and matching point cloud data sets.

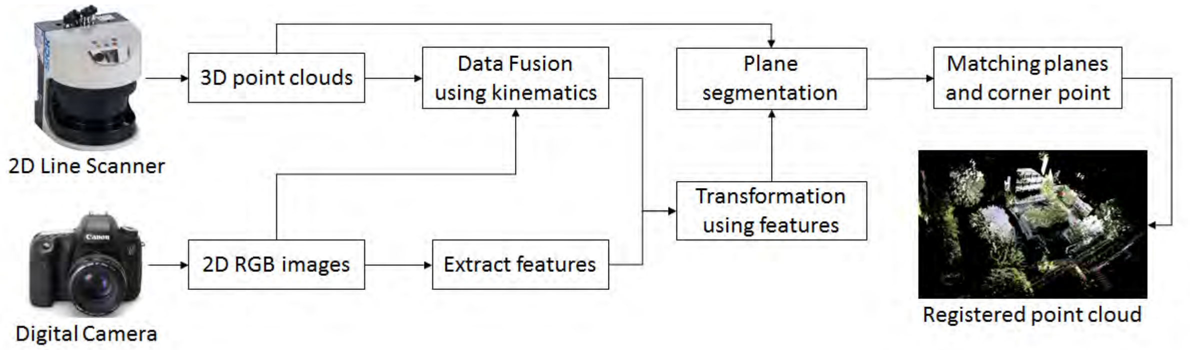


Fig. 1: Framework of the automatic point cloud registration

4.1 Data acquisition

To obtain point clouds and RGB images, a robotic hybrid Light Detection And Ranging (LiDAR) system was used, consisting of four SICK LMS511 2D line laser scanners, and a regular digital camera, as shown in Figure 2. Multiple degree-of-freedom (DOF) kinematics problems were solved based on the built-in mechanical information between laser scanners and a digital camera. The schematic diagram of the kinematics solution of the equipment used in this paper is shown in Figure 2.

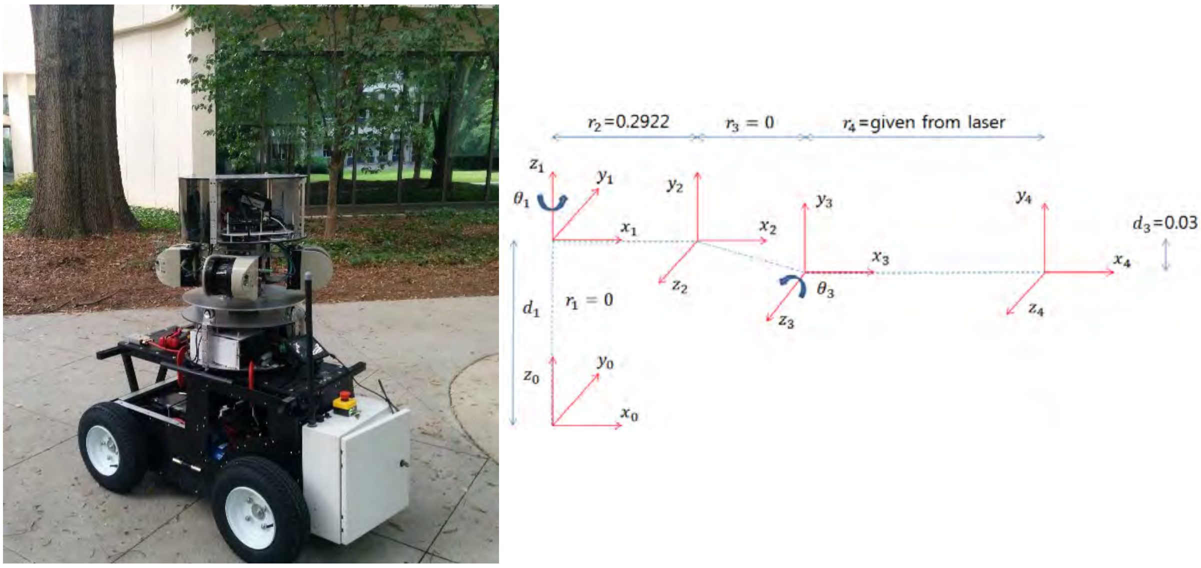


Fig. 2: Robotic hybrid 3D LiDAR System and its kinematics solution

The local Coordinate (x_0, y_0, z_0) means the mobile robot body coordinate located on the ground level, and the coordinate (x_1, y_1, z_1) is the laser scanner coordinate system located at the center of body frame. The local coordinates 2 and 3 are fixed at each laser scanner center. Finally, the local coordinate 4 indicates a measured point (x_4, y_4, z_4) on an object surface. In addition, θ_1 is a body rotate angle and θ_3 is an angle from laser scanner. From the relationship among these information, the kinematics problem is solved as shown in Equation (1).

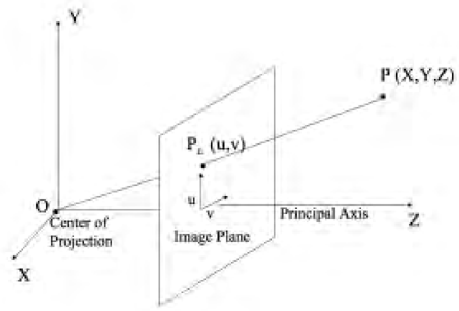
$$\begin{bmatrix} X \\ Y \\ Z \\ 1 \end{bmatrix} = \begin{bmatrix} \cos(\theta_1)\cos(\theta_3) & -\cos(\theta_1)\sin(\theta_3) & \sin(\theta_1) & r_2\cos(\theta_1) + d_3\sin(\theta_1) \\ \sin(\theta_1)\cos(\theta_3) & -\sin(\theta_1)\sin(\theta_3) & -\cos(\theta_1) & r_2\sin(\theta_1) - d_3\cos(\theta_1) \\ \sin(\theta_3) & \cos(\theta_3) & 0 & d_1 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} r_4 \\ 0 \\ 0 \\ 1 \end{bmatrix}$$

$$= \begin{bmatrix} r_2\cos(\theta_1) + d_3\sin(\theta_1) + r_4\cos(\theta_1)\cos(\theta_3) \\ r_2\sin(\theta_1) - d_3\cos(\theta_1) + r_4\sin(\theta_1)\cos(\theta_3) \\ d_1 + r_4\sin(\theta_3) \\ 1 \end{bmatrix} \quad (1)$$

In Equation (1), $d_1, d_3, and\ r_2$ are fixed distance between a laser scanner and digital camera because of the mounted location on the robot, whereas r_4 is the sensed distance data from each laser scanner. The kinematics solution will be applied to the extrinsic parameters of digital camera while the intrinsic parameters including focal length, image sensor format, and principal point are estimated by the pinhole camera model as shown in Figure 3.

4.2 RGB texture mapping

A digital camera takes pictures for RGB data from the surroundings of scan area, which can be mapped on the 3D point cloud data. To get this fusion data, the pinhole camera model concept should be used. Using these intrinsic and extrinsic parameters, the laser scanned 3D point cloud can be transformed to 3D camera coordinates according to Equation (2) and (3). Thus, the coordinate systems of 3D point cloud data and RGB image data are aligned



$$\begin{bmatrix} x \\ y \\ z \end{bmatrix} = K_{int}K_{ext} = \begin{bmatrix} f_x & 0 & c_x \\ 0 & f_y & c_y \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} R_{11}R_{12}R_{13}T_x \\ R_{21}R_{22}R_{23}T_y \\ R_{31}R_{23}R_{33}T_z \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \\ 1 \end{bmatrix} \quad (2)$$

$$\begin{bmatrix} u \\ v \end{bmatrix} = \begin{bmatrix} \frac{x}{z} \\ \frac{y}{z} \end{bmatrix} \quad (3)$$

using the concept of perspective projection. This
enables a correct texture mapping between a point cloud and digital camera images.

Fig. 3: Pinhole camera model

4.3 RGB feature extraction and transformation

In this study, SURF feature points are used to obtain the initial transformation between point clouds. Once the feature points of each image are extracted, corresponding points in the 3D point cloud can be tracked by matching feature points in the image plane to the RGB-fused point cloud data set. The Kabsch algorithm (root mean square distance concept) is used to estimate the transformation matrix between point clouds.

To match each point cloud set, the initial rigid transformation matrix is defined. In this case, the transformation is a perspective projection for six degrees of freedom, composed of a rotation matrix and a translation vector in 3 dimensions. This transformation can be written as 3x4 matrix. Then, a point P can be projected, where $P = [x\ y\ z\ 1]^T$, simply by applying this transformation matrix to the point:

$$P' = TP = \begin{bmatrix} U_{11} U_{12} U_{13} D_x \\ U_{21} U_{22} U_{23} D_y \\ U_{31} U_{23} U_{33} D_z \end{bmatrix} \begin{bmatrix} x \\ y \\ z \\ 1 \end{bmatrix} = \begin{bmatrix} x' \\ y' \\ z' \end{bmatrix} \tag{4}$$

4.4 Plane matching

The two point clouds can be further registered using the method of plane-to-plane matching. This method relies on finding three plane correspondences between the point cloud to be registered and the reference point cloud. The selected planes have to be linearly independent and intersect at a unique point in order to fully recover the transformation parameters. For example, one of the planes can be the ground plane whereas the second plane is a vertical wall in the x-axis whereas the third plane is a vertical wall in the y-axis.

First, the Random Sample Consensus (RANSAC) algorithm is used to perform plane segmentation for each point cloud. Second, the rotation component R of the transformation matrix is calculated using the plane normal vectors found in the previous step. Third, the translation component T of the transformation matrix is calculated by comparing corner points between the two point clouds. This process is illustrated in Figure 4 where the rotation R is derived from aligning the blue planes while the translation T is derived from matching the red corner points.

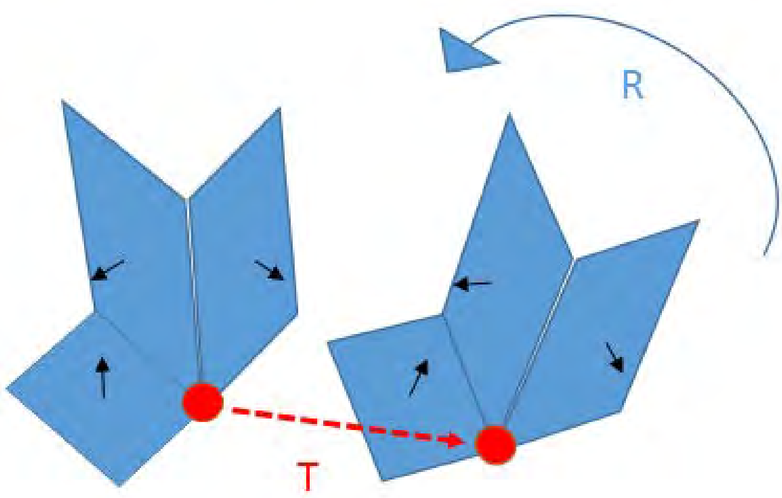


Fig. 4: Plane and corner point matching

5. EXPERIMENT

The data acquisition process for validating the proposed framework was performed near the Mason building in Georgia Tech campus. To register two point cloud sets, it was needed to find the point of the extracted features. Figure 5 shows two RGB images of interesting building captured at different position. At each position, a point cloud also was collected. Figure 6 shows RGB colored point cloud of the scene that is shown in Figure 2 with the proposed texture mapping algorithm. It is possible to find (x, y, z) information of point cloud data from 2D feature information because they are already connected.

Fig. 5: RGB feature extraction

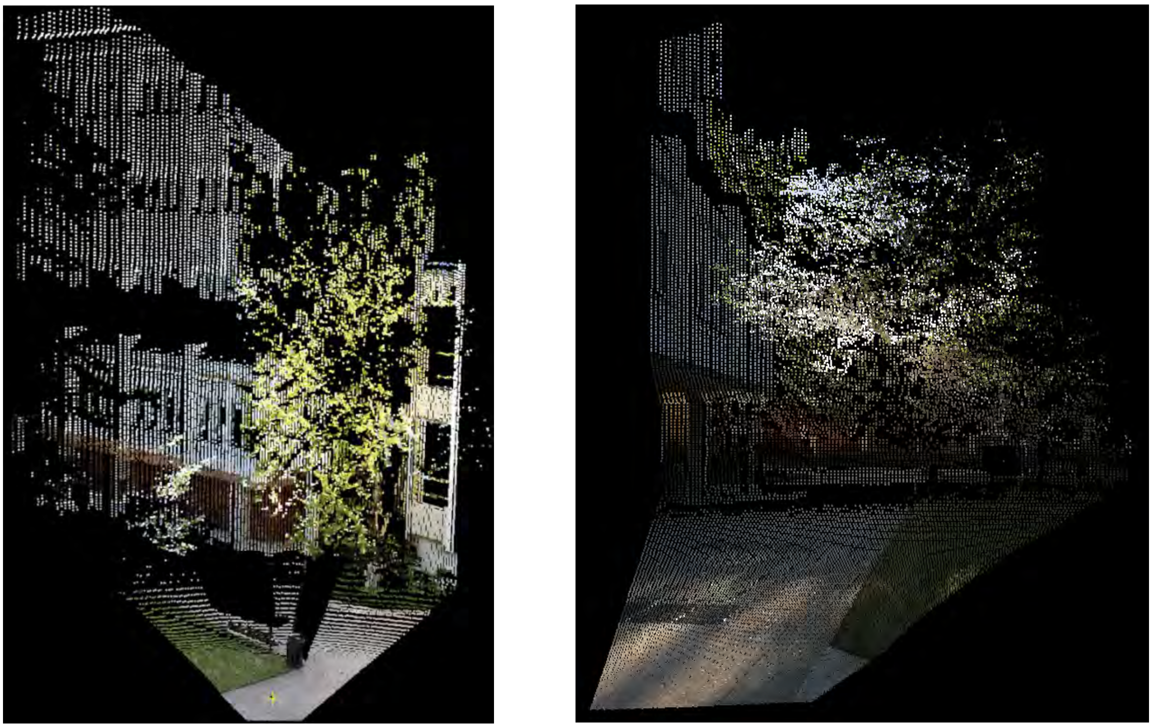


Fig. 6: RGB texture mapped point cloud

Figure 7 shows another test result for RGB feature extraction, and Figure 7 shows RGB colored point cloud of the scene that is shown in Figure 7.

Fig. 7: RGB feature extraction

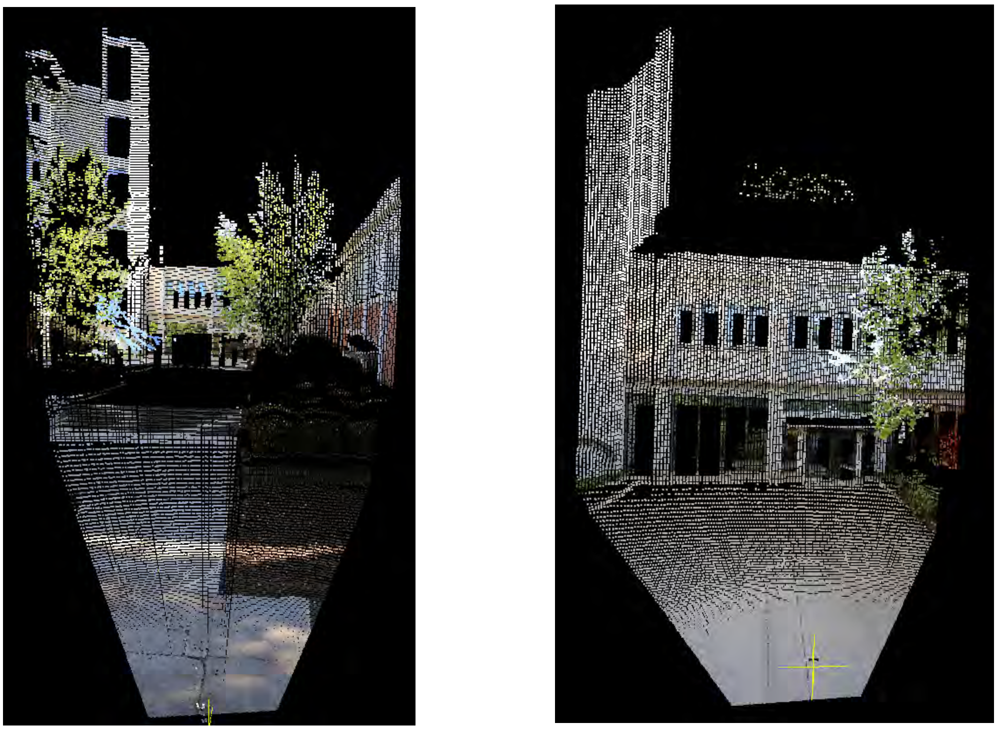


Fig. 8: RGB texture mapped point cloud

Fig. 9: Registered point cloud

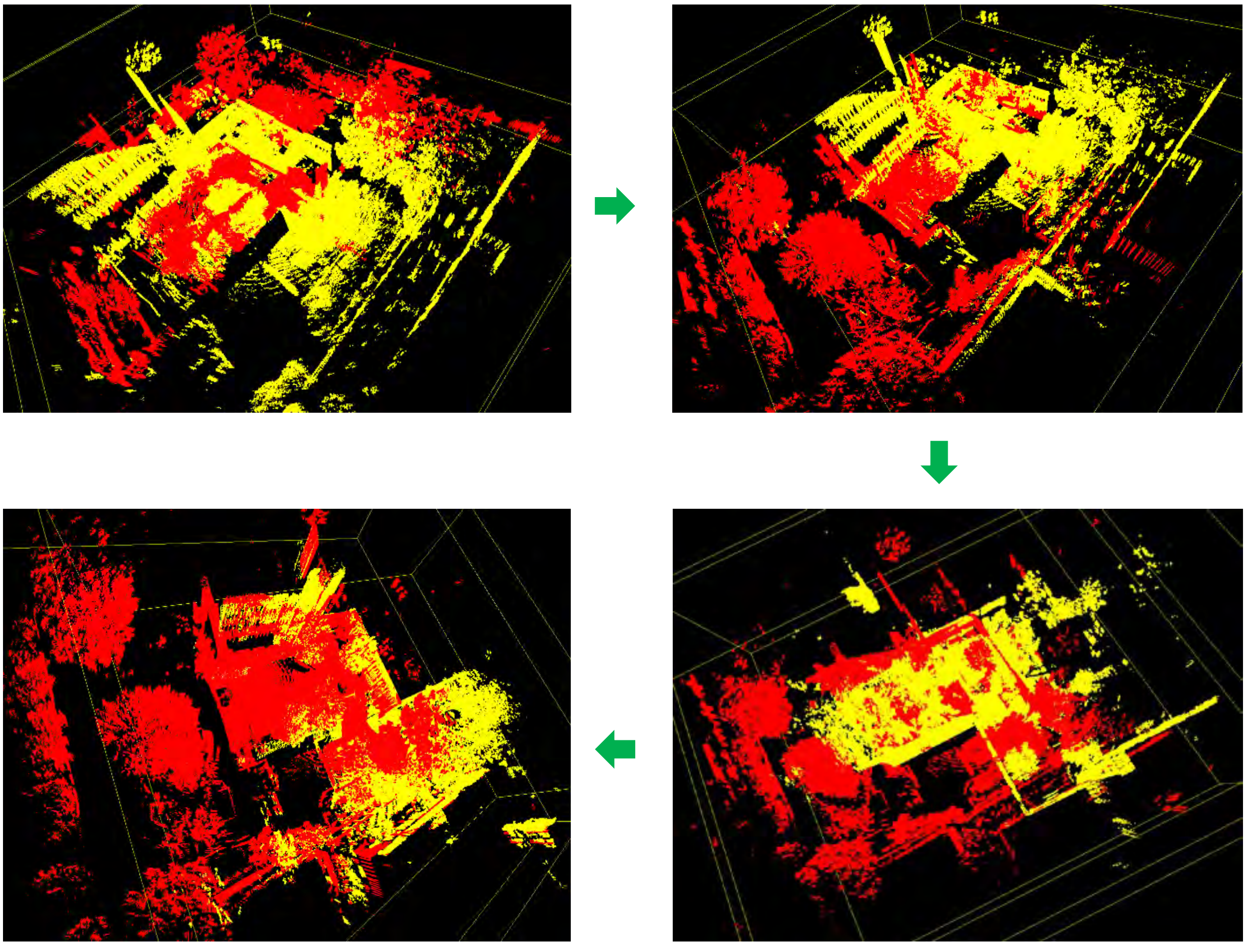


Fig. 10: Sequence for point cloud registration for three different scan position

Figure 9 shows the final registered point clouds with three different scan positions marked with red circles. Figure 10 reveals the difference between point clouds during the registration process. The red points in Figure 10 are from the aligned point cloud and the yellow points are from the reference point cloud. To verify the result for this experiment, the second scan position was assumed as a ground truth for the first registration process and measured the deviation angle from each reference axis at each step of the proposed framework. Then, the third scan position was assumed as a ground truth for second registration process. It can be verified from the reduced deviation angles in Table1.

From the experimental results (Table 1), it can be observed that the initial transformation using RGB feature points is effective in obtaining a coarse estimate for registration. The measured deviation angle after the initial transformation is between 1^{o} and 13^{o}. On the other hand, the final transformation obtained using plane and corner point matching is necessary for a more precise estimate of the transformation parameters. For both registration sequences, the final transformation is able to reduce the deviation angle to less than 1^{o}.

Table 1: Deviation angle in degrees

	First registration sequence			Second registration sequence		
	Original point clouds	After initial transformation	After final transformation	Original point clouds	After initial transformation	After final transformation
X axis	-19.326	-5.823	0.872	9.201	2.238	-0.621
Y axis	-5.962	-1.402	0.259	-14.692	-4.217	0.365
Z axis	174.652	10.276	-0.923	191.421	12.726	0.427

6. CONCLUSIONS

A unique method for automatic point cloud registration without using marked targets was demonstrated and validated for an outdoor environment. A laser scanning system with a digital camera was used to obtain point clouds with mapped RGB texture data. The proposed framework consists of four steps. The first step involves data acquisition. The next step fuses the point clouds from laser scanner and RGB information from digital images. The following involves attaining an initial transformation by common features extracted from digital images and finding their corresponding 3D positions in point clouds. Lastly, plane matching is performed for accurate registration using a plane segmentation algorithm. Although the presented framework must have three plane with one corner point on overlapped area, it accomplished automatic point cloud registration without any target references and manual adjustments. For future work, the research team will apply this approach to commercial laser scanner products. The advantage of this framework can be extended to any types of laser scanners which have a built-in digital camera as long as the kinematic relationship between collected 3D point cloud data and captured RGB images are known.

7. ACKNOWLEDGEMENT

This material is based upon work supported by the National Science Foundation (Award #: CMMI- 1358176). Any opinions, findings, and conclusions or recommendations expressed on this material are those of the authors and do not necessarily reflect the views of the NSF.

8. REFERENCES

Akca, D. (2003) Full automatic registration of laser scanner point clouds. Optical 3-D Measurements VI, pp. 330–337.

Bay, H., Ess, A., Tuytelaars, T., Gool, L. (2006) Speeded Up Robust Features, ETH Zurich, Katholieke

Universiteit Leuven

Besl, P.J. and McKay, N.D. (1992) A method for registration of 3-d shapes, IEEE Trans. Pattern Anal. Mach. Intell. 14 (2): pp. 239–256.

Chen, Y., Medioni, G. (1992) Object modelling by registration of multiple range images. Image Vision Comput., 10(3), pp. 145–155.

Cho, Y., Wang, C., Gai, M., and Park, J. (2014) Rapid Dynamic Target Surface Modeling for Crane Operation Using Hybrid LADAR System. Construction Research Congress 2014, pp. 1053-1062.

Eo, Y. D., Pyeon, M. W., Kim, S. W., Kim, J. R., and Han, D. Y. (2012) Co-registration of Terrestrial Lidar Points by Adaptive Scale-Invariant Feature Transformation with Constrained Geometry. Automation in Construction, 25, pp. 49-58.

Gai, M., Cho, Y., and Qinghua, X. (2013) Target-free automatic point clouds registration using 2D images. Proceedings of the 2013 ASCE International Workshop on Computing in Civil Engineering, University of Southern California, LA, USA, pp. 865-872,

Hu, F., Ren, T., and Shi, S. (2014) Discrete Point Cloud Registration using the 3D Normal Distribution Transformation based Newton Iteration. Journal of Multimedia, Vol 9, NO 7, pp. 934-940.

Huhle, B., Magnusson, M., Straber, W., and Lilienthal, A. (2008) Registration of Colored 3D Point Clouds with a Kernel-based Extension to the Normal Distributions Transform. IEEE International Conference on Robotics and Automation, Pasadena, CA, USA, pp. 4025-4030

Kim, P., Cho, Y., and Chen, J. (2016) Target-free Automatic Registration of Point Clouds, International Symposium on Automation and Robotics in Construction, Auburn, AL, USA,

Mastin, A., Kepner, J. and Fisher, J. (2009) Automatic Registration of Lidar and Optical Images of Urban Scenes. IEEE Conference on Computer Vision and Pattern Recognition, pp. 2639–2646.

Men, H.,Gebre, B., and Pochiraju, K. (2011) Color Point Cloud Registration with 4D ICP Algorithm. International Conference Robotics and Automation, IEEE, Shanghai, China, pp. 1511-1516.

Moussa, W., Abdel-Wanhab, M., and Fritsch, D. (2012) An Automatic Procedure for Combining Digital Images and Laser Scanner Data. International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Vol. XXXIX-B5, pp. 229-234.

Liu, Y. (2006) Automatic Registration of overlapping 3D point clouds using closet points, Image and Vision Computing 24, pp. 762-781.

Olsen, M. J., Johnstone, E., Kuester, F., Driscoll, N., and Ashford, S. A. (2011) New Automated Point-Cloud Alignment for Ground-Based Light Detection and Ranging Data of Long Coastal Sections. Journal of Surveying Engineering, ASCE, 137(1), pp. 14-25.

Pandey, G., McBride, J. R., Savarese, S., and Eustice, R. M. (2012) Toward Mutual Information Based Automatic Registration of 3D Point Clouds. In Proceedings of IEEE/RSJ International Conference on Intelligent Robots and Systems, Algarve, Portugal, pp. 2698–2704.

Tournas, E., and Tsakiri, M., (2009). Automatic 3D point cloud registration for cultural heritage documentation. Bretar F, Pierrot-Deseilligny M, Vosselman G (Eds) Laser scanning IAPRS, Paris, France, Vol. XXXVIII, Part 3/W8

Valero, E., Adan, A., and Cerrada, C. (2012) Automatic Construction of 3D Basic-Semantic Models of Inhabited Interiors Using Laser Scanners and RFID Sensors. Sensors, 12(5), pp. 5705-5724.

Wang, C., Cho, Y., and Park, J. (2014) Performance Tests for Automatic Geometric Data Registration Technique for Construction Progress Monitoring. International Conference Computing in Civil and Building Engineering (ICCCBE), ASCE, Orlando, FL, pp. 1053-106.

Wang, Y., Ewert, D., Schilberg, D., and Jeschke, S. (2013) Edge extraction by merging 3D point cloud and 2D image data. IEEE International Conference of the Center of Excellence in Wireless and Information Technology.

Xiong, X., Szedmak. S., and Piater, J. (2013) A study of point cloud registration with probability product kernel functions. In Proc. 2013 Int. Conf. 3D Vision, IEEE, Seattle, USA, pp. 207–214

香港科技大學
THE HONG KONG UNIVERSITY OF
SCIENCE AND TECHNOLOGY

ISBN No. : 978-988-14032-6-1

ACKNOWLEDGEMENT

CONSTRUCTION INDUSTRY COUNCIL
建造業議會

SPONSORS

新世界發展有限公司
New World Development Company Limited

AECOM

協興 HIP HING

Global VDC

Syn