CONVR 2019

Enabling digital technologies to sustain construction growth and efficiency

19th International Conference on

Construction Applications of Virtual Reality

13-15 November 2019, Bangkok, Thailand

Organising Committee: Prof. Nashwan Dawood, Chair

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Keynote session

Speakers	Organisation	Title
 Prof. Nashwan Dawood	Teesside University, UK	CONVR past and present, the role of digital technology to Transform Construction, UK perspective.
 Prof. Raymond Issa	University of Florida, USA	Modular Off-Site Construction and BIM in the US: Case Studies
 Dr.-Ing. Racha Chahrour	BIM Project Manager HOCHTIEF ViCon, Germany	BIM implementation strategies in Germany
 Prof. Nobuyoshi Yabuki	Osaka University, Japan	Digital Construction in Japan: Current and Future Trends
 Dr. Jack Cheng	Hong Kong University of Science and Technology	BIM Adoption and Researches in Hong Kong: Opportunities, Challenges and Lessons Learnt.
 Dr. Farzad Rahimian	Teesside University, UK	Open BIM-VR Paradigm: How BIM-VR Integration will influence AEC Industries
 Assoc.Prof. Tanit Tongthong	Chulalongkorn University, Bangkok Thailand	Advanced Technologies for Supporting Infrastructure Structure Project Management In Bangkok, Thailand

Keynote session

 Mr. Patai Padungtin	CEO - BUILK ONE GROUP, Thailand	Digital Marketing towards Construction Industry Improvement
 Prof.Amorn Pimanmas	President Thailand Building Information Modeling: TBIM Association	Current Stage of BIM Development in Thailand Construction Industry
 Dr. Satakhun Kosavinta	King Mongkut's Institute of Technology Ladkrabang	BIM Initiative in Thai Construction Industry
 Mr. Songpol Yomnak	BIM committee, Architect Council of Thailand	BIM Initiative in Thai Construction Industry

Outline Programme

Venue: Chulalongkorn University, Conference building, 7FL Chamchuri 10 Bangkok, Thailand				
Day 1 13 Nov	Registration and Opening 06:00 PM Thai cultural Performance with cocktail and food			
Day 2 14 Nov	09:00 – 09:30	09:30 – 10:00	10:00 – 10:30	
	Keynote: Prof. Nashwan Dawood **Title**: CONVR past and present, the role of digital technology to Transform Construction, UK perspective.	**Keynote:** Prof. Raymond Issa **Title**: Modular Off-Site Construction and BIM in the US: Case Studies	**Keynote**: Professor Nobuyoshi Yabuki **Title:** Digital Construction in Japan: Current and Future Trends	
	Coffee Break (10:30 – 10:45)			
	Industrial Seminar sessions			
	10:45 – 11:30	11:30 – 12:15	12:15-12:45	
	Speaker: Prof. Amorn Pimanmas, President Thailand Building Information Modelling (TBIM) Association **Title**: Current Stage of BIM Development in Thailand Construction Industry	**Speaker**: Dr.Satakhun Kosavinta and Mr.Songpol Yomnak **Title**: BIM Initiative in Thai Construction Industry	**Speaker**: Prof. Nashwan Dawood **Title**: UK implementation road map of BIM	
	Lunch Break (12:45 – 14:00)			
	Industrial Seminar sessions			
	14:00 – 14:30	14:30 – 15:00	15:00 – 15:30	15:30 – 17:00
	Speaker: Dr. Jack Cheng **Title**: BIM Adoption and Researches in Hong Kong: Opportunities, Challenges and Lessons Learnt.	**Speaker:** Assoc. Prof. Dr. Tanit Tongthong **Title**: Advanced Technologies for Supporting Infrastructure Structure Project Management In Bangkok, Thailand	**Speaker**: Dr. Racha Chahrour **Title**: BIM implementation strategies in Germany	**Discussion** about construction and development of digital construction road map in Thailand
	Conference Dinner: River banquet https://www.supatrariverhouse.net/			
Day 3 15 Nov	09:00 – 09:30		09:30 – 10:00	
	Keynote: Dr Farzad Rahimian **Title**: Open BIM-VR Paradigm: How BIM-VR Integration will influence AEC Industries		**Keynote**: Mr. Patai Padungtin, CEO - BUILK ONE GROUP **Title**: Digital Marketing towards Construction Industry Improvement	
	Coffee Break (10:00 – 10:15)			
	10:15 – 11:45		10:15 – 11:45	
	Parallel session 1A: BIM & GIS Venue: Room 1		**Parallel session 1B**: Collaboration & Design Support Systems Venue: Room 2	
	11:45 – 13:15		11:45 – 13:15	
	Parallel session 2A: Sensing & AI Venue: Room 1		**Parallel session 2B**: AR & VR, Serious Games & Wearables Venue: Room 2	
	Lunch Break (13:15 – 14:30)			
	14:30 – 16:00		14:30 – 16:00	
	Parallel session 3A: BIM & GIS Venue: Room 1		**Parallel session 3B**: AR & VR, Serious Games & Wearables Venue: Room 2	
	16:00 – 17:30		16:00 – 17:30	
	Parallel session 4A: AR & VR, Serious Games & Wearables Venue: Room 1		**Parallel session 4B**: Knowledge & Theory Frameworks Venue: Room 2	
	Conference Closing Remarks			

Detailed Programme

Day-1: 13th November 2019

Time	Session	Location
5:30- 9:00 PM	Registration and Opening Thai Cultural Performance with cocktail and food https://www.chula.ac.th/museum/702/	Thai House Chula University

Day-2: 14th November 2019

Time	Session detail Morning Session	Location
8:45-9:00	Arrival	
	Session Chair Prof. N Dawood and Asst. Prof. Vachara Peansupap	
9:00-9:30	**Keynote:** Prof. Nashwan Dawood **Title**: CONVR past and present, the role of digital technology to Transform Construction, UK perspective.	(Conference building)
9:30-10:00	**Keynote:** Prof. Raymond Issa **Title:** Modular Off-Site Construction and BIM in the US: Case Studies	
10:00-10:30	**Keynote:** Prof. Nobuyoshi Yabuki **Title**: Digital Construction in Japan: Current and Future Trends	
10:30:10:45	Coffee break	
	Session Chair Asst. Prof. Vachara Peansupap	
10:45-11:30	**Keynote:** Prof. Amorn Pimanmas, President BIM association Thailand **Title:** Current Stage of BIM Development in Thailand Construction Industry.	**Industrial Seminar sessions** (Conference building)
11:30-12:15	**Keynote**: Dr. Satakhun Kosavinta and Mr. Songpol Yomnak **Title**: BIM Initiative in Thai Construction Industry	
12:15-12:45	**Keynote**: Prof. Nashwan Dawood **Title**: UK implementation road map of BIM	
12:45-14:00	Lunch	
	Session Chair: Prof. Ray Issa	
14:00-14:30	**Keynote**: Dr. Jack Cheng **Title**: BIM Adoption and Researches in Hong Kong: Opportunities, Challenges and Lessons Learnt.	**Industrial Seminar sessions** (Conference building)
14:30-15:00	**Keynote**: Assoc. Prof. Tanit Tongthong Title: Advanced Technologies for Supporting Infrastructure Structure Project Management In Bangkok, Thailand	
15:00-15:30	**Keynote:** Dr. Racha Chahrour **Title:** BIM implementation strategies in Germany	
15:30-17:00	Discussion about construction and development of digital road map in Thailand	
19:00-21:00	**Conference Dinner**: https://www.supatrariverhouse.net/	

Day-3: 15th November 2019

Time	Session detail Morning Session, Chair Prof. Nobuyoshi Yabuki	Location
9:00-9:30	**Keynote**: Dr. Farzad Rahimian **Title**: Open BIM-VR Paradigm: How BIM-VR Integration will influence AEC Industries	Conference building
9:30-10:00	**Keynote:** Mr. Patai Padungtin, CEO - BUILK ONE GROUP **Title**: Digital Marketing towards Construction Industry Improvement	Conference building
10:00-10:15	Coffee break	

Breakout sessions

Session 1A *Room:* ***701***
Session Name: BIM & GIS
Session Chairs: Atif Hafeez

Time	Author(s)	Paper Title
10:15-11:45	Mikael Johansson & Mattias Roupé	BIM and virtual reality (VR) at the construction site
	Kishor Bhagwat & Venkata Santosh Kumar Delhi	Perception of construction stakeholders towards applicability of BIM to ensure project safety during planning and execution phase
	Chavanont Khosakitchalert, Nobuyoshi Yabuki & Tomohiro Fukuda	Automatic concrete formwork quantity take-off Using building information modelling
	Michael Jenewein & Peter Ferschin	Validation of construction deviations using Parametric BIM and augmented reality

Session 1B *Room:* ***702***
Session Name: *Sensing & AI*
Session Chairs: Anderson Akponeware

Time	Author(s)	Paper Title
10:15-11:45	Takayuki Fujii, Hiroshige Dan & Yoshihiro Yasumuro	Examination of photography quality index in UAV aerial shooting for 3D reconstruction
	Rio Takahashi, Hiroshige Dan & Yoshihiro Yasumuro	2D-3D AR visualization of physical barrier for wheelchair users with RGB-D sensing
	Satoshi Kubota, Kotaro Nishi & Chiyuan Ho	Construction and usage of three-dimensional data for road maintenance using various measurement instruments
	Natthapol Saovana, Nobuyoshi Yabuki, and Tomohiro Fukuda	Quantitative effect evaluation of the unwanted features removal of infrastructure digital images
	Noppadol Jaisue, Vachara Peansupap & Tanit Tongthong	Potential use of big data and artificial intelligence for delay problem resolution by construction management consultancy services in Thailand

Session 2A *Room:* ***701***
Session Name: AR & VR, Serious Games & Wearables
Session Chairs: Dr. Farzad Rahimian

Time	Author(s)	Paper Title
11:45-13:15	Meinhardt Thorlund Haahr, Kjeld Svidt & Rasmus Lund Jensen	How can virtual reality and augmented reality support the design review of building services
	Mattias Roupé, Mikael Johansson, Elke Miedema, Saga Karlsson, Lin Tan, Göran Lindahl & Christine Hammarling	Exploring different design spaces – VR as a tool during building design
	Sunseng Tea & Kriengsak Panuwatwanich	Application of virtual reality based remote collaboration system in construction
	Mehdi Hafsia, Yasmine Ouarti, Laure Ducoulombier, Eric Monacelli & Hugo Martin	Assessing the cognitive load of a tower crane operator's workstation using virtual reality and electroencephalography: a methodological overview

Session 2B *Room:* ***702***
Session Name: BIM & GIS, Collaboration & Design Support Systems
Session Chairs: Dr. Petcharat Limsupreeyarat

Time	Author(s)	Paper Title
11:45-13:15	Nawari. O Nawari, Shriraam Ravindran & Adel Alsaffar	Block chain technology and BIM: automated code compliance processes
	Ryu Izutsu, Nobuyoshi Yabuki & Tomohiro Fukuda	As-built detection of bridge structure using deep learning and volume detection system using BIM model
	Kayla Manuel, Nobuyoshi Yabuki & Tomohiro Fukuda	A BIM-based user-specific fire evacuation guidance system using customized earphones
	Ivaylo Ignatov & Peter Nørkjær Gade	Data formatting and visualization of BIM and sensor data in building management systems
	Vigneshkumar C, Urmi Ravindra Salve, Roode Liias & Rita Yi Man Li	Developing a database to capture, store and share fall-related safety knowledge to enhance fall prevention in construction industry

Session 3A		*Room:* ***701***
Session Name: AR & VR, Serious Games & Wearables		
Session Chairs: Amna Salman		
Time	Author(s)	Paper Title
14:30-16:00	Loporcaro G., Bellamy L., McKenzie, P. & Riley, H.	Evaluation of Microsoft HoloLens augmented reality technology as a construction checking tool
	Md Nazmus Sakib, Megha Yadav, Theodora Chaspari & Amir H. Behzadan	Coupling virtual reality and physiological markers to improve public speaking performance
	Jan Spilski, Christoph Giehl, Sabine Schlittmeier, Thomas Lachmann, Jan-Phillipp Exner, Alina Makhkamova, Dirk Werth, Mareike Schmidt & Martin Pietschmann	Potential of VR in the vocational education and training of craftsmen
	Amna Salman	Pedagogical transformation in building structures' classroom: immersing students into a virtual world for in-depth understanding of steel connections
	Dongnyeok Han, Swarnali Ghosh Dastider, Salman Azhar & Amna Salman	Strategies and lessons learned to create virtual reality immersive games for construction safety training

Session 3B		*Room:* ***702***
Session Name: AR & VR, Serious Games and Wearables		
Session Chairs: Mikael Johansson		
Time	Author(s)	Paper Title
14:30-16:00	Sokkeang Try & Kriengsak Panuwatwanich	Virtual reality application to aid civil engineering Laboratory preparation for undergraduate students
	Gulbin Ozcan-Deniz & Carmen Cordero	A comparative analysis of non-immersive and Immersive VR on improving students' understanding of Building systems
	Noppadon Jokkaw, Tanit Tongthong & Somjintana Kanangkaew	An application of virtual environmental technology For reducing the problems of construction works Change orders
	Wei-Cheng Chen, Hui-Ping Tserng & Jiasheu Josh Huang	A novel solution of continuous monitoring tunnel worker's physical and psychological status using wearable PPG heart-rate detection wristband and BLE IoT system
	Lauren Donatelli, Robert Leicht & John Messner	Exploring the use of virtual reality to support value engineering decisions

Session 4A		*Room:* ***701***
Session Name: AI, Knowledge & Theory Frameworks		
Session Chairs: Giuseppe Loporcaro		
Time	Author(s)	Paper Title
16:00-17:30	Satoshi Kubota, Kokichiro Horishita, Chiyuan Ho & Kotaro Nishi	Creation and quality evaluation of three-dimensional Road space data using camera footage
	Giorgos Sfikas, João Patacas, Charalampos Psarros, Antigoni Noula, Dimosthenis Ioannidis, Dimitrios Tzovaras	A deep neural network-based method for the detection and accurate thermography statistics estimation of aerially surveyed structures
	Mounter W., Dawood D., Dawood H.	Augmenting building energy usage models with data segmentation
	Gudlaugsson B., Dawood H., Pillai G.	A review of sustainability assessment and integrated modelling for urban energy planning
	Hafeez M., Dawood H., Rodriquez S., Patacas J., Schaik P., Dawood N.	A conceptual framework for integrating user experience with design parameters for residential buildings
	Akponeware A., Dawood N., Rodriquez S., Dawood H.	Exploring model techniques of measuring the carbon footprint of rail systems: a systematic review
	Alani Y., Dawood N., Rodriquez S., Dawood H.	Reviewing semantic WEB technologies in the architecture, engineering and construction industry
17:30-17:45	Closing Ceremony	

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BIM and Virtual Reality (VR) at the construction site

Mikael Johansson & Mattias Roupé
Chalmers University of Technology, Sweden

ABSTRACT: *In Scandinavia, recent years have seen an increased effort to move away from traditional 2D-drawings at the construction site, and instead let site personnel extract necessary information directly from the Building Information Model (BIM). However, although BIM-viewers and mobile applications are constantly improving, there are still issues around user-friendliness and ability to extract information and correct measurements directly from the model. In order to improve on the current situation, this paper presents a VR-application that allows construction workers to interact with the BIM through a user-friendly interface. By using modern VR hardware, such as HTC Vive, they can enter and freely navigate, inspect, and interact with the BIM in scale 1:1 and extract information, take measurements, define section planes, and control visibility of individual components or sub-models. A core component in this interface is the concept of "3D-labels", which let the user easily place and arrange information and measurements as needed. From within the VR environment it is then possible to take snapshots that can be uploaded and accessed on portable units on the construction site. In addition to present technical details of the developed VR-system, we also present an evaluation of it performed at four different construction sites.*

KEYWORDS: *BIM, VIRTUAL REALITY, VR.*

1. INTRODUCTION AND BACKGROUND

Using the concept of Building Information Modeling (BIM), architects and designers can nowadays produce parametric, object-oriented 3D-models embedded with information to describe any building or facility in detail. As a digital representation of the physical and functional characteristics of a building, a BIM serves as a repository of information supporting a multitude of applications along the design and construction processes, including cost-estimation, energy analysis and production planning (Eastman et al., 2011). Still, due to regulations and use of conventional construction contracts, 2D-drawings remain the primary source of information that is handed over from design to construction (Jamil and Fathi, 2017). As a consequence, designers needs to put in additional effort to produce 2D-drawings from the BIM, at the same time as all of the rich data produced during design does not reach the construction site.

However, recently, there has been an increased effort in Scandinavia to move away from traditional 2D-drawings at the construction site. Prime examples include the Slussen project, Röfors bridge, as well Oslo Airport Terminal 2, where Building Information Models (BIM) has been used as the primary source of information (Cousins, 2017; Götborg and Olsson, 2016; Merschbrock and Nordahl-Rolfsen, 2016). In the case of the Röfors bridge – *a project realized entirely without traditional drawings* – construction workers had direct access to the BIM on tablets for easy overview and understanding of the project. In addition, BIM managers and designers placed at the construction site created so-called Production-Oriented Views (POV) from the BIM in consultation with the construction workers. These views are essentially enhanced screenshots from the BIM, typically containing color-coded elements, specific measurements and dimensions, object information, 3D-sections, or any other information the construction workers consider is necessary in order to perform the actual work on site (Fig. 1). After creation, the views are uploaded as images to a shared model repository and can then be accessed and used as a complement to the complete BIM on portable units, such as iPads. Nevertheless, although found to be a very powerful and successful concept, the actual creation of POVs currently requires a designer or BIM-specialists on site, thus putting additional demands on the project organization (Malmkvist, 2018).

Increasing use of BIM, together with a new generation of affordable head-mounted displays (HMD) has also lead to the AEC industries adopting Virtual Reality (VR) more and more. With BIM, the required 3D data can be extracted directly instead of creating it from scratch, making it more accessible in practice. Typical applications for VR today include construction safety planning and training (Hafsia et al., 2018; Azhar, 2017), production planning (Muhammad et al., 2019), as well as design review sessions (Roupé et al., 2016; Zaker and Coloma, 2018; Wolfartsberger, 2019). In the case of design review sessions, previous studies has shown that VR can clarify many aspects of the design that is difficult to comprehend from traditional design documents, such as clashes and lack of space for installations and maintenance (Zaker and Coloma, 2018). In addition, it has been found that people with less experience in using desktop CAD/BIM viewers (e.g. MEP subcontractors, people who work in service and maintenance) has a preference for using VR as it better resembles their real work environment (Wolfartsberger, 2019). Still, as with BIM, we mainly see the use of VR during the design phase, and almost not at all during actual construction.

In this paper we present a user-friendly Virtual Reality (VR) system targeted for use at the construction site office. The primary application is to allow construction workers and supervisors to have easy access to the BIM through a simple VR interface. By using modern VR hardware, such as Oculus Rift or HTC Vive, they can enter and freely navigate, inspect, and interact with the BIM in scale 1:1 and extract information, take measurements, define section planes, and control visibility of individual components or sub-models. From within the VR environment it is then possible to take snapshots of the created Production-Oriented Views that can be uploaded and accessed on portable units on the construction site. In addition to present technical details of the developed VR-system, we also present an evaluation of it performed at four different construction sites.

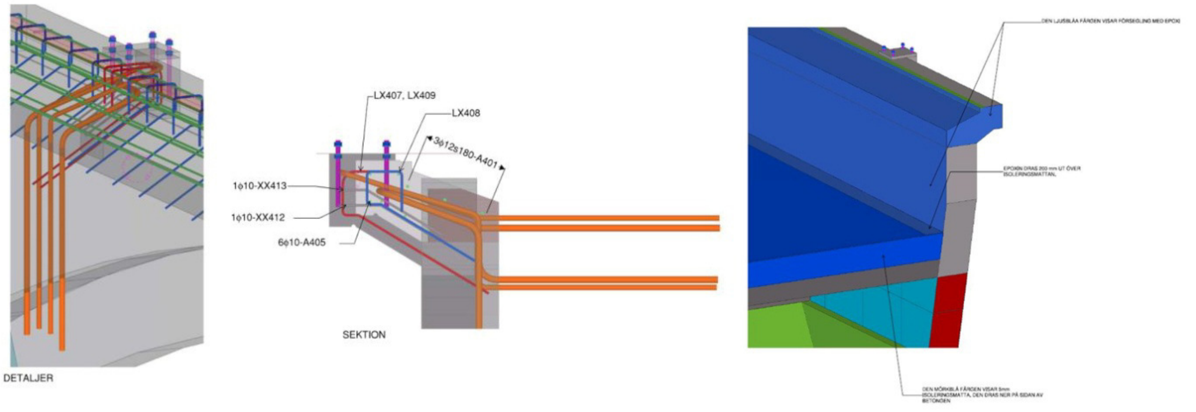

Fig. 1: Example of Production-Oriented Views (POV) from the Röforsbron project (Götborg and Olsson, 2016).

2. A VR INTERFACE FOR ON-SITE ACCESS TO BIMs

To support the ability to extract information and create POV directly in VR, we have used BIMXplorer as a platform and further customized it (BIMXplorer, 2019). BIMXplorer is a software application that has been specifically designed to allow real-time visualization of large and complex BIMs in VR. By taking advantage of efficient occlusion culling it allows very large and complex BIMs to be visualized in VR without the need for any preparation or optimization of the input dataset (Johansson, 2016). It works either as a plugin to Revit or as a standalone application that can import IFC-files through the xBIM Toolkit (Lockley et al., 2017). In the following subsections we further describe the VR interface and the different tool that were developed for use at the construction site office.

2.1 General VR interface

The VR user interface is based on a tools palette connected to one of the controllers (left). Using the other controller (right) the user can point and click to select a specific tool or change navigation mode (Fig. 2, left). Two navigation modes are available; Free flying, or "point-and-teleport", where the user points at a location in the scene and then instantly teleports there. In general, selecting a tool will bring up instructions and any options on a panel connected to the right controller. Using the touch button on the right controller, the user can press left/right/up/down/middle to control the options. By using the layers tool the names of the individual sub-models (e.g. Architectural, Structural, Electrical, etc.) are displayed in a list on a panel connected to the right controller. The user can then press up/down/middle to select and toggle the visibility of the individual sub-models. It is also possible to select and hide individual objects by ray select (i.e. point-and-click). Using the section tool, it is possible to define a section plane through the model, either by selecting a face in the model that acts as a cut plane, or by using the controller as a real-time cut plane. In this mode the outlines of the sectioned geometry is also displayed to further indicate that only a subset of the model is visible (Fig. 2, right).

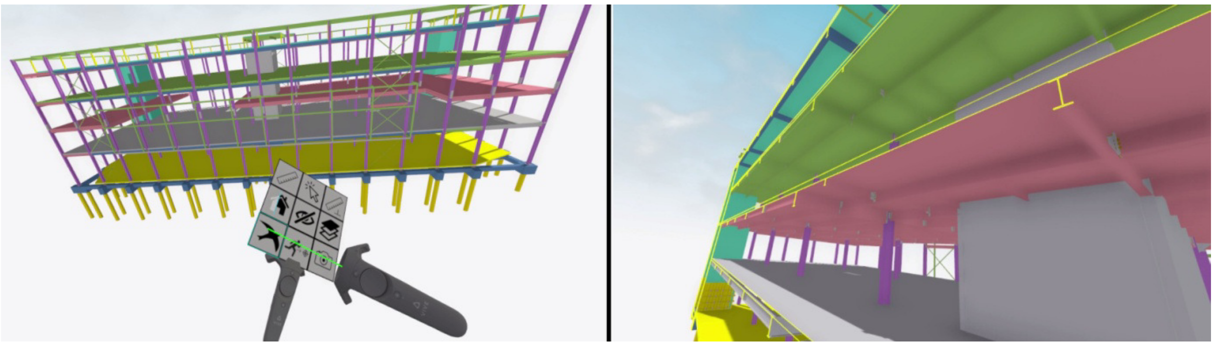

Fig. 2: BIMXplorer general VR-interface (left) and sectioning (right).

2.2 3D Labels

In order to create and fully control the arrangement of information for the Production-Oriented Views (POV) a concept referred to as 3D Labels has been implemented (Fig. 3). Upon selecting object properties or taking measurements (See 2.3 and 2.4) a 3D Label containing the information is automatically placed in the 3D scene. By aiming at the top bar the user can then grab the label and replace it if the initial placement was not optimal. Grabbing a 3D Label is similar to holding a mobile phone using a “selfie stick”, which was found to be the most practical and intuitive approach to control placement and orientation among several different options tested during early prototyping (e.g. transform gizmo, fully automatic placement). Furthermore, a label can be deleted or folded/expanded by clicking the respective icon for it.

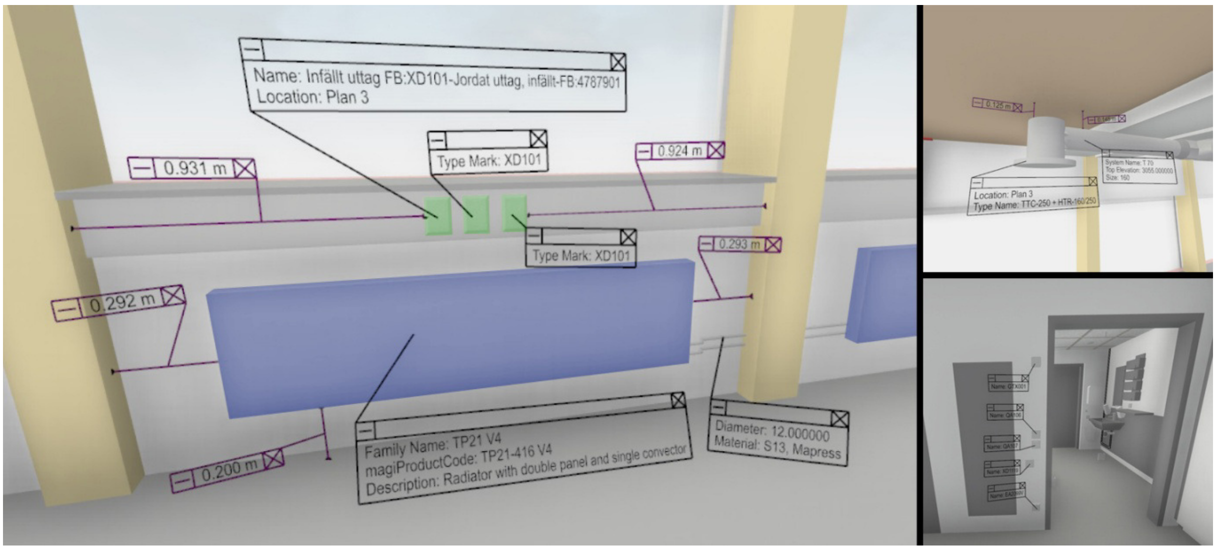

Fig. 3: Example of Production-Oriented Views (POV) created directly in VR.

2.3 Measurements

The system supports two types of distance measurements – perpendicular distance from a surface to any other surface, or distance between two arbitrary points. With perpendicular distance, the user selects an arbitrary position at a surface. The system then finds the closest intersection on a ray originating from that point in the direction of the surface normal. The perpendicular measurement is useful for quickly measuring the width of corridors or distance from floor to ceiling. Distance measuring between two arbitrary points works similar, with the exception that two points needs to be selected.

2.4 Information and recommendation system

By selecting an object, available PropertySets and Properties for that object will be displayed on a panel connected to the controller. By using up/down/middle on the controller it is then possible to select which properties that should be displayed on the corresponding 3D label. With BIM objects typically containing a large number of properties, a simple recommendation system was implemented that automatically adds the same properties onto the 3D Label as what has been previously selected for an object of similar type (Fig. 4).

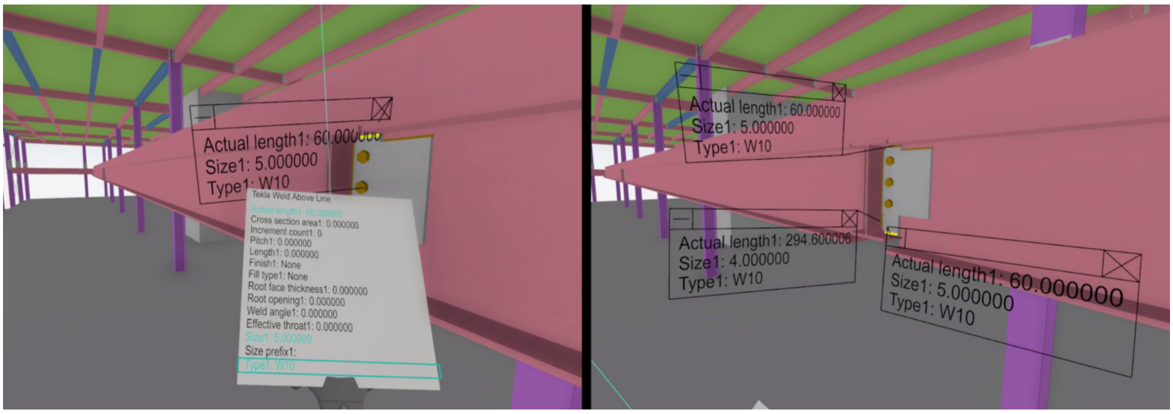

Fig. 4: The first time a weld object (i.e. IfcFastener) is selected, the user selects which properties that should be displayed on the 3D Label (left). When selecting subsequent welds, the previously selected properties are automatically added to the 3D Label (right).

2.5 Screenshots and production-oriented views

The user can easily take screenshots of what is displayed in VR, either on a fully prepared production-oriented view, or if it is just an arbitrary view of some detail in the model. These images are stored on the computer and can then be transferred to an iPad or smartphone for mobile use at the construction site. Using the add-on program VRCapture (VRCapture, 2019) it is also possible to record movie clips on what is being done in VR, which can, for example, be used to create instructional movies for various work tasks.

3. EVALUATION

The VR system has been evaluated at the site office at four different projects (Fig. 5). These projects where all ongoing, but in different stages (e.g. main structure has been erected, MEP work has just been started, MEP work was fully ongoing). In Table 1, model statistics for the different BIMs is presented. As can be seen, complete BIMs from these types of project tend to become very large and challenging to render in VR in real-time. However, this has not presented itself as a problem using BIMXplorer. All four projects has been either imported as IFC-files or taken directly from Revit without any need for further optimization. No issues regarding frame rate or lag has been noted.

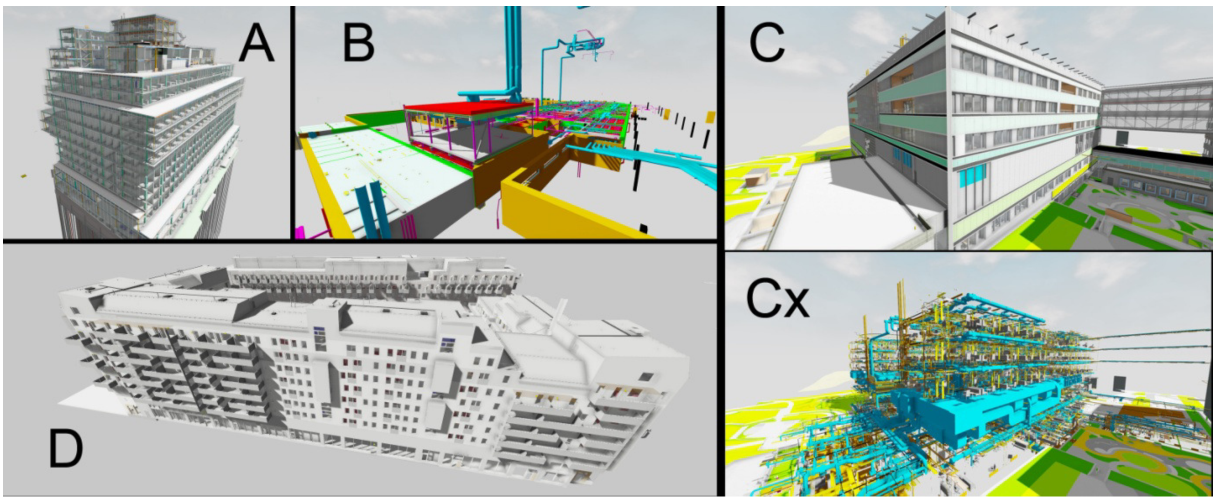

Fig. 5: The four different projects used during the evaluation (Cx shows the MEP sub-models in project C)

Table 1: Project and model statistics.

Project	Type	Source	# of objects	# of triangles
A	Office/hotel	IFC	299,273	44,878,455
B	Hospital	IFC	67,641	4,059,012
C	Hospital	Revit	386,169	165,155,703
D	Residential building	IFC	267,846	52,838,080

3.1 Data collection

During the evaluation phase we (i.e. the authors) visited the site office for each one of the four test projects. The VR equipment used for all projects was a gaming laptop with a NVIDIA GTX 1080 graphics card (GPU) and a HTC Vive VR-headset. On every site-visit a short presentation of the project and its purpose has been kept for an initial test group, and then the equipment has been available for the rest of the day to allow site personnel to come and test it continuously (Fig. 6). Except for the site manager in each project, none of the respondents had been given any information about the visit in advance. No particular tasks were given to the users other than asking them to try out and evaluate the VR interface and the different tools. In that sense we can consider the user tests as more explorative than driven by specific objectives or tasks to perform in VR.

Prior the site visits, a questionnaire was prepared containing both open and closed questions regarding the respondents' professional role, their knowledge and use of BIM, what information they require to perform their work, and how they experienced different aspects of the VR system and its functionality. In addition, data has been collected by means of observations and conversations with the participants during and after their tests in VR.

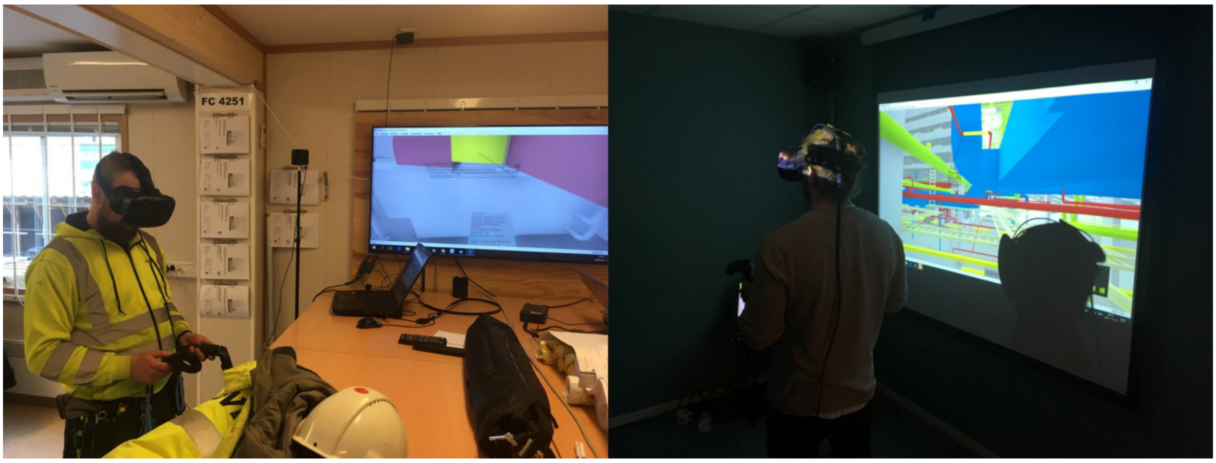

Fig. 6: Photos from the evaluation at project C and D.

4. RESULTS AND DISCUSSION

28 people completed the questionnaire directly after testing the VR system on site. In addition, 29 persons tested the system, but for various reasons were unable to conduct the questionnaire (e.g. time constraints, something happened at the construction site that needed immediate attention, etc.). However, by always being present as an observer/assistant, in cases where the test persons have not been able to complete the questionnaire, we have still been able to capture their thoughts, opinions, and wishes linked to the system and the way of working. Overall, we have not been able to see any significant difference between the people who tested and completed the questionnaire and those who only tested the system but were unable to do the questionnaire. We therefore believe that the results from the questionnaire provide a representative overall picture of the evaluation

4.1 Overall rating of the system

The questionnaire contained 10 questions where the respondents we're asked to rate various aspects of the VR interface on a scale from 1 (poor) to 5 (excellent). In Figure 7 we present the results on how the respondents rated the user-friendliness of the different tools. Figure 8 further presents how the respondents rated the VR systems ability to get them an understanding of the project as a whole, as well as how they perceived the VR interface in comparison to 2D-drawings and other BIM-viewers.

As the results clearly show, it is a predominantly positive image of the VR technology being conveyed. Given that it is almost exclusively the first time these users came in contact with VR, it can be concluded that this is technology that is perceived as user-friendly already in an initial test. Of particular note is "Understanding of the project as a whole", which is also very clear from the observations and the open questions (see section 4.2.3).

Based on these ratings, we can see that "Measure distance" has the most potential for improvement (discussed in more detail in 4.2.2). However, even here, there is a clear overweight to the positive, which means that even more advanced applications such as measurement and information extraction based on BIM models are fully possible even for non-experienced users.

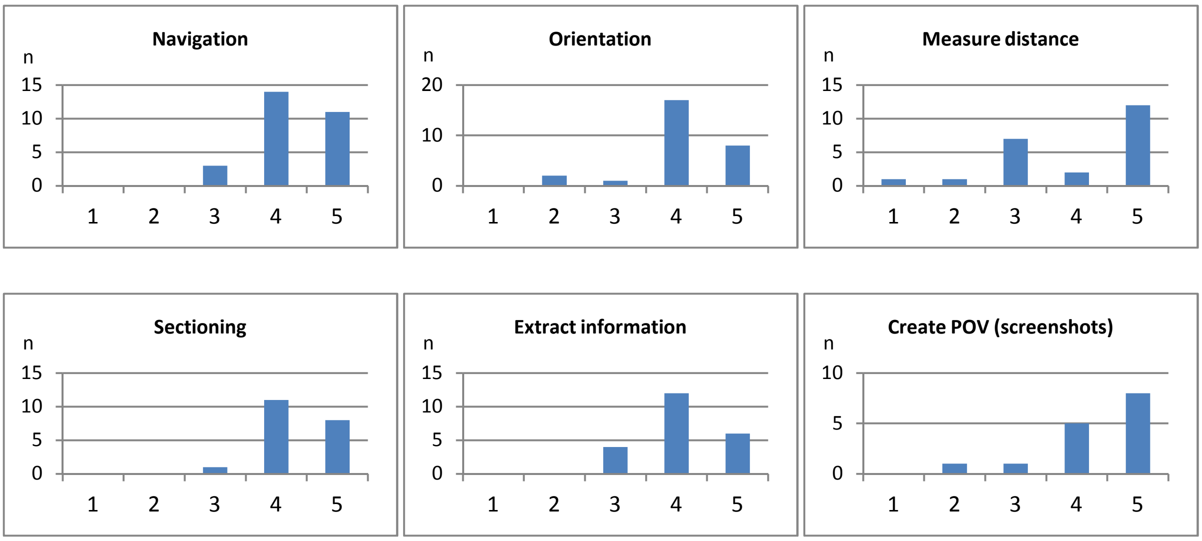

Fig. 7: General rating of the VR interface and different tools on a scale from 1 (poor) to 5 (excellent).

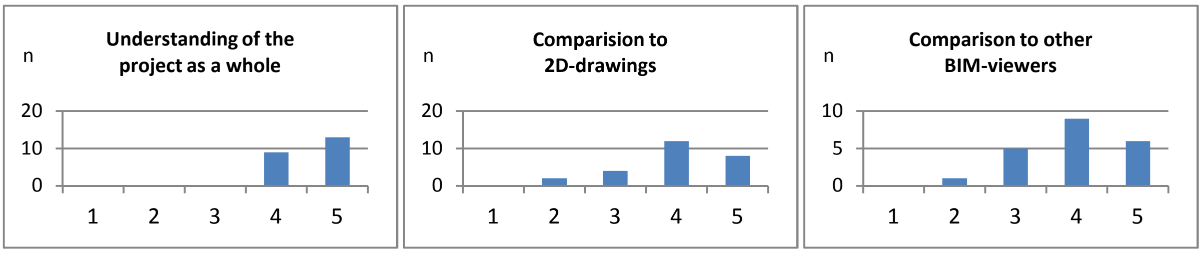

Fig. 8: Rating of different aspects regarding the VR interface on a scale from 1 (poor) to 5 (excellent).

4.2 Observations and open questions

A first interesting observation is that the users almost exclusively navigate to the place in the BIM where they currently work or have their focus. Although this may be considered obvious, it also demonstrates how important it is to present and evaluate new technology in its actual context and with examples that the people in question can relate to. Without offering them a model or project that they can relate to it merely becomes a demonstration of the technology itself, only allowing the respondents to speculate how they *can* use the technology, as opposed to how they actually *will* use it in a real project. In the following subsections we further present and discuss the results that were collected during observations, open questions, and discussions with the respondents.

4.2.1 Information content

As BIM elements typically contain a lot of information and properties, it might be a challenge for a user to quickly find only the relevant information for a specific task. One of the aims with the study was therefore to identify which information the different users felt was important to have quick access to, in order to be able to "filter out" less important information based on professional group. In Table 2 we list information and properties that was mentioned as important by several respondents within each professional group.

Table 2: Important information and properties according to MEP subcontractors and construction workers.

MEP subcontractors	Construction workers
MEP supports and hangers (3D geometry and properties)	Material information (e.g. layers in a wall)
System name (which system the component belongs to)	Sill height
Information about insulation	Dimensions for wall penetrations
Mounting height (in relation to floor/ceiling)	AMA codes (Swedish classification codes/instructions)
General component dimensions	General component dimensions
Floor/room identification (where the component is located)	Floor/room identification (where the component is located)

In addition, there were many requests for specific information which is difficult to generalize beyond "detailed information about the object", such as information connected to electrical components, electrical cabinets or control valves. There is also no clear consensus regarding if certain dimensions, such as sill height or installation mounting height, should be in the form of object properties or instead could be measured by the user in VR.

The BIMs in the various projects differed somewhat in terms of information content and during the evaluation we have seen examples of when the desired information is there, but also cases when it is missing. However, overall it has been difficult to clearly see what information they do not need, when the overweight instead has been that respondents want more information than what was available in the BIM. In this context, the recommendation system has proven to work well as an alternative to filtering or limiting information. In most cases, the user wants to have access to the same type of information, but on different objects, which in the case of the recommendation system means that you only need to specify what you want once.

4.2.2 Interface and tools

When it comes to navigating the VR environment, both the questionnaire and observations show that this is something that users - after a few simple instructions - master almost immediately. Still, several people express a desire for access to a map or overview that makes it easier to understand where you are in the model. Regarding motion sickness, about 20% of the users express that they experience some form of it, with comments ranging from "a bit", "slightly dizzy while flying" to "yes". However, it is also important to add that these users chose to "fly" around in the model, much because they felt it gave them more freedom to get anywhere quickly. Still, the problem of motion sickness should not be underestimated and it might be preferable to only allow teleport navigation, at least for inexperienced users.

With regard to the different tools, such as measurement and sectioning, not all respondents have chosen to use all the functions. Therefore, the evaluation basis cannot be considered as strong here as in navigation or general understanding of the project via the VR model. However, for standard dimensioning, it is clear that a snapping function is needed to make it more user-friendly, since many of the dimensions that the users want to put out are from an edge or corner. In this context, perpendicular dimension measurement is considered simpler as it is only an arbitrary point on a flat surface to be selected. Especially MEP workers also express a need to be able to easily take center-to-center measurements between components or between component and wall. Furthermore, the concept of 3D labels proved to work very well. As soon as users were given instructions on how to "grab" a 3D label, they could continue to move around easily and place them how they wanted. The same was true of the use of the sectioning tool.

Although the above gives a good picture of what the users experienced and wanted from the VR system, the overall purpose of the research project has been to simplify and streamline work in production. In this context, the comparison with what they use today becomes extra interesting. To better illustrate the respondents' thoughts, we give some examples of what they answered to the question *"How user-friendly is this interface compared to what you are using now?"*

"Can be good if you use it often"
"It goes a lot faster"
"Easier to see and get an idea, would have gone faster"
"Good complement to Solibri and Dalux"
"Great overall picture, good for quality assurance, understanding, coordination etc."
"Very user friendly"
"Does not use BIM today, but compared to drawings - a lot"
"No major difference compared to current 3D models"

Overall, we can see that the interface works well, but is far from perfect from a user perspective. To some extent, this is also due to the fact that the VR technology as such is new and there is currently no clear interface that users have experience of or can relate to. There is therefore definite potential for improvement, especially in terms of measurement. Despite this, we see how people without any previous experience with VR can almost directly navigate in - and extract information from - a BIM.

4.2.3 Understanding and communication

The overwhelming main advantage of VR was considered to be that it contributes to a much better understanding and overall picture of the project. The ability to "step into" a model and experience it on a 1:1 scale is highlighted as a great advantage and basically everyone who has tested the system believes that it provides a much better understanding of the whole project than 2D drawings do. A recurring description in this context is that "everyone sees the same thing" with VR, which is predicted to facilitate communication between different parties as it reduces the risk of different interpretations from, for example, 2D-drawings.

In addition to evaluate the various tools and explore the information content of the BIM, the people who tested the system mainly used it to get a better overview of the project as a whole and to gain a better view and understanding of current or imminent work. As such, the evaluation setting was not that of an actual design or constructability review. However, despite this somewhat unconditional inspection of the model the respondents have still been able to quickly identify many problems, such as clashes, design errors, or lack of space for a certain work task. To better illustrate this, a number of examples of comments that emerged during the course of the study are given below:

"Here we will not be able to fit all the pipes. It is not possible, I see that immediately. There you also have one..., no, two clashes." [Ventilation subcontractor]

"In this room I have just looked at the blueprint, I know we should pull in three [...] here but I could not find out where ... Well, there you have those two! Ok, and then the third one is ..? No, it should actually come in here." [Electrical subcontractor]

"I saw surprisingly many clashes, particularly with the fixed furnishings. I mean, if they should have the closets there, then we can't pull the pipes that way." [Supervisor]

Still, comments like these must also be put into context. As the design often runs parallel to construction, it is not certain that the design was finalized in the places where the problems were identified. It is also very likely that a deeper examination of the drawing material could have clarified the respective situation or collision. However, it clearly demonstrates how intuitively people perceive the situation when they are in the VR environment, thus confirming findings in previous studies (e.g. Zaker and Coloma, 2018; Wolfartsberger, 2019)

4.2.4 Color coding

Color coding of objects was something that most people commented on and also had wishes about. There is a clear desire for objects to be color-coded as it facilitates understanding and clarifies individual objects. However, several respondents also expressed wishes around more flexible and "dynamic" color coding. For instance, in project B, the construction workers wanted to color the interior walls based on their classification code according to the Swedish building standard. In BIMXplorer it is possible to control visibility and color of objects based on their properties in a similar way that can be done in Solibri. By defining a set of rules the BIM was then color coded according to request from the respondents (Fig. 9). However, although this was perceived as very powerful and exactly what they wanted, they still consider the actual creation of the color coding rules an unwanted step and they simply wished to select – in VR – from a list of predefined color coding rulesets, such as "Color by material" or "Color by classification code", etc..

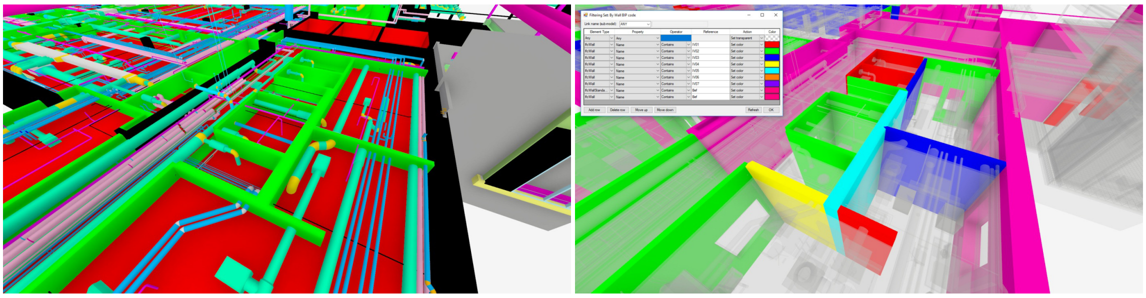

Fig. 9: Object colors from IFC-file (left) and colors by wall type (right)

4.2.5 Production-oriented views

Although the project's primary goal was to evaluate the concept of creating POVs directly in VR, it is difficult to give a clear answer to how well this concept actually worked in practice. Although many used the different tools to extract dimensions, information, and create screenshots of different details (Fig. 10), we cannot compare this with the examples highlighted from previous studies, where the production-oriented views were created and actually used in production. As previously mentioned, this can largely be due to the explorative nature of the evaluation with no explicit tasks given to the users. With the exception of two users, this was also the first time they tested VR, which was considered to be a totally new experience and concept in itself.

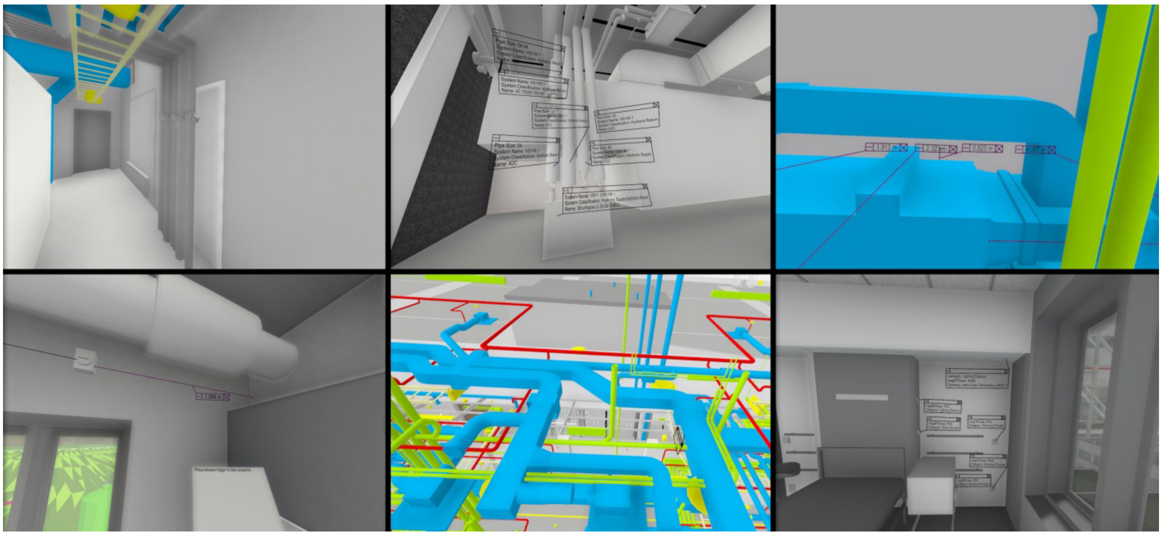

Fig. 10: Example of Production-Oriented Views created by the users during the evaluation.

5. CONCLUSIONS

The results from the evaluation show that there are great opportunities with a VR system at the construction site office. The greatest advantage is considered to be in understanding and overall picture of the project, but it is also a clear overweight to the better when compared to traditional 2D-drawings and other BIM tools. A recurring description is that "everyone sees the same thing" with VR, which is predicted by the users to facilitate communication and understanding between different parties as it reduces the risk of different interpretations based on, for instance 2D-drawings. Furthermore, it is also clear how the users, just by "stepping in" and viewing the model on a scale of 1:1, can almost immediately form an idea of any problems, such as clashes, design errors, or lack of space for a certain work task.

The developed VR interface was considered very user friendly. However, there is still development potential, especially when it comes to measurement. To fully satisfy the needs of all users, the measurement function needs to be both more powerful (e.g. support c/c dimensioning) and more easy to use (e.g. snapping functionality).

Regarding the concept of production-oriented views, it is difficult to give a clear answer to how well this actually worked in practice. The views that were created were primarily made for testing purposes and only in a few cases were they created for actual use on the construction site. However, the evaluation clearly shows that the technology is ripe enough for staff at the construction site to be able to create their own views from the BIM. Almost directly they handle navigation in the model and after a brief introduction to the various tools they can extract information and take measurements in the model. Given that for almost all users this was the first time they came into contact with VR, the technology must therefore be considered user-friendly and easy to take advantage of at the site office.

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PERCEPTION OF CONSTRUCTION STAKEHOLDERS TOWARDS APPLICABILITY OF BIM TO ENSURE PROJECT SAFETY DURING PLANNING AND EXECUTION PHASE

Kishor Bhagwat & Venkata Santosh Kumar Delhi
Department of Civil Engineering, Indian Institute of Technology Bombay, India.

ABSTRACT: *Construction industry is considered to be hazardous. Research on construction safety has pointed out at the fact that construction safety should be considered across the life-cycle of a project. Previous research has highlighted the potential of Building Information Modelling (BIM) in improving safety on a construction project. BIM in construction safety has predominantly been used in the design stage where the project is designed for safe execution. However, the potential of BIM during other phases of the construction project are understudied at the present moment. The present study looks at the potential of BIM during the planning and execution of a construction project. To this end, a questionnaire survey was conducted across the construction projects in India to understand the perception of the industry in the applicability of BIM to ensure safety in the construction phase of the project. 164 responses were elicited from management representatives, workers and BIM professionals across construction projects in India. The results of the questionnaire survey revealed that a majority of the participants agree that BIM would be extremely useful in hazard identification and risk perception and site safety planning in the planning stage. Also, effective in safety communication and training during the execution stage of the project. This study observed BIM implementation for safety is in the initial stage of adoption along with major barriers and enablers. Thus, the present study points at the potential of using novel platforms like BIM in the area of construction safety planning, training, and management in construction projects.*

KEYWORDS: *Building Information Modelling, Construction Management, Safety Management, Construction Safety, Project Lifecycle.*

1. INTRODUCTION

The construction industry is considered to be one of the hazardous industries across the world (Idoro, 2008). Such hazards could be a result of unsafe actions by the actors working in construction or due to contextual conditions that pose unsafe work conditions on the site. Historically, the domain of project management was interesting in delivering projects on time and within costs. The objective of safe construction is now one of the prime objectives of construction managers all over the world. However, the construction industry remains to be one of the more accident-prone industries in the world. More than 60,000 fatalities in the construction industry every year (Edrei and Isaac, 2017; Lingard, 2013; Namian et al., 2016; Patel et al., 2016). The statistics obtained from occupational Safety and Health Administration (OSHA) reveal that 856 fatalities in 2013 (Senouci et al., 2015), and 908 fatalities in 2014 reported in the United States construction industry (Namian et al., 2016). This scenario becomes critical when statistics come to a developing country like India which is facing approximately 11,614 to 22,080 fatal accidents every year on construction sites (Patel and Jha, 2016). To deal with this, the literature on construction safety constantly highlighted that unsafe acts and unsafe working conditions are the origins of various accidents happening on the site. The advent of new information management paradigms like Building Information Modelling (BIM) offers novel approaches to ensure safe construction sites by improving safe behavior and site conditions. Use of technologies like BIM could have potential implications across the life-cycle of a construction project. In the present research, authors focused on understanding the implications of BIM and allied technologies across the life-cycle of a construction project. To do so, survey of extant literature to understand the possible technologies involved and their potential contributions to construction safety. Based on the literature review, a survey was conducted to understand the knowledge and readiness of construction industry in India about the applications of BIM in construction safety. This research offers the first step in understanding the penetration of BIM and allied technologies in the field of construction safety on sites.

2. LITERATURE REVIEW

BIM developed in the 1970s by name Building Product Models (Charles M. Eastman, 1975). Eastman et al. (Eastman et al., 2008) define BIM as modeling technology and associated set of processes to produce, communicate and analyze building models. BIM is defined as a digital representation of physical and functional characteristics of a facility (Wong et al., 2009). BIM is gaining momentum in the construction industry on planning, design, construction, operation, and demolition phase. The possible application of BIM for all phases of the construction project presented systematically in figure 1. The use of BIM in the construction industry raised from 28% in 2007 to 71% in 2012 (McGraw-Hill Construction, 2012). The major benefits of BIM are an accurate geometrical representation of object along with its properties, better planning, design, and execution in construction projects. The remarkable benefits are up to 40% elimination of unbudgeted change, cost estimation accuracy within 3% as compared to traditional estimates, up to 80% reduction in time taken for cost estimate, saving up to 10% of the contract value through clash detection, and up to 7% reduction in project duration (CRC Construction Innovation, 2007).

Figure 1. Application of BIM for Construction Project Lifecycle

It is also now understood that BIM helps in proactive safety management and thus can be utilized to avoid accidents on the site. Recent directions in construction safety management (CSM) also looks at the integration of BIM with other technologies (figure 2) such as Automated Safety Rule Checking Platform, Wireless Technology, Virtual Reality (VR), Augmented Reality(AR), and Game Technology to provide solutions for the safety issues on the construction site.

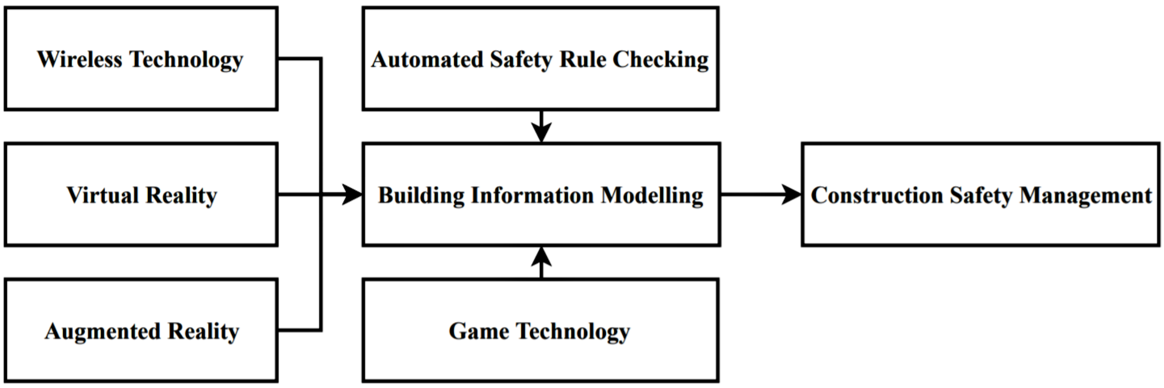


Figure 2. Application of BIM and other Technologies for Construction Safety Management

2.1 BIM for CSM

BIM provides a visualization platform for all stakeholders to initiate the safety management plan at the startup of the construction project. Such visualization platforms also provide an opportunity to develop safety education and training modules for the execution phase of the construction project. The sample pictures in figure 3 showing the violations of safety with the visualization platforms. Figure 3 (a) depicts that the site supervisor is busy in mobile phone and standing in the vicinity of working equipment, specifically in the rotating boom area of the crane.

Because of restrictions on visibility while working on the crane the accident may happen. The figure 3 (b) depicts that opening in the floor is not guarded at all, in addition material being stacked at the edge of the opening which may lead to struck by accident. Figure 3 (c) depicts that opening in the wall is not being guarded, it may lead to falling from the height which is a major mode of accident all over the world. Similarly, figure 3 (d) depicts that the opening on the floor is not properly guarded, in addition workers laid down planks to have a route for their work. Such safety rules violations can be shown and used by many researchers with the help of visualization platforms.

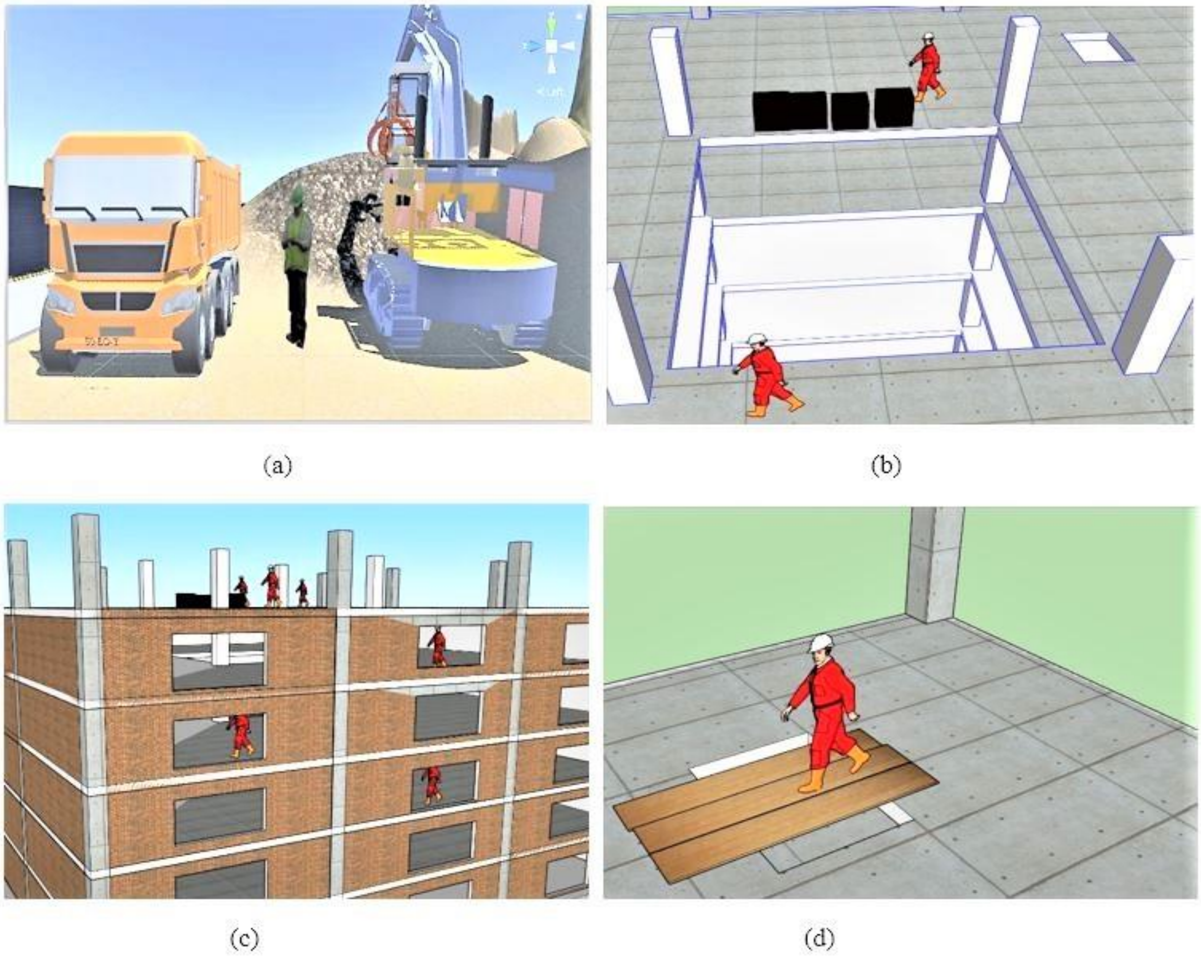


Figure 3. Application of Visualization Platforms for Safety Education and Training

For example, Guo et al. (2013) developed a framework, which enables to develop a model and simulate, identify hazards, and provide safety training. The framework consists of converting a 2D drawing to 3D model, providing a walkthrough in a simulated site environment, identifying hazardous situations and practices, and providing safety training to project managers, supervisors, and workers. BIM has the potential to change the current approach of construction health and safety planning by effective toolbox talk, safety meetings (Ganah and John, 2015). BIM helps in increasing the safety performance of the stakeholders by facilitating Job Hazard Analysis, Safety Education and Training, real-time site safety monitoring and warning to unsafe acts (Guo et al., 2017).

2.2 BIM and Automated Safety Rule Checking Platform for CSM

OSHA and International Organization for Standardization (ISO) safety standards are the widely accepted standards all over the world. Also, many countries like India is having their construction safety standards for safe practices on site. Safety standards collection, reading and understanding, interpretation, and application to each design became a cumbersome task for safety practitioners. To deal with such issues, researchers like Zhang et al. (2013) developed an automated safety checking model by integrating BIM, scheduling technique, and model checking system. Such model automatically checks the developed BIM model against a set of rules, identifies critical areas and provides suggestions to improve safety at the design phase itself.

2.3 BIM and Wireless Technology for CSM

Wireless Technology helps to reduce non-value adding activities such as unnecessary site visits and too many site visits. In addition, it provides an immediate response to safety hazards and enables to use of that data for training purposes (Nuntasunti and Bernold, 2006). Cheng and Teizer (2013) developed an integrated framework with the help of BIM and wireless sensing technology to monitor the construction sites from a remote place. Costin et al. (2015) also developed an integrated platform using BIM and RFID for real-time tracking and visualization. It resulted in real-time resource tracking, data analysis, ordinance compliance, zone of safety violations, improved safety and security, improved quality, billing, and record-keeping, etc.

2.4 BIM and VR for CSM

Unsafe acts at the construction site cannot be explained with the help of actual demonstration on the site because of the chances of injuries in the demonstration itself. Therefore, to deal with such issues, the researcher focused on the integration of BIM and VR. VR facilitates to perform or observe the unsafe acts for the training purpose. In addition, VR also facilitates to have a view of 2D drawings virtually in 3D environment which enables a proper understanding of objects and tasks to be performed. Therefore, Hadikusumo and Rowlinson (2004) developed a BIM-based virtual environment for training to students and inexperienced safety engineers to identify hazards on site. Pedro et al. (2016) also developed a BIM-based Virtual construction site environment that increased workers' safety knowledge, the ability of hazard identification.

2.5 BIM and AR for CSM

Augmented reality provides an opportunity for users for communication regarding some critical issues in the design and construction activities. Therefore, Park and Kim (2013) developed a safety management platform with the help of BIM, Augmented Reality, Wireless Technology, and Game Technology for job hazard analysis, communication among stakeholders, to develop a proper safety training program. Albert et al. (2014) also developed System for Augmented Virtuality Environment Safety (SAVES) using BIM, Unreal Development Kit, on-site pictures, to increase the hazard recognition ability. The result depicted that there is an increase in the ability of hazard recognition from 46% to 77%.

2.6 BIM and Game Technology for CSM

Literature shows that integration of BIM and Game Technology has been done along with either wireless technology or Virtual Reality or Augmented Reality. Game technology provided support in the animation and developing the scene of the construction site. Li et al. (2015) developed a proactive construction safety management system with the help of wireless technology and game engine like Unity for resource tracking, quick feedback, and safety training purpose. Almeida et al. (2015) developed a virtual construction scenario with the help of VR (OCULUS Rift) and Game Engine (Unity) to test the alertness and behavioral change in workers on warnings provided in the virtual environment.

Broadly, the researchers are trying to enhance the safety performance of the construction projects either in the design phase, or in the planning phase, or execution phase, or all phases. The literature has provided many pieces of evidence of the successful implementation of such novel approaches to improve safe behaviors and site conditions on the projects. But when it comes to actual implementation to construction projects, the scenario is very different especially countries like India. Where construction professionals are hardly aware of such available technological development, and due to many issues, BIM professionals are not able to implement on construction sites to its full extent. Therefore, this study aimed at understanding the penetration of BIM for effective construction safety management in the Indian construction industry.

3. RESEARCH METHODOLOGY

To understand the penetration of BIM in the Indian construction industry in terms of its applicability to construction safety management following (as shown in figure 4) research methodology was followed. The very first step was the literature survey. It provided a detailed idea about the possible applications of BIM along with allied technology such as Automated Safety Rule Checking Platform, Wireless Technology, VR, AR, and Game Technology for effective construction safety management. Further, it was understood from the literature that

Perception Based Survey method is appropriate for this study. Following the literature survey, a questionnaire was designed. Questions were relating to the usefulness of BIM in various areas of construction safety management were posed to understand the perspective of the construction and BIM professionals. More specifically, questions were asked in terms of statements to capture the level of agreement with the mentioned statement. Here following statements were asked, ‘BIM can be used for identification of unanticipated problem and inconsistency in design stage’, ‘BIM can be used for better communication and collaboration’, ‘BIM can be used for better site layout planning’, and ‘BIM can be used for better safety performance of the workers’. The questionnaire survey and data collection were performed through well experienced and diversely located 148 construction professionals and 16 BIM professionals from India. Further details of respondents are presented in table1.

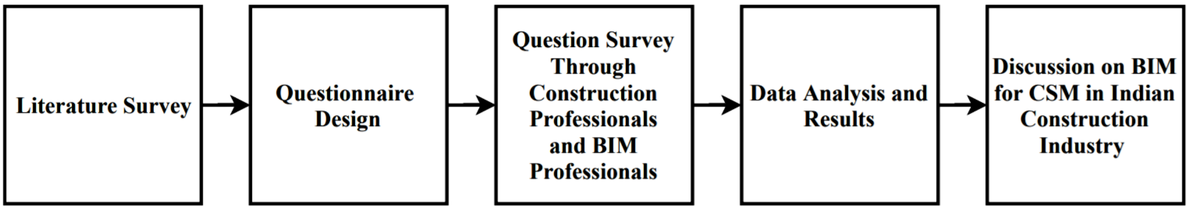


Figure 4. Research Methodology

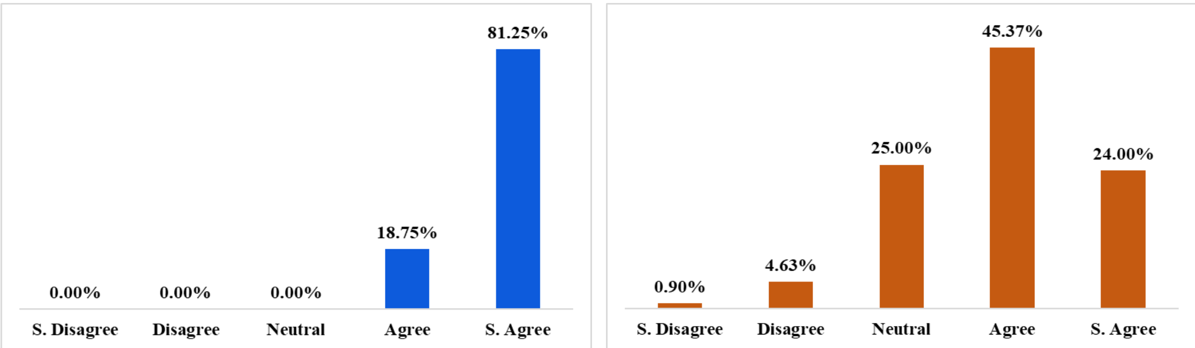
Table 1. Respondents’ Characteristics

Construction Professionals' Designation	*Number*	*BIM Professionals' Business Type*	*Number*
Engineer	60	Consultant	5
Manager	15	Architects/Engineers	4
Worker	71	Software Vendor	2
Director	1	Subcontractors	4
Owner	1	General Contractors And Construction Managers	1
Construction Professionals' Experience		*BIM Professionals' Current Project Types*	
0 to 5 Years	70	Industrial	3
Above 5 to 10 Years	35	Residential	2
Above 10 to 15 Years	19	Healthcare	1
Above 15 to 20 Years	7	Commercial	5
Above 20 Years	17	Infrastructure and Heavy construction	3
		Other	2
BIM Professionals' Designation			
Engineer (Project + BIM + Senior)	6	*BIM Professionals' Expertise with BIM*	
Manager (Assistant + Senior)	4	Just started	1
Leader (Team + Project)	2	Advanced	4
Architect	1	Expert	11
Modeller	1		
Coordinator	2	*BIM Professionals' Current Projects*	
		Private	9
		Public	7
BIM Professionals' Experience			
0 to 3 Years	5	*BIM Professionals' Current Project Cost*	
Above 3 to 5 Years	7	1 Crore - 10 Crore	5
Above 5 to 10 Years	2	Above 10 Crore - 100 Crore	6
Above 10 Years	2	Above 100 Crore	5

The majority of respondents from construction sites were engineers, managers, workers, director, and owner. Here, engineers include junior engineer, senior engineer, site engineer, safety engineer, and planning engineer. Managers include assistant manager, senior manager, planning manager, production manager, project manager, etc. Workers include stakeholders related to shuttering, flooring, brickwork, plastering, carpentry, waterproofing, plumbing, rebar, electrician, fabrication, painter, excavation activities. The responses were collected using both online as well as offline survey forms on the 5-point Likert scale (1 – Strongly Disagree to 5 – Strongly Agree). This was followed by a series of questions to BIM professionals to understand the barriers and enablers for the adoption of BIM and allied technologies in the field of construction safety management. More specifically, the questions were, 'Have you ever used BIM for CSM?', 'If yes, please mention the construction safety issues solved by using BIM', 'If no, please mention the barriers or why you have not used BIM to solve construction safety issues on the site', and 'According to your experience as a BIM professional, please suggest strategies to overcome the barriers or to strengthen the application of BIM for construction safety management'. The next sections illustrate the data analysis and results and key findings of this study.

4. DATA ANALYSIS AND RESULTS

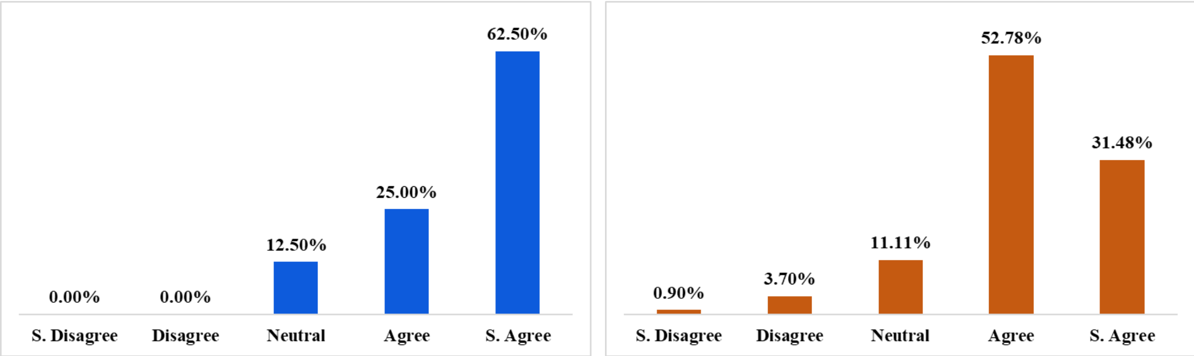
The data analysis was done with the help of statistical calculation, which presented the potential of BIM for Construction Safety Management in the Indian construction industry. The percentile score of the level of agreement with asked research questions has been calculated and presented in figure 5 to figure 8. Here, (a) and (b) parts of figure 5 to figure 8 represent the responses of BIM professionals and construction professionals respectively. Here data analysis approach such as the percentile score method of analysis was used to understand the perception of construction and BIM professionals because of its simple and quick method of analysis and self-explanatory results. Due to such advantages, many studies have adopted the percentile score method of analysis for understanding the perceptions of different stakeholders (Joannides et al., 2012; Tymvios and Gambatese, 2016). Figure 5 depicts that there is a potential of BIM for identifying unanticipated issues and inconsistencies in the designs. Identifying inconsistencies and unanticipated issues in the design are the proactive measures for safety management in the design phase. Literature proved that the experienced practitioner also missed some of the critical safety issues in the design, which can be easily recognized using BIM-based technologies (Kim et al., 2016). The result shows that 100% BIM professionals and 69.37% construction professionals are positive towards the potential of BIM for identifying unanticipated issues and inconsistencies in the design phase. Result also supported by Azhar (2017) that BIM can facilitate visual access to the construction sites for identifying the possible hazards in the near future.



(a) (b)

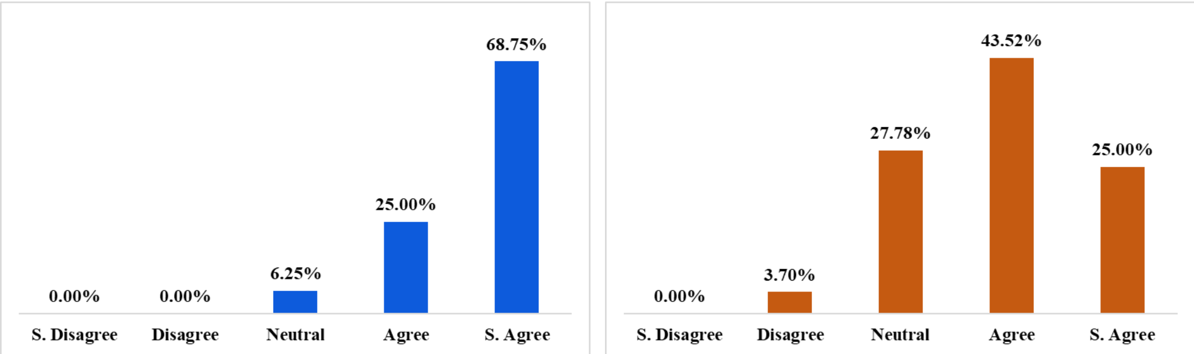
Figure 5. Application of BIM for Identification of Unanticipated Problem and Inconsistency in Design Stage

Figure 6 depicts that there is a significant potential of BIM in providing better communication and collaboration platform for the project team. Ineffective communication among stakeholders leads to unsafe acts. Traditional paper-based or classroom-based safety education and training program are now becoming old methods because of one-way communication. Also, the language barrier is the major hurdle for ethnic workers to understand the instruction and training program on the site. Whereas BIM has great potential to enable effective communication among all stakeholders, thus 87.5% BIM professionals and 84.26% construction professionals are positive towards the potential of BIM for effective communication and collaboration for safety management. Result supported by Lingard et al. (2015) as, BIM can be an appropriate solution for effective communication because worker prefers the visualized safety training and communication over written safety rules and policies. Figure 7 depicts that there is a significant potential of BIM in proper site planning and facility management. Poor site planning leads to unsafe site conditions, which can result in accidents. Crane accidents, struck by construction equipment and falling object accidents, improper facility location-based accidents are the most frequently observed outcomes of poor site layout planning. To facilitate effective site planning BIM has significant potential; therefore, 93.75% BIM professionals and 68.52% construction professionals are positive towards the potential of BIM for site planning.



(a) (b)

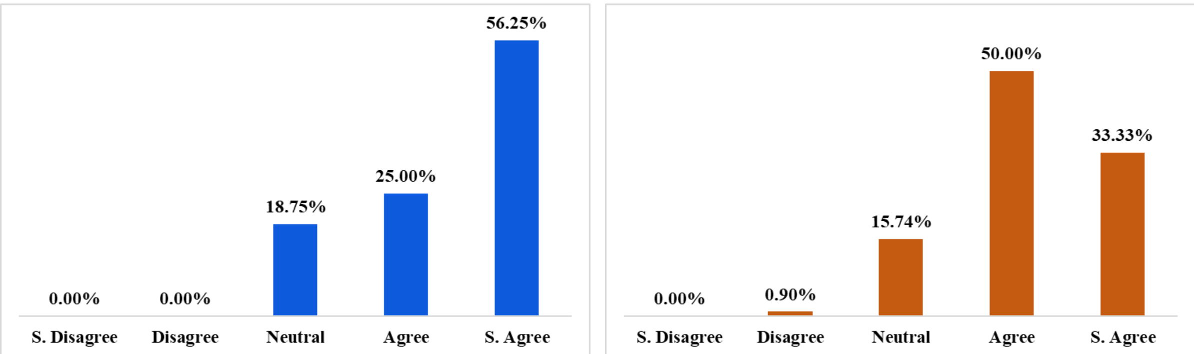
Figure 6. Application of BIM for Better Communication and Collaboration



(a) (b)

Figure 7. Application of BIM for Better Site Layout Planning

Figure 8 depicts that there is a huge potential in BIM to improve the safety performance of the workers. Safety education and training is the key element to improve safety performance. Worldwide, BIM has been utilized for safety education and training because of its collaboration ability with other techniques like Virtual Reality, Augmented Reality, Game Engine, etc. Therefore 81.25% BIM professionals and 83.33% construction professionals are positive towards the potential of BIM for improvement of the safety performance of the construction workers.



(a) (b)

Figure 8. Application of BIM for Better Safety Performance of the Workers

As the figures indicate, there is an overwhelming majority of the BIM and construction professionals who are aware and supportive of the use of BIM in the field of construction safety management. But it is also observed that a majority of these construction sites do not employ BIM for construction safety management. Thus to understand the gap between the potential expectations of professionals and actual implementation of BIM on the site, further questions were asked to BIM professionals to understand the barriers to the use of BIM for construction safety. Based on the responses, it is clear that 31% BIM professionals have used and 69% have not used BIM for construction safety management. Specifically, BIM for safety management has been used for 'scaffolding location coordination,' 'barricading and logistic movement' and 'proper planning of complex structures using 4D simulation'. Based on the further responses, the following barriers and enablers were found to be significant for the implementation of BIM for construction safety management.

- **Economics of BIM and cost involved:** The first barrier related to the cost of implementing BIM, which involves both the licensing costs of the software involved in the creation of BIM models in safety. Presently in the country, such costs of BIM are perceived to be costly to enable viable implementation of BIM in safety.
- **Lack of skilled personnel in the area of BIM:** The second barrier relates to the dearth of skilled personnel who have knowledge of the BIM tools as well as domain knowledge related to the safety to utilize the potential of BIM in construction safety. Therefore, there is a need for more training sessions to develop skilled BIM personnel along with CSM knowledge.
- **Lack of life-cycle outlook towards safety:** Though concepts like a design for safety are well known in academic circles, the percolation of life-cycle approach towards safety is not yet present in the industry thus acting as a barrier to the tools which promote such thinking. Therefore, promoting the potential of BIM towards life-cycle safety management is a need for the current scenario.
- **Lack of return on investment on BIM:** This argument was commonly heard. The idea of why BIM in the area of safety and does BIM offer sufficient return on the investment in terms of time, personnel and resources in BIM tools acts as a barrier. Though the industry realizes the potential of BIM, they are not sure whether the value added by BIM will be greater than investments in the tools. Therefore, a benefit to ration cost analysis of BIM adoption will help to win the trust of the stakeholders.
- **Use of BIM in construction execution as opposed to design:** The use of BIM in construction planning and execution is not yet achieved in the country. Though BIM platforms are increasingly being used in the design and documentation of construction projects, the use of BIM in planning, execution and in operations and maintenance of the constructed facilities is still at its infancy in the construction industry. Therefore there is a need for developing hands-on sessions for promoting the application of BIM in all the phases of the construction projects.
- **Lack of demand from the client:** This is also a major barrier to the utilization of BIM potential in safety management. Most of the clients/owners of public or private projects are not aware of the benefits of BIM for safety management. Therefore, there is a need for education and training to all the stakeholders related to the project for introducing the applicability of BIM on multiple aspects of the project.

5. DISCUSSION

The safety performance of the industry, organization, and or specific site can be enhanced if stakeholders are concern about the safety on site. Currently, to improve safety performance, the construction industry follows traditional strategies such as paper-based and classroom type learning in safety education and training program (Li et al., 2015), conducting safety meetings, arranging safety talks, providing warnings on unsafe work practices, etc. These are quite necessary strategies to ensure safe working sites. However, these methods should be augmented by BIM-related methods which take into account the entire life-cycle of the project. Therefore, researchers applied and validated the benefits of the integration of BIM along with above mentioned traditional methods for safety performance improvement (Pedro et al., 2016; Zhang et al., 2013). Here, data analysis and results highlighted that Indian construction stakeholders are positive towards the applicability of BIM for CSM. Though the industry realizes that BIM has the potential to improve safety on construction sites, various barriers exist at present which is hindering its adoption in safety management. The primary function of BIM at present is still in the domain of design and documentation of the designs rather than the information management paradigm assisting throughout the life cycle of the project. This study also observed a similar scenario, as only 31% of BIM professionals have used BIM for CSM. Thus, the use of BIM and allied technologies in the area safety planning and management is still not taking off in the Indian construction industry. This also points out that the safety on construction sites is still a secondary objective as compared to the cost and time aspects of the projects (Ng et al., 2005). Though the priorities of the objectives are transforming, they did not transform to such an extent of adopting new technologies to ensure safe construction practices. The costs of investment in BIM related technologies is again proving to be a big barrier further to the above aspects, this supports the finding of Ahn et al., (2016). Such barriers relate to the challenges of the adoption of new technology and products in any context. Thus this research gives some preliminary intuitions on the strategies needed to realize the full potential of BIM and allied technologies in achieving safe construction sites.

6. CONCLUSION

Preventing construction accidents is a global challenge. Therefore CSM becomes a key aspect of overall project management. BIM has the potential as a value-adding paradigm augmenting the traditional safety management methods for the betterment of the safety performance of the industry. This study is a preliminary step in understanding the applicability of BIM for construction safety management. The extant literature in the area strongly validates and advocates the benefits of BIM in construction safety management. This study observed a positive approach of construction professionals and BIM professionals towards the applicability of BIM for CSM in the Indian construction industry. This study also observed BIM implementation for CSM in initial stage of adoption, it reflects that industry realizes the potential of BIM for CSM, but significant barriers exist in terms of economics, priorities, and mindset related to life-cycle outlook on the project, which is proving to be barriers of BIM adoption for safety management. The major contribution of the study lies in the identification of the welcoming approach of construction stakeholders towards the applicability of BIM for CSM. Further, this study provides the initial basis for strategies to enable BIM adoption for construction safety management. Future studies can look at the implementation in various other contexts and countries, which can highlight the key drivers in a context towards technology adoption. The study also exposes the key challenges in terms of imbibing life-cycle principles in the construction safety management of a project.

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AUTOMATIC CONCRETE FORMWORK QUANTITY TAKEOFF USING BUILDING INFORMATION MODELING

Chavanont Khosakitchalert, Nobuyoshi Yabuki, and Tomohiro Fukuda
Osaka University, Japan

ABSTRACT: *Quantity takeoff using building information modeling (BIM) gains more popularity in recent years because of its speed, reliability, and accuracy over the traditional 2D-based method. However, if building elements do not exist in the BIM model, the material quantities cannot be extracted from them. Concrete formwork is a building element that is usually absent from the BIM model because it is a temporary component used during a construction process to form a concrete structure. This makes quantity takeoff of the concrete formwork difficult and time-consuming because construction practitioners have to calculate its quantity manually or have to create a specific BIM model that has concrete formwork for the quantity extraction. The quantity of concrete formwork is the surface area of the formworks that are used as molds. This paper presents a method that automatically calculates the quantities of concrete formwork from the surfaces of reinforced concrete (RC) elements. The RC elements, which are foundations, columns, beams, slabs, walls, and stairs, are imported from a BIM model. They are combined and the overlapping regions are removed before extracting their surfaces. Then the surfaces that represent the concrete formworks are selected and the areas are calculated. The validation was done by applying an actual building construction project as a case study. The results show that the proposed method provides the accurate quantities of concrete formwork when compared to the quantities from the 3D model that the surfaces represented the formworks were selected manually. With this method, construction practitioners can get the quantities of concrete formwork without creating formwork elements in a BIM model or calculating them manually. The time spent on manual calculation or creating formwork models is saved and the human errors are reduced.*

KEYWORDS: *Building Information Modeling (BIM), Quantity takeoff, BIM-based quantity takeoff, Concrete formwork*

1. INTRODUCTION

Quantity takeoff is a process of measuring and calculating quantities of building elements or work tasks in a construction project (Holm et al., 2005). It is an important task in the construction process because the measured quantities are used for several other tasks such as cost estimating, cost control, project scheduling, project management, and material purchase (Firat et al., 2010). Traditionally, quantity takeoff is a manual process that requires construction practitioners' knowledge and effort. They have to measure and calculate different building elements based on 2D construction drawings and their interpretation, which is time-consuming and error-prone (Monteiro and Martins, 2013).

The emergence of Building Information Modeling (BIM) technology introduces a new approach for quantity takeoff called BIM-based quantity takeoff. A virtual building is designed and constructed as a digital 3D model, which carries computable graphics and data attributes in its model elements (Sacks et al., 2018). The quantity of each building model element can be extracted directly from the BIM model. Therefore, BIM-based quantity takeoff provides more reliability, accuracy, and speed than the traditional quantity takeoff method (Bečvarovská and Matějka, 2014; Sacks et al., 2018; Sattineni and Bradford, 2011). However, if some building elements are not created in a BIM model, the quantity of those building elements cannot be extracted.

Concrete formwork, temporary molds that are used to form concrete, is one of the building elements that is usually not present in the BIM model (Olsen and Taylor, 2017). This is because it is a temporary component used during the construction process, which will not exist when the building is complete. Furthermore, there is no specific tool in general BIM software products for modeling concrete formwork (Monteiro and Martins, 2013). Construction practitioners have to measure and calculate the quantity of concrete formwork manually. Otherwise, they have to create a concrete formwork model using alternative BIM elements to extract its quantity from the BIM model. Both methods are time-consuming and error-prone, especially in a large scale building in which the geometry of concrete formwork is complex.

The objective of this research is to develop a new method that automatically calculates the quantity of concrete formwork from any structural BIM model. The main contribution of this paper is to propose a method that can calculate the quantity of concrete formwork from a BIM model that does not contain formwork elements. The quantity of concrete formwork is measured as its surface area (Royal Institution of Chartered Surveyors (RISC), 2012). The surface area of the concrete formwork can be measured from the surfaces of the reinforced concrete (RC) elements that the formworks are applied to. For example, the area of the formwork for RC columns is equal to the area of the vertical surface of the column. The proposed method imports RC elements from a BIM model, which are foundations, columns, beams, slabs, walls, and stairs. The algorithms will combine and remove the overlapping regions before extracting their surfaces. Then the surfaces that represent the concrete formworks are selected and are calculated their areas. The proposed method is validated using an actual building construction project as a case study. Finally, the results are discussed and the conclusions are summarized.

2. LITERATURE REVIEW

2.1 BIM-based quantity takeoff in practice

Since the appearance of BIM technology, quantity takeoff using BIM gains more popularity in recent years. Ideally, BIM-based quantity takeoff is faster and provides more accuracy and reliable outcome than the traditional method (Sacks et al., 2018). However, some studies investigated the issues and limitations of the BIM-based quantity takeoff in practice. A study by Firat et al. (2010) concluded that to perform quantity takeoff straightforwardly, the guidelines for making the appropriate BIM model should be applied. Smith (2014) examined the use of BIM for project cost management in the construction industry. He reported that inadequate or incorrect information in the BIM model is a major issue that all firms are concerned with. Sattineni and Bradford (2011) reported that contractors cannot use most of the BIM model received from architects and engineers for cost estimation purposes because the models do not contain all the necessary information. Olsen and Taylor (2017) reported that up to fifty percent of the data needed for quantity takeoff is absent from BIM models. Concrete formwork is one of the elements that are usually absent.

2.2 Concrete formwork quantity takeoff

The focal building element in this research is concrete formwork. As mentioned in the section above, because concrete formwork is usually absent from BIM models, there are two solutions to deal with the issue.

The first solution is to measure and calculate the quantity of concrete formwork manually. The quantity of concrete formwork is measured as its surface area, and the measurement unit is the square meter (Royal Institution of Chartered Surveyors (RISC), 2012). According to RISC (2012) and Packer (2016), the area of concrete formwork can be measured from the surfaces of the RC element that touch the formworks. For the RC foundations, RC columns, and RC walls, the formwork is measured from the side surfaces of the RC elements. For the RC beams, RC slabs, and RC stairs, the formwork is measured from the side and the soffit surfaces of the RC elements. Furthermore, the intersected surfaces, such as the surfaces of beams that intersect with slabs or the surfaces of columns that intersect with beams, must be subtracted during the calculation. Fig. 1 illustrates the surfaces of the RC elements that are used to measure the area of concrete formworks.

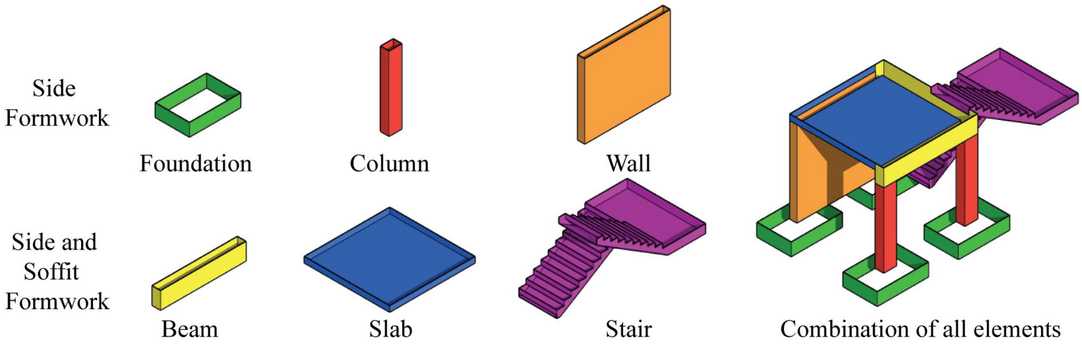

Fig. 1: The surfaces of the RC elements that are used to measure the area of concrete formworks.

The second solution is to model the concrete formworks in a BIM model and then extract their quantities. This solution requires extra time and cost to develop the BIM model. However, this solution is not straightforward since there is no direct tool for modeling concrete formwork in the BIM model and the modeling time is approximately doubled when the formwork is modeled using alternative tools (Monteiro and Martins, 2013). Furthermore, surface areas of RC elements extracted from a BIM model cannot be used as surface areas of the formworks. This is because if the RC elements intersect each other, the formwork is overestimated (Monteiro and Martins, 2013).

2.3 Related research

Several studies have been done to improve the quantity takeoff of concrete formwork using the capabilities of BIM. Meadati et al. (2011) developed a concrete formwork repository through BIM, which can be used for visualization, material takeoff, design analysis, constructability analysis, and shop drawing production. They found that the lack of formwork modeling tools in BIM software increases the 3D model development time. Kannan and Santhi (2013) developed concrete formwork components and apply them to a high-rise building BIM model. The limitation of their formwork components is the cut-outs or opening in structural concrete elements are ignored by the formwork components, which cause inaccuracy when extracting their quantities. Lee et al. (2017) develop a labor productivity measurement method for structural formwork. They exported dimensions of structural concrete elements from a BIM model and calculate areas of the formwork by using calculation formulas. Singh et al. (2016) and Singh et al. (2017) proposed the utilization of application programming interface (API) and calculation algorithms to automatically create formwork models for concrete walls in a BIM model. Cho and Chun (2015) proposed an automatic quantity takeoff system for concrete formwork. Their system utilized dimensions and areas information from structural concrete elements in a BIM model and calculate the quantity of formworks through their algorithms. However, each structural concrete element is processed separately. Therefore, the areas that the structural concrete elements intersect each other are excess.

To summarize, some studies created concrete formwork components in a BIM model using manual or automatic method to achieve quantity takeoff. Other studies developed algorithms to calculate the quantity of concrete formwork from structural elements in a BIM model. Nevertheless, almost all studies do not consider the intersection area of concrete structure, which can cause the excess material quantity when calculating the formwork areas.

3. PROPOSED METHOD

This study focuses only on the RC elements that are cast-in-place concrete elements, which require concrete formworks on a construction site. The possible RC elements that can be cast-in-place concrete elements are foundations, columns, beams, slabs, walls, and stairs. The explanation of the proposed method is divided into two main parts. The first part is the method for finding the formwork surfaces. The second part is the method for classifying formworks by element categories and finding the formwork areas.

3.1 The method for finding the formwork surfaces

The first part is to find the formwork surfaces from the RC elements that are cast-in-place concrete. All cast-in-place concrete elements are connected as a single building structure. Therefore, the intersections of all elements should be eliminated before finding the formwork surfaces. The method for eliminating the overlapping regions of building elements is developed from our previous research (Khosakitchalert et al., 2018, 2019). To eliminate all intersections between each RC elements, the RC elements are combined into an integrated geometry. The combination process combines the RC elements into two groups of integrated geometries, which are the group of RC elements that require only side formworks and the group of RC elements that require side and soffit formworks. After that, the surfaces that represent the formworks will be selected from the integrated geometries.

Fig. 2 shows the flowchart of the method for finding the formworks surfaces. The first step is to prepare the building elements for the calculation. The building elements that are foundations, columns, beams, slabs (floors), walls, and stairs are imported from a BIM model. The building elements that do not have a structural property will be filtered out. After that, the building elements that do not have a cast-in-place concrete material will be filtered out. The remaining building elements will be sorted and grouped by the elevation height.

The second step is to find the formwork surfaces from the RC elements that require only side formworks, which are foundations, columns, and walls. All of these elements are combined and converted into an integrated geometry. Then it is exploded into surfaces. The top and bottom horizontal surfaces will be filtered out. The remaining surfaces are the side surfaces that represent the side formworks. However, the surfaces could intersect with horizontal elements, which are beams and slabs. This is because the horizontal elements are not combined with the integrated geometry. Therefore, the beams and slabs are combined and converted into an integrated geometry to be used to check for the intersections with the surfaces. The regions of the surfaces that intersect with the integrate geometry (beams and slabs) will be subtracted. The result is the net surfaces that represent the formworks for foundations, columns, and walls.

The third step is to find the formwork surfaces from the RC elements that require side and soffit formworks, which are beams, slabs, and stairs. All of these elements are combined and converted into an integrated geometry. Then it is exploded into surfaces. The top horizontal surfaces will be filtered out. The remaining surfaces are the side and soffit surfaces that represent the side and soffit formworks. Similar to the second step, the surfaces could intersect with the vertical elements, which are foundations, columns, and walls. Therefore, the foundations, columns, and walls are combined and converted into an integrated geometry and it will be used to check for the intersections. The regions of the surfaces that intersect with the integrated geometry (foundations, columns, and walls) will be subtracted. The result is the net surfaces that represent the formworks for beams, slabs, and stairs.

In the last step, the surfaces that represent the formworks for foundations, columns, and walls from the second step and the surfaces that represent the formworks for beams, slabs, and stairs from the third step will be carried on in the second part of the proposed method.

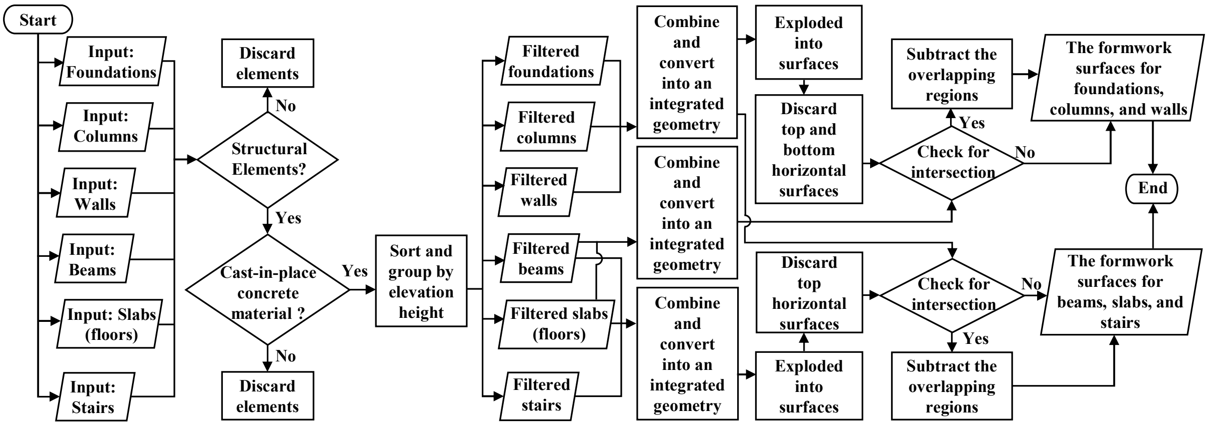

Fig. 2: The flowchart of the method for finding the formworks surfaces.

3.2 The method for classifying formworks and finding the formwork areas

The second part is to classify formworks by element categories and find the formwork areas. The process for each element category is similar to each other. The formwork surfaces from the first part will be used in this part. There are two groups of the formwork surfaces. The first group is the formwork surfaces for foundations, columns, and walls, which is retrieved from the second step in the first part. The second group is the formwork surfaces for beams, slabs, and stairs, which is retrieved from the third step in the first part.

Fig. 3 shows the flowchart of the method for classifying formworks and finding the formwork areas. The first step is to find the area of foundation formworks. The foundation elements from the first part are converted into geometries. These geometries are checked for the intersections with the formwork surfaces for foundations, columns, and walls. The surfaces that intersect with the geometries will be classified as the foundation formwork surfaces. The area of the foundation formwork is then calculated from these surfaces.

The second step and the third step are to find the area of column formworks and the area of wall formworks. These steps are similar to the first step except the input elements. In the second step, the column elements are converted into geometries. In the third step, the wall elements are converted into geometries. The geometries from the second step and the third step are then checked for the intersections with the formwork surfaces for foundations, columns, and walls. The surfaces that intersect with the geometries will be classified as the column formwork surfaces or the wall formwork surfaces. The areas of the column formwork and the wall formwork are then calculated from these surfaces.

The fourth step, the fifth step, and the sixth step are to find the area of beam formworks, slab formworks, and stair formworks. Similar to the previous step, the beam elements, the slab elements, and the stair elements are converted into geometries in the fourth step, the fifth step, and the sixth step. The geometries are then checked for the intersections with the formwork surfaces for beams, slabs, and stairs. The surfaces that intersect with the geometries will be classified as the beam formwork surfaces, the slab formwork surfaces, or the stair formwork surfaces. The areas of the beam formwork, the slab formwork, and the stair formwork are then calculated from these surfaces.

The final step is to find the total area of formworks. The formwork areas from the first step to the sixth step are summed up to form the total area of formworks.

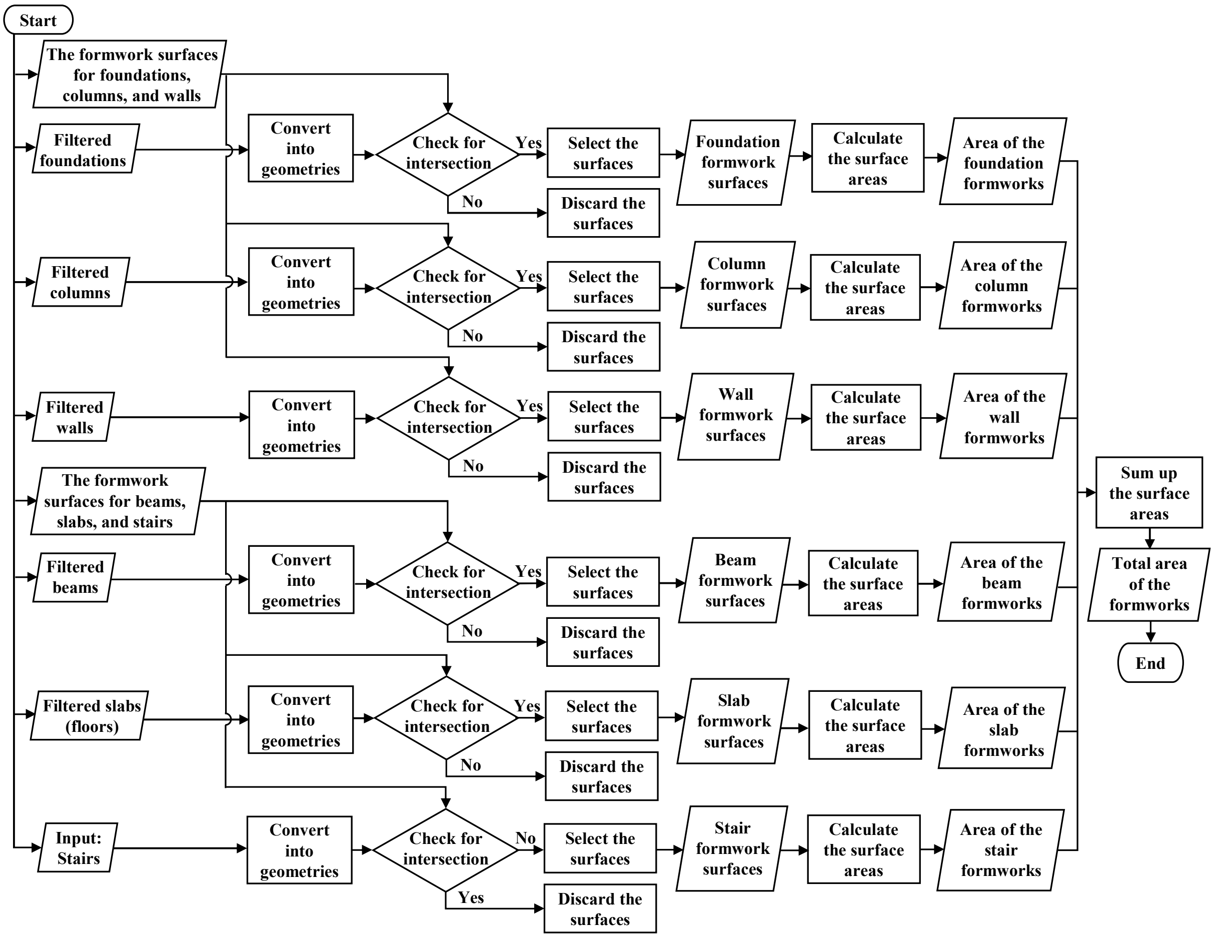

Fig. 3: The flowchart of the method for classifying formworks and finding the formwork areas.

4. PROTOTYPE SYSTEM

A prototype system was developed to test the proposed method. Autodesk Revit 2018.2 and Dynamo 1.3.3.4111, a visual programming extension, were used to develop the prototype system. Fig. 4b shows the formwork surfaces of a simple two-story building that are calculated from the prototype system. The simple two-story building consists of foundations, columns, shear walls, beams, slabs, and stairs (see Fig. 4a). The formworks of each RC element are visualized in separated colors. The formwork area of each RC element is automatically exported to a spreadsheet file.

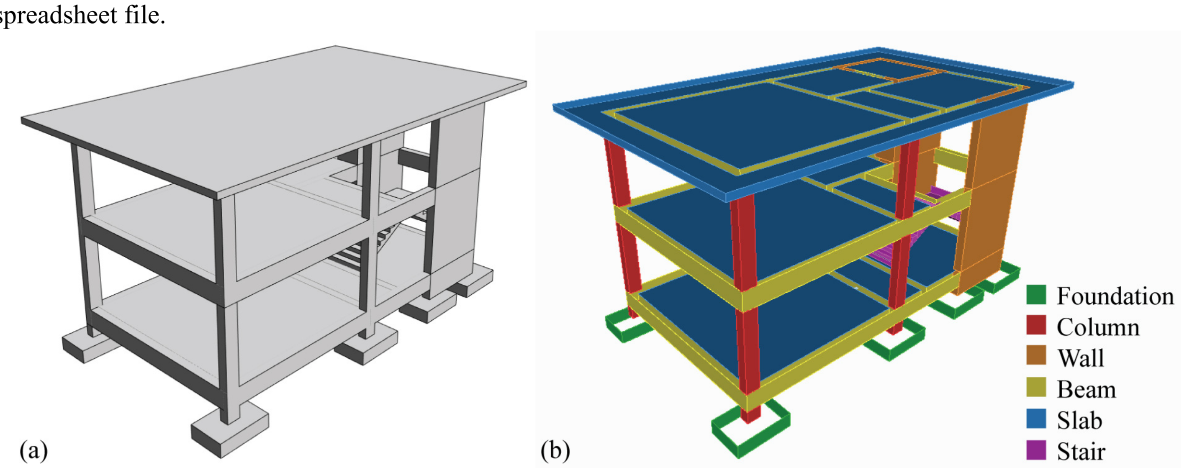

Fig. 4: (a) The simple two-story building model in Autodesk Revit 2018.2. (b) The formwork surfaces of the simple two-story building that are calculated from the prototype system.

5. VALIDATION

An actual construction project was used as a case study to verify the prototype system and validate the proposed method. The construction project is the new building of the Faculty of Architecture, Chulalongkorn University, Bangkok, Thailand. It is an eleven-story building with the approximate total construction area of 4,700 m^2 (see Fig. 5a). The building structure is RC frames, which consists of foundations, columns, shear walls, beams, slabs, and stairs. All RC elements are cast-in-place concrete; therefore, this building is chosen as the case study.

The BIM model of the case study was obtained from the Faculty of Architecture, Chulalongkorn University (see Fig. 5b). It was made by the general contractor of the construction project using Autodesk Revit 2015. Therefore, it was upgraded to Autodesk Revit 2018 before applying the prototype system. The prototype system extracted 2,636 surfaces from the entire model, separated them into different RC element categories, and calculated their areas. Fig. 6a shows the visualization results from the prototype system. Each color on the surfaces indicated the formwork surfaces of each RC element category. The formwork areas of each RC element were exported to a spreadsheet file, which is shown in Table 1.

(a) (b)

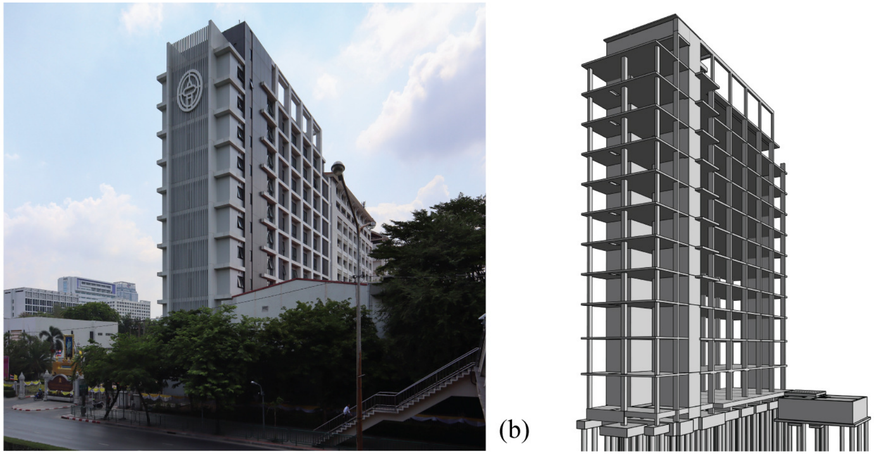

Fig. 5: (a) The case study building, which is the new building of the Faculty of Architecture, Chulalongkorn University, Bangkok, Thailand. (b) The structural BIM model of the case study building.

To examine the accuracy of the proposed method, the formwork areas from the prototype system should be compared with the reliable formwork areas. The formwork areas from the manual calculation done by quantity surveyors were not usable because they calculated formwork areas from a different source, which is 2D construction drawings, and human-errors could occur during the calculation. Therefore, the formwork areas from the prototype system were compared with the formwork areas from the digital 3D model that the surfaces represented the formworks were selected manually. The BIM model of the case study was exported into a digital 3D model. This 3D model was imported into SketchUp 2018 software. The surfaces of the 3D model that represented the concrete formwork were manually painted using different material colors for different RC element category (see Fig. 6b). The intersections between surfaces were carefully checked during the painting process to make sure that there were no excess materials. The area of each material color was extracted from the software and input in Table 1.

Table 1: Comparison of the quantities of concrete formwork between the proposed method and the manual selected surfaces.

Concrete Formworks	Manual Selected Surfaces	Proposed Method	Deviation
	Area (m^2)	Area (m^2)	(%)
Columns	1,359.63	1,359.63	0.00
Walls	3,104.13	3,104.13	0.00
Beams	514.46	514.46	0.00
Floors	4,940.91	4,940.91	0.00
Stairs	253.38	253.38	0.00
Foundations	330.34	330.34	0.00
Total	10,502.84	10,502.84	0.00

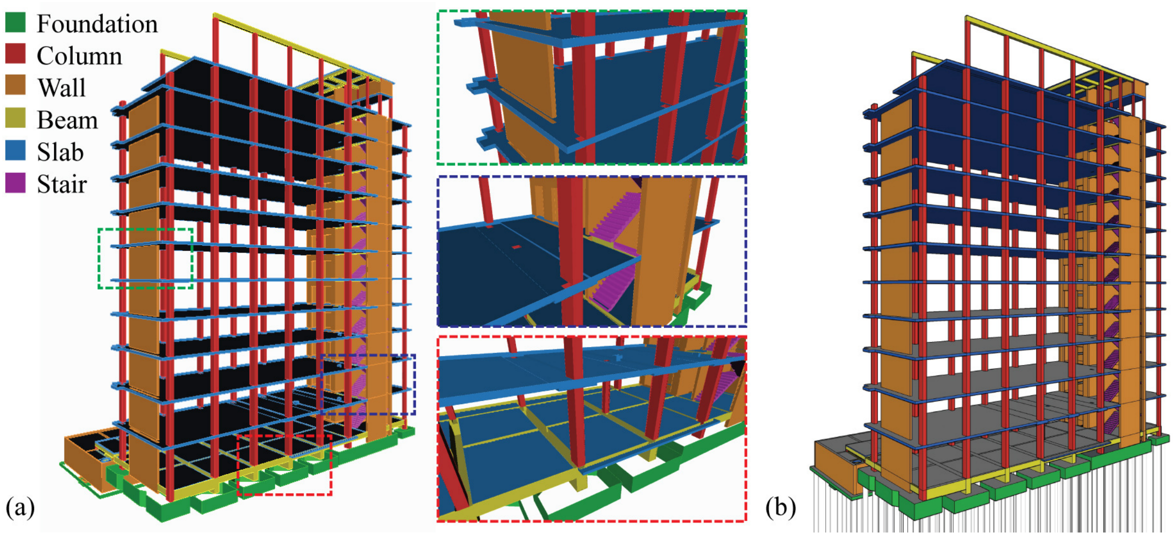

Fig. 6: (a) The visualization results from the prototype system. (b) The 3D model in which the surfaces represented the formworks were selected manually.

The result from Table 1 shows that the quantities of concrete formwork from the proposed method are equal to the quantities of concrete formwork from the manual selected surfaces. It can be confirmed that the automatic algorithms select the correct surfaces and calculate the accurate quantities of concrete formwork.

6. CONCLUSION

Concrete formwork is a temporary component that usually absent from a BIM model and hence it is impossible to directly extract its quantity from the model. This paper presented a method to automatically calculate the quantities of concrete formwork from the surfaces of the RC elements that touch the concrete formwork. The proposed method imports RC elements from a BIM model and filters out the elements that are not cast-in-place concrete. Afterward, the RC elements are combined before extracting their surfaces. The purpose of this process is to remove the overlapping surfaces of the RC elements because, in actual construction, the cast-in-place concrete elements are connected as a single piece of a concrete structure. The extracted surfaces are then classified into each RC element category. Finally, the surface areas are calculated from these surfaces.

The validation was done by using a new building of the Faculty of Architecture, Chulalongkorn University, Bangkok, Thailand. A structural BIM model made by the general contractor was obtained from the Faculty of Architecture, Chulalongkorn University. To compare the accuracy of the proposed method, the formwork areas from the prototype system were compared with the formwork areas from a digital 3D model that the surfaces represented the formworks were selected manually. The BIM model was exported to the digital 3D model; therefore, the comparison was based on the same geometric model. The results showed that both quantities of concrete formwork are equal and hence the proposed method is validated.

With this method, construction practitioners can obtain quantities of concrete formwork from a BIM model that does not contain concrete formwork elements. They do not need to create concrete formwork elements in a BIM model or calculate the quantities of concrete formwork using the traditional method, which is time-consuming and error-prone.

In the future, the proposed method shall be validated with more various designs of buildings. The method for finding formworks from various shapes of RC elements, such as slanted columns, sloped floors, arches, or other complex RC shapes, shall be explored and developed. Furthermore, the formwork surfaces from the proposed method shall be automatically converted to components in a BIM model, which can be used for construction planning or other purposes in a collaborative work environment.

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VALIDATION OF CONSTRUCTION DEVIATIONS USING PARAMETRIC BIM AND AUGMENTED REALITY

Michael Jenewein & Peter Ferschin
Digital Architecture and Planning, Vienna University of Technology, Austria

ABSTRACT: *The use of Building Information Modeling (BIM) in the entire lifecycle of a building is becoming increasingly important. The construction of buildings is quite often deviating from the original planning. Reasons for discrepancies are errors in plans or in the building process. However, constructional modifications from the building phase have to be updated to maintain consistent as-built BIMs, which can also lead to achieve digital twins of built assets. Surveying for building reconstruction is normally done by using total stations, laser scanners or photogrammetry. Planning corrections are performed later on, manually at the office. Possible errors in this process can occur during the data collection, the data transfer and in 3D modeling. To overcome this large effort for manual updating of BIMs we propose a new real-time method based on parametric BIM and Augmented Reality (AR). The fundamental approach is that on-site augmentation of planning data should match the real building situation. Recognizable differences in AR will indicate potential building deviations. Necessary adjustments of the parametric BIM to the physical building structure in AR are performed by using a wireless connected handheld tablet for manual user interaction. BIM by nature is parametric and object oriented. But because of missing interfaces for parametric data exchange directly into AR, at the moment conventional BIM software is not quite adequate for real-time editing of BIMs by using on-site AR. Therefore, the prototypical implementation has been performed using Unity as parametric developing environment and Vuforia as an extension. Precise augmentation is enabled through tracking by use of image targets, multi targets and an AR camera. The proposed method has been developed and tested using a prototype scale model as laboratory environment and could be validated through a real-world industrial use case in the environment of a cement loading facility. The results show that the parametric BIM-AR method is very sensitive to smallest changes of surrounding conditions. But the outcome also demonstrates that on-site tracing of construction deviations using BIM and AR is already possible.*

KEYWORDS: *As-built BIM; Parametric BIM; Augmented Reality.*

1. INTRODUCTION

Building Information Modeling (BIM) has become a basic feature in planning buildings and facilities nowadays and the use of BIM in the entire lifecycle of a building is becoming increasingly important. Referring to (Barlish and Sullivan, 2012) there is a high potential for BIM benefits to be realized. BIM offers a novel approach to design, construction, and facility management in which a digital representation of the building product and process is used to facilitate the exchange and interoperability of information in digital format (Sacks et al., 2018). Building Information Modeling can also lead to the vision of achieving digital twins of built facilities. However, according to (Bolton et al., 2018), it is a challenge bringing together digital and physical realms.

During the construction phase of a building, errors can happen. Discrepancies between planning BIMs and built facilities result in deviations that have to be updated to maintain correct as-built BIMs. This is important for future planning steps and referring to (Nicał and Wodyński, 2016), a warrant for more efficient facility management processes as well as for well-executed interoperability (Pishdad-Bozorgi et al., 2018). According to (Chu, Matthews and Love, 2018), the combination of BIM and AR offers the potential to improve on-site information extraction. Generating BIMs of existing buildings from point cloud data is becoming common practice (Anil et al., 2013). Usually building deviations are measured by use of survey with total stations and laser scanners (Mill, Alt and Liias, 2013), or using photogrammetry (Tuttas et al., 2014). Analyzed patterns of deviations between as-built data and as-planed data result in a manually updated as-built BIM.

Classical surveying for updating of as-built constructions is time-consuming, inefficient and expensive. Because of this, it is important to provide a new real-time method for on-site updating of BIMs using AR technology. Referring to (Wang et al., 2014), the integration of both systems will improve on-site effectiveness.

Standard BIM by nature is parametric as well as object oriented. But at the moment, conventional BIM software does not provide parametric real-time data exchange for interaction of BIMs with on-site AR. Therefore, the implementation for an integrated BIM - AR system is created using Unity as developing environment (Unity, 2018), Archimatix for parametric modeling (Archimatix, 2018) and Vuforia as AR extension (Vuforia, 2018).

2. RESEARCH BACKGROUND

During the construction phase of buildings and facilities errors can occur for a variety of reasons with different effects on the accuracy of the as-built situation. Sources of failure often are errors in plans or in the construction process and decisions of local construction supervisors. However, to maintain a correct as-built BIM, these discrepancies have to be updated. Usually building deviations are measured by surveying using total stations, laser scanners or photogrammetry (Fig. 1).

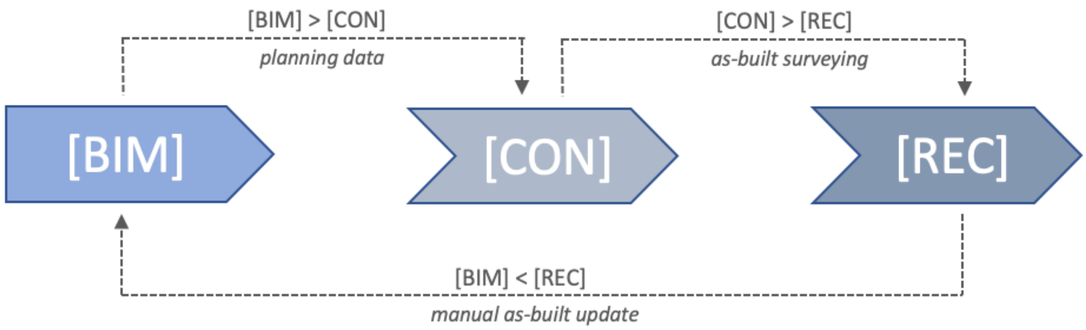


Fig. 1: BIM planning, construction phase and manual as-built updating using classical surveying.

Corrections of the original planning BIM are performed later, manually at the office. Classical survey and manual update take much time and a lot of effort. Possible errors in this process can occur during data collection, data transfer and in the 3D reconstruction phase. To overcome the effort for manual updating of BIMs, a new effective method is needed.

3. PARAMETRIC BIM - AR METHOD

According to (Wang et al., 2013), a conceptual framework for BIM-AR integration enables the comparison of as-built data and as-planed data in real-time. Referring to (Meža, Turk and Dolenc, 2014), the use of AR can significantly narrow the semantic gap between a digital model and the real world.

The fundamental idea in the proposed integrated BIM-AR method is to update BIMs directly after construction phase by using on-site AR technology with the advantage of rapid verification of building deviations.

There are three basic preconditions for developing an effective system for on-site AR reconstruction of BIMs: (1) a data source that can provide parametric model information through real-time data exchange to enable adjustments in AR; (2) a tracking method that can provide on-site information of physical facilities for real-time tracing of parametric BIM data; (3) a user-friendly interface that enables on-site interaction for BIM updating.

As already explained, at the moment standard BIM software is not quite adequate for parametric data export and further use with interactive AR systems. Therefore, additional software tools have to be used for the methodical development of parametric BIM and AR. Augmented Reality can be classified into marker-based and marker-less applications. Existing environments in industry are often unstructured or low contrasted. So, marker-based tracking is more suitable for industrial applications than marker-less tracking. The AR software detects and tracks the features which are found in an image target itself by comparing these features with an already known target resource in the database. Once the image target is detected in a trackable object, the AR software will track the image in the as-built environment as long as it is in the AR camera's field of view. In order to achieve accurate tracking, it is fundamental to have clearly identifiable high contrasted image targets or multi targets as trackable objects. An image target is a trackable object that consists of one image. A multi target is a trackable object made up of multiple images combined in a given spatial configuration. Multi targets can be for instance cuboid shaped objects. Environmental conditions have to be considered very carefully because lighting, wind, fog or dust can interfere the on-site AR process. The correct position and orientation of AR components is essential for accurate tracking between physical world and virtual reality. Therefore, positioning should be performed by using laser measurement.

The approach of the proposed method in this paper is that tracked on-site AR of BIMs should match the corresponding physical building or facility. Recognizable geometric differences in AR will indicate potential construction discrepancies in relation to the original planning model. To achieve an updated as-built BIM these deviations have to be adjusted by tracing and updating of relevant model parameters. The on-site user interaction with the BIM-AR database is enabled by a wireless connected handheld tablet (Fig. 2).

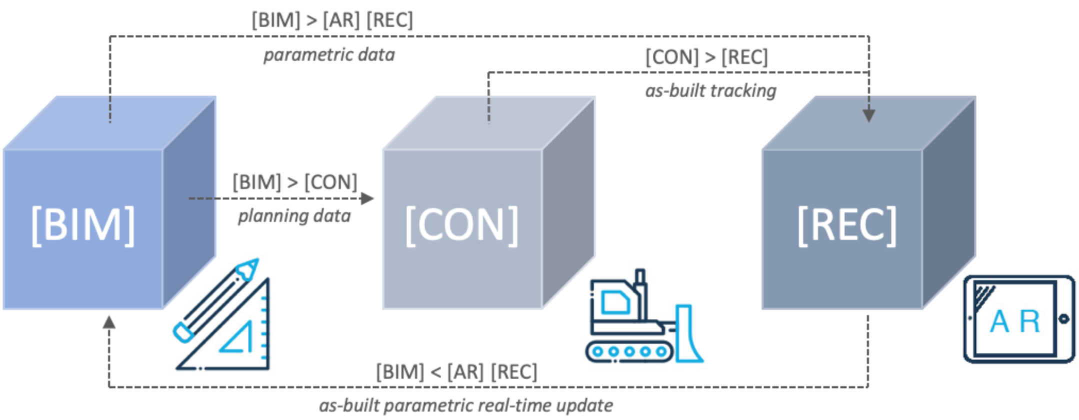


Fig. 2: BIM-AR method for real-time updating of parametric as-built BIMs using on-site AR.

The example below shows a parametric truss girder with construction parameters as length (L), height (H) and number of isosceles triangles with linear distance (D) and represents an exemplary BIM object that can be edited and updated in real-time using AR technology (Fig. 3).

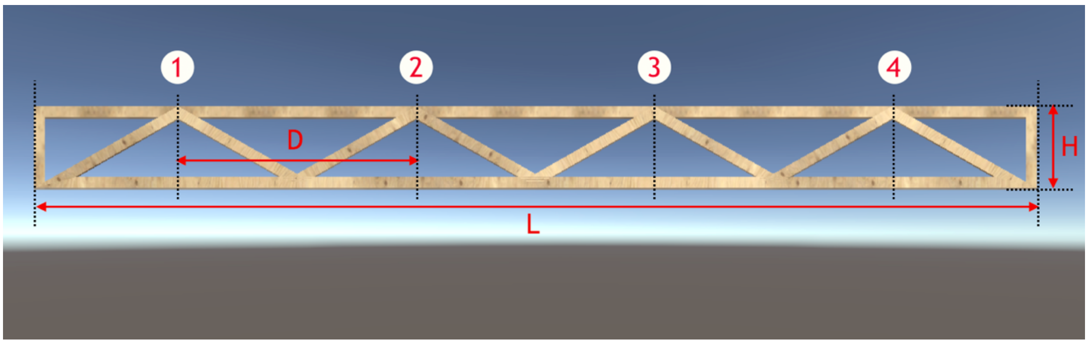


Fig. 3: Parametric truss with parameters length (L), height (H) and number of isosceles triangles with distance (D).

4. PARAMETRIC BIM - AR IMPLEMENTATION

The individual steps of the proposed parametric BIM-AR implementation for real-time updating of planning BIMs have been elaborated using a prototype scale model and were then validated in an industrial use case. The BIM-AR process is based on Unity as parametric modeler, Archimatix as node-based programming tool and Vuforia as implemented AR extension within the parametric Unity database. The scale model use case has been carried out using an image target as trackable object based on the ground plan view of the scale model´s base plate. Contrast plays a major role for accurate AR tracking. To achieve this, the ground plan layout of the scale model was generated by using high contrasted colors for lettering and axes. The environment of the later following industrial use case required a specific multi target as a trackable object. A plain image target based on the low contrasted industrial surroundings would not have worked for accurate on-site tracking. Therefore, a cuboid multi target made up of multiple QR-code images has been used for the industrial use case. This high contrasted cuboid target was mounted on a tripod and allowed exact positioning and orientation in relation to the AR camera and the physical environment. Both image target (scale model use case) and multi target (industrial use case) have been generated using the Vuforia online Target Manager. The parametric BIM-AR database is controlled remotely using a wireless connected handheld tablet running a TouchOSC software (TouchOSC, 2018) and a modified UniDeck extension (UniDeck, 2018) as manual multi touch control surface for parametric adjustments both in Unity editor mode and AR run-time mode. The functional relationship of the individual BIM and AR modules is shown in the following diagram (Fig. 4).

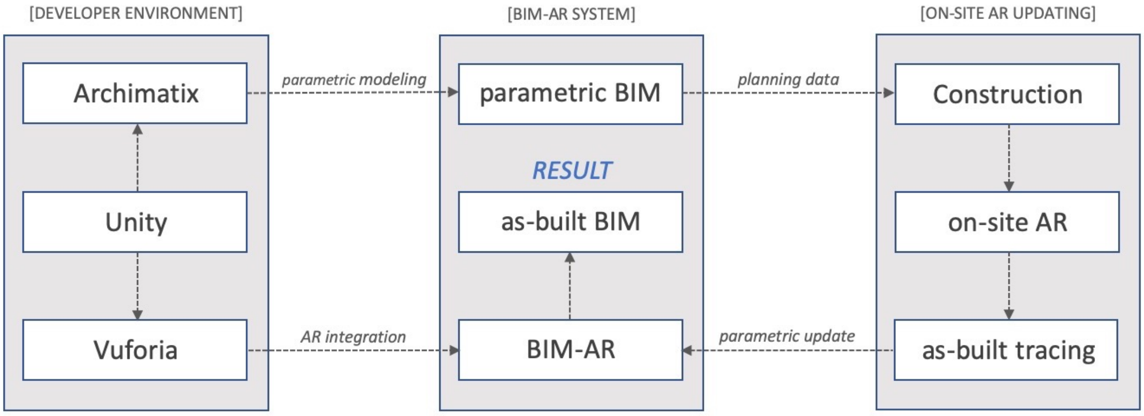


Fig. 4: Modules and graphical illustration of the BIM-AR process based on Unity, Vuforia and Archimatix.

4.1 Model Use Case

The parametric BIM-AR method has been developed, implemented and tested in a laboratory environment of a prototypical industrial building in scale 1:33 1/3. At this scale the dimensions of available scale model making materials such as pinewood columns and truss girders correspond well with real-world constructions (Fig. 5). The model shows a typical conception of an industrial hall based on a grid of 1.5 m with 8 fields on the X-axis (red) and on the Z-axis (green). The axis spacing of the planning BIM is 12.0 x 12.0 m and the zero point (0,0) of the ground plan is at the intersection of axis E and axis 7. The overall dimensions of the scale model are 36.0 x 36.0 x 13.5 cm (equivalent to 12.0 x 12.0 x 4.5 m in real-world scale 1:1).

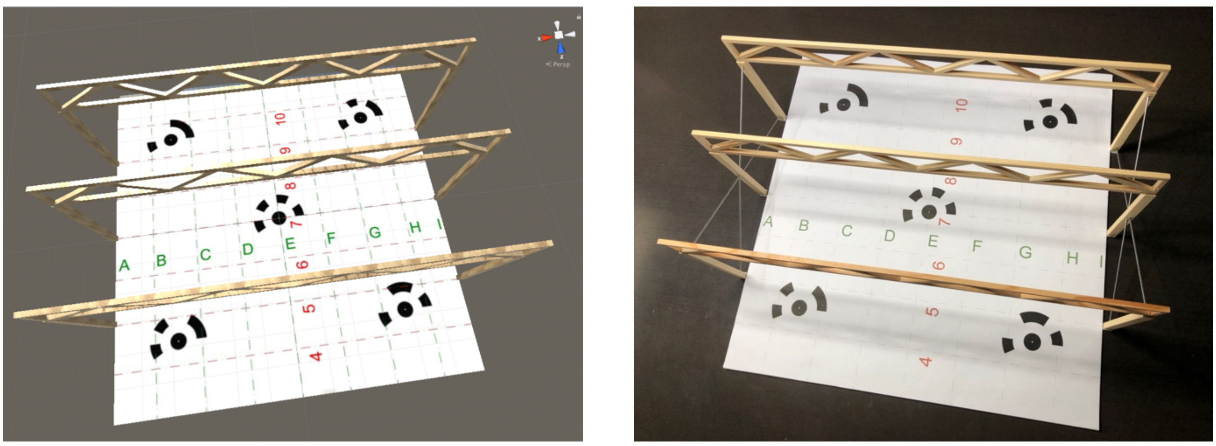
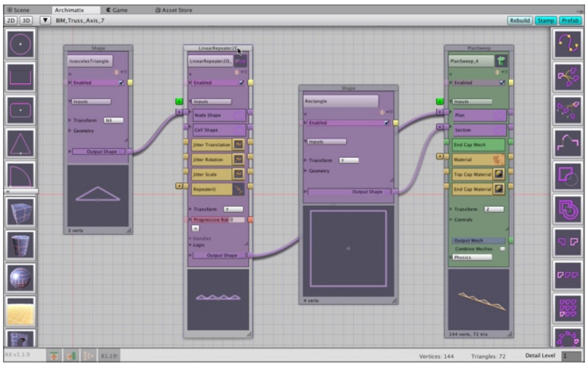
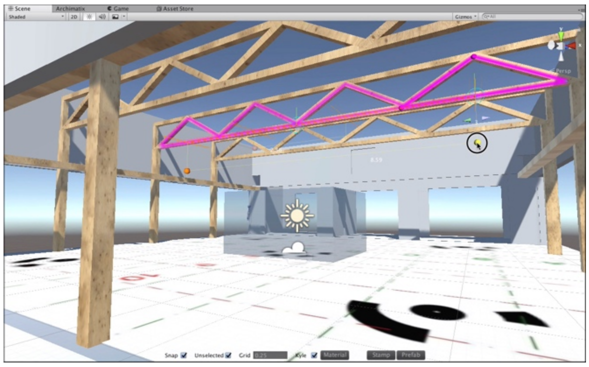


Fig. 5: Parametric BIM in Unity (left) and photo of model in scale 1:33 1/3 with image target trackable (right).

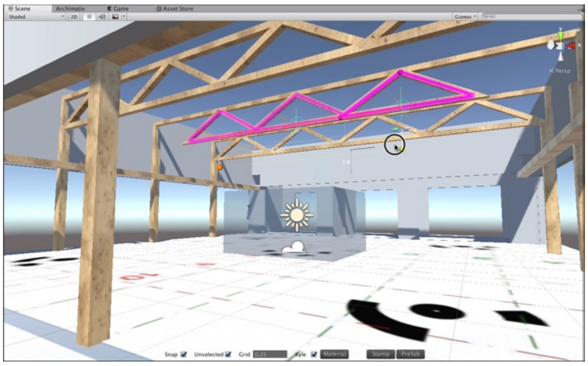
The BIM-AR implementation has been created using Unity with Archimatix as a node-based parametric programming tool and Vuforia as AR extension. Various tests with planar image targets as trackable objects have been evaluated to optimize AR tracking in the prototypical scale model environment. The final image target is based on the ground plan view of the scale model´s base plate. The ground plan layout was generated by using high contrasted colors for lettering and axes. Additional 12-bit markers helped to improve the tracking performance. Surrounding conditions such as lighting and viewing angles have also been tested and evaluated. The conception of the parametric truss girders in Unity editor view with Archimatix as parametric modeling extension is demonstrated by the following images (Fig. 6).



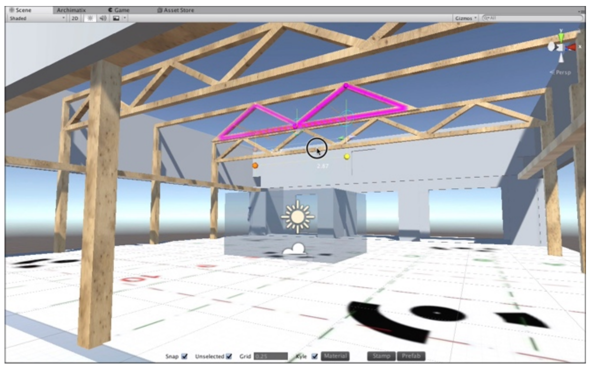
(a) Parametric modeling in Unity and Archimatix.



(b) Parameters: triangles = 4; linear distance = 8.59 m.



(c) Parameters: triangles = 3; linear distance = 5.60 m.

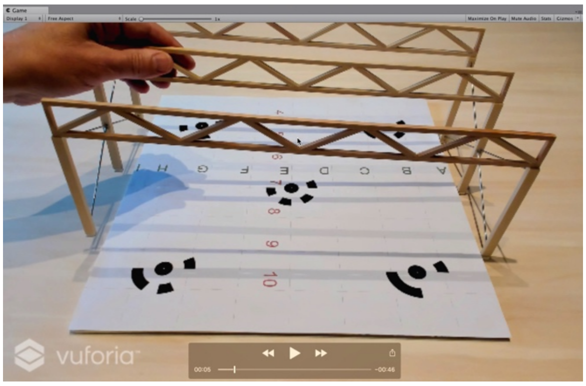


(d) Parameters: triangles = 2; linear distance = 2.87 m.

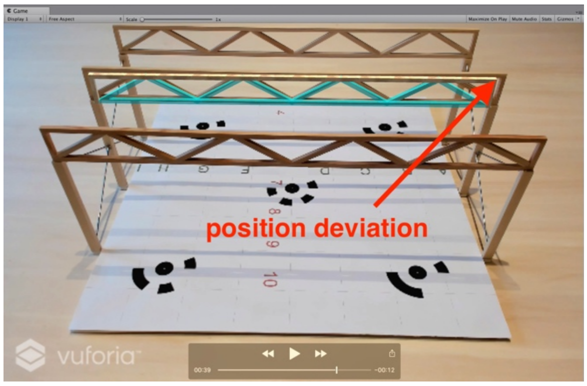
Fig. 6: Conception and parametric editing of a truss girder in Unity and Archimatix developer environment.

The node-based parametric modeling of the truss girders by using Unity and Archimatix is based on isosceles triangles and a 2D linear repeater. The rectangle 3D profile of the individual truss girder components is generated by using a plan sweep extruder tool in Archimatix and linear repeated triangles (Fig. 6a). The parametric truss girder has a span length of 36.0 cm and a height of 3.0 cm (equivalent to 12.0 m and 1.0 m in real-world scale 1:1). The parametric conception of the truss girder´s framework is shown with 4 linear repeated triangles (Fig. 6b), with 3 linear repeated triangles (Fig. 6c), and with 2 linear repeated triangles (Fig. 6d). These relevant parameters as well as the basic position of the truss girder on axis 7 are adjustable both in Unity editor and in Unity AR run-time. Numeric measurements of dimensional deviations can be performed by using the integrated virtual ruler with a zero point and a measuring point based on a distance script. The parametric BIM database is controlled using a wireless connected handheld tablet running a TouchOSC application as manual multi touch control surface for parametric adjustments in Unity editor mode and AR run-time mode. The prototype building in model scale 1:33 1/3 enables to explore simulated constructive errors in the experimental environment based on the parametric BIM-AR system. The verification of simulated scale model deviations has been tested by an incorrect positioned scale model truss girder in relation to the parametric planning BIM. The real-time AR tracing of the truss girder´s position and the geometric deviation of the truss framework is demonstrated by the following images in AR view.

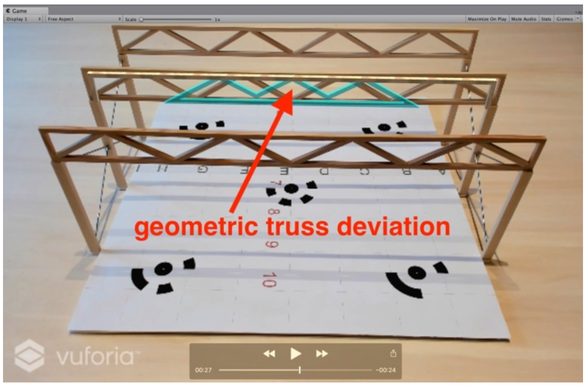
The simulated incorrect position and geometry of the scale model´s truss girder could be validated and updated in AR view with an accuracy of 1.0 mm, equivalent to 3.33 cm in real-world scale 1:1 (Fig. 7).



(a) Merging of scale model and Vuforia AR.



(b) Parameters: triangles = 4; linear distance = 8.59 m.



(c) Parameters: triangles = 3; linear distance = 4.33 m.

(d) Parameters: triangles = 2; linear distance = 2.87 m.

Fig. 7: AR updating of simulated incorrect truss girder position and inaccurate parametric framework geometry.

4.2 Industrial Use Case

An industrial use case in the environment of a cement loading facility has been performed in order to verify the findings of the experimental prototype scale model stage under real world conditions (Fig. 8).

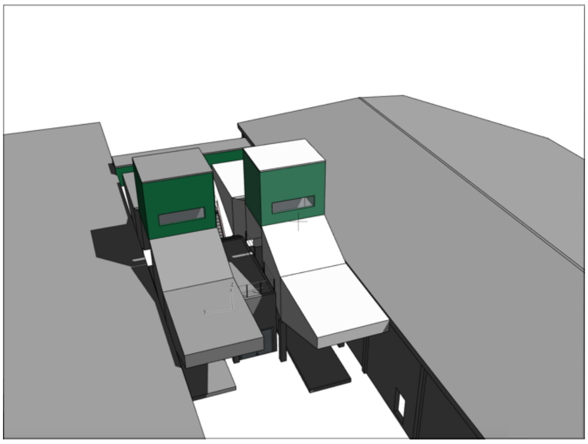


Fig. 8: Basic planning BIM from Archicad (left) and aerial photo with the new cement loading facility (right).

The plant planning concept for the construction of a new cement loading facility represents a good example for deviations after completed construction phase. According to the original planning BIM the additional loading facility on the right side should have the same size and shape as the existing one on the left side. But because of technical requirements during the construction phase, the shape of the filter´s roof has been changed. The planned flat roof of the filter was modified to a pitched roof. Such modifications during construction phase happen quite often in industrial building, and they have to be updated to maintain accurate as-built BIMs.

The parametric BIM for the application in the industrial use case has been generated in three steps: (1) geometric model import from the original Archicad BIM (Archicad, 2019) into Unity; (2) further processing of the import data using Archimatix as node-based parametric modeling extension within Unity; (3) adaption of the generated parametric Unity and Archimatix BIM for use in the Vuforia AR environment.

For better detectability of details in the on-site BIM-AR use case, the parametric model of the new cement loading facility has been textured in Unity using an orthogonal collider structure in green color. Because of the low contrasted concrete surfaces in the industrial surroundings, a corresponding plain image target would not have been suitable as trackable object. Therefore, a high contrasted cubic-shaped multi target with QR-code images and a dimension of 19.0 cm has been used as trackable object mounted on a tripod. This enabled exact positioning and orientation of the multi target in relation to the AR camera and the environment using a total station (Fig. 9).

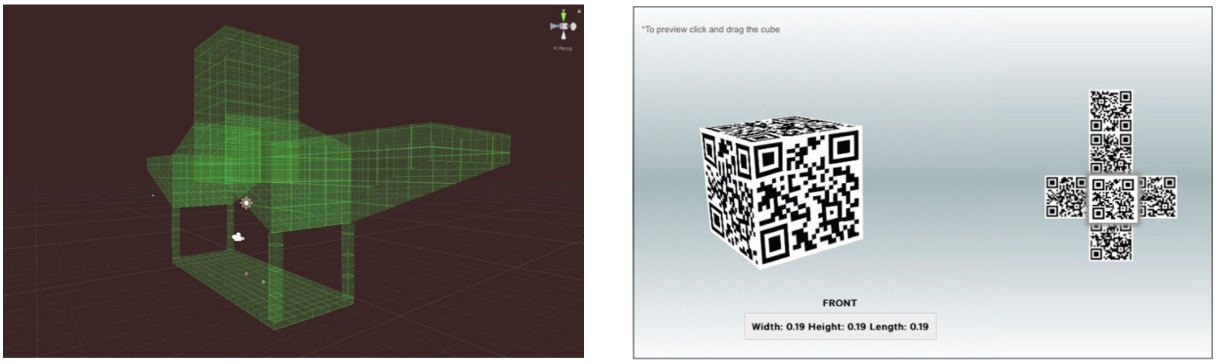


Fig. 9: Parametric BIM of cement loading facility (left) and QR-code multi target as trackable object (right).

Because of ongoing industrial work in progress, the AR setup had to be positioned in a non-critical area of the cement loading facility (Fig. 10).

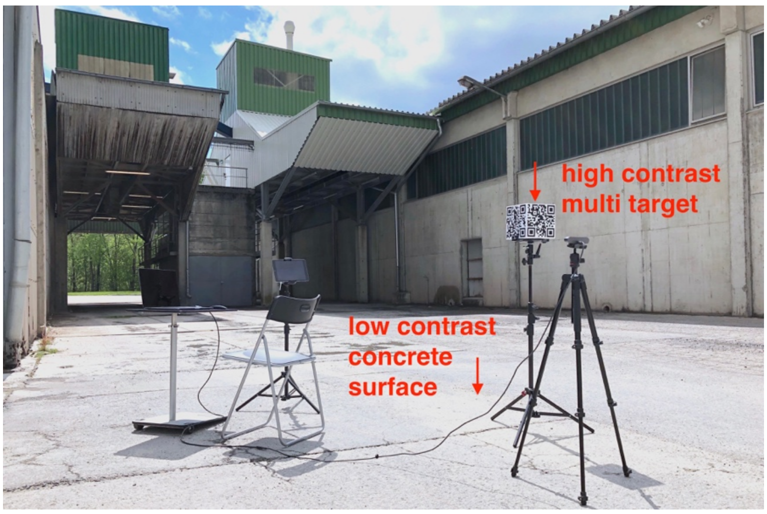


Fig. 10: On-site BIM-AR equipment using the high contrasted cubic QR-code multi target as trackable object.

The visible differences of the right loading facility in relation to the planning BIM in AR view indicated a roof deviation of the upper filter. The originally planned flat roof was modified to a slightly pitched roof. The on-site AR updating of the changed roof construction could be successfully carried out by use of a wireless connected handheld tablet running a special TouchOSC application as manual multi touch control surface for updating the parametric BIM database in Unity and Vuforia (Fig. 11).

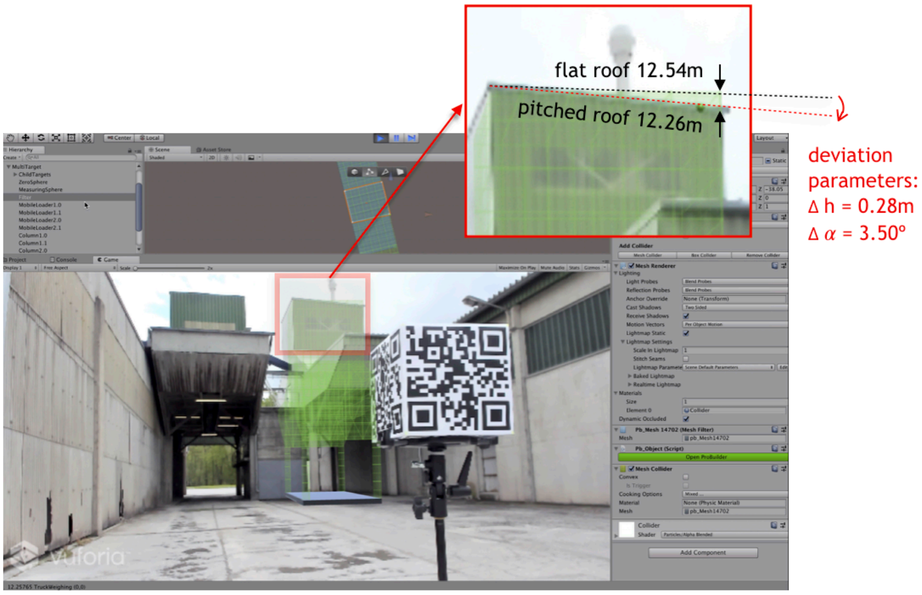


Fig. 11: AR real-time updating of the original planning BIM with a flat roof to the as-built pitched roof.

In spite of complicated conditions in regard of positioning the AR multi target trackable and sudden changes of lighting and wind that brought the cubic trackable to vibrate on the tripod, the AR tracking and validation of construction deviations worked in principle. But it took several attempts to achieve accurate tracking and geometry tracing of the parametric BIM. Numeric measurements of dimensional deviations in AR view could be performed by using the integrated virtual ruler. The lower eave of the pitched roof has been measured in AR with 12.26 m. The relevant points of the parametric roof could be traced to their as-built position. The height of the original planned flat roof is 12.54 m. The height deviation between the planned flat roof and the lower eave of the as-built pitched roof is 0.28 m. The angle of the pitched roof could be calculated with 3,50º at the office.

The validation of the industrial use case application was performed by using a Leica TS06 total station. The laser control measurement height of the lower eave is 12.23 m (AR measurement = 12.26 m). The difference of 3.0 cm between AR measurement and total station verification means a quite high accuracy for the on-site BIM-AR system.

5. RESULTS AND DISCUSSION

The proposed parametric BIM-AR method for on-site updating of planning BIMs has been developed in two phases. First the basic BIM-AR components have been developed, integrated and tested in a laboratory environment by use of a prototypical model in scale 1:33 1/3. Then the findings of the experimental model phase have been applied and validated under real world conditions in an industrial use case.

The simulated errors in the scale model phase could be updated by use of the BIM-AR method with an accuracy of 1.0 mm (equivalent to 3.33 cm in real-world scale 1:1). The height deviation between the planned flat roof and the as-built pitched roof in the industrial use case BIM could be updated with a validated accuracy of 3.0 cm. This means a quite high accuracy for the proposed BIM-AR method.

Despite of difficult outdoor conditions and limitations as for instance changing of light or wind, ongoing industrial traffic or low contrasted surrounding materials, the on-site AR tracking and parametric BIM tracing of construction deviations worked quite well. But the right setup on the location is very important and must be watched carefully.

There is still room for further software improvements (parametric BIM interfaces, BIM-AR integration, etc.) and hardware improvements (AR cameras, AR tracking objects, etc.). Special online platforms already offer services for BIM to real-time 3D (Unity Reflect, 2019) and publishing of BIMs for real-time use (Tridify, 2019).

Recent studies show differrent approaches for on-site BIM and AR combination. A current case study approach is to visualize two-dimensional print projects with the help of AR (Protchenko, Dąbrowski and Garbacz, 2018). The developed method allows communication in a simple manner, which can lead to improve the on-site effectiveness and preventing the risk of construction errors. Another recent case study is based on an application, which integrates a location-based system (Ratajczak, Riedl and Matt, 2019). Construction information and performance indicators on the progress of tasks are superimposed onto the real-world using AR, while a site manager is walking through the construction site.

The research work presented in this paper differs from both abovementioned studies. To overcome the large effort for manual updating of BIMs after completed construction phase by use of classical surveying, a new real-time method based on parametric BIM and AR is proposed to streamline the process for generation of as-built BIMs. Recent studies and online platforms demonstrate that the importance of on-site integration for BIM and AR has already been detected by other sides.

6. CONCLUSION AND OUTLOOK

The novelty and main advantage of the BIM-AR method proposed in this paper consists in creating a parametric BIM-AR environment for rapid on-site updating of construction deviations. BIM by nature is parametric and object oriented but at the moment, conventional BIM software does not provide adequate interfaces for parametric data exchange to enable real-time adjustments directly with on-site AR. Therefore, the development and implementation in this research project has been performed using the alternative software environment of Unity as parametric modeler and Vuforia as AR extension.

The results show that the BIM-AR system is sensitive to smallest changes of limiting conditions in the surrounding of the AR setup and that it is essential to have a well calibrated AR setup for accurate tracking. Lighting conditions and viewing angles have to be watched very carefully, and the function of AR tracking can be influenced by dust, fog or wind. The remote connection to the integrated BIM-AR system has been carried out by use of a wireless connected handheld tablet as manual multi touch control surface for parametric adjustments. On the construction site, it was sometimes difficult to access a WiFi hotspot, but basically it worked by using a cell phone that was connected to the internet. Nevertheless, it could be demonstrated that AR on-site tracing of parametric BIMs is possible with quite high precision, and numeric measurements of dimensional deviations could be performed directly in AR by use of the implemented virtual ruler based on a distance script.

Future developments in industrial BIM-AR context as for instance parametric data interfaces, advanced AR applications and enhanced AR equipment will help to derive a robust and reliable method and recent research activities even focus on streaming protocols for parametric data exchange instead of common file-based interfaces. In any case, all of this will increase the performance of BIM-AR on-site applications. Another important aspect is that the presented parametric BIM-AR method will not only be applicable in the building industry but also in the production industry with impact and implications for manufacturing facilities. Besides the usage for as-built reconstruction of industrial halls, the method is also usable for production layouts inside of industrial buildings. Such machinery layouts first can be updated and then be optimized using the BIM-AR method. Different variants of layouts can be run through to find an optimized layout for production and logistics. So, BIM can also lead to the vision of achieving digital twins of built facilities and factories. Building Information Modeling (BIM) and Augmented Reality (AR) are key technologies for the future. The combination of both systems will help improving future effectiveness both in building and production. However, it is a great challenge bringing together digital and physical realms in industrial context.

7. ACKNOWLEDGMENT

Our thanks go to Schretter & Cie GmbH & Co KG, Dr. Reinhard Schretter and Dipl.-Ing. Ernst Herzinger. This research work would not have been possible without their support throughout the industrial use case in the environment of the cement loading facility.

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EXAMINATIOM OF PHOTOGRAPHY QUALITY INDEX IN UAV AERIAL SHOOTING FOR 3D RECONSTRUCTION

Takayuki Fujii, Hiroshige Dan and Yoshihiro Yasumuro
Kansai University, Japan

ABSTRACT: *Since the aging of a large amount of infrastructure built during the high growth period has become a problem, the maintenance and management of ICT (Information and Communication Technology)-utilized infrastructure is an urgent matter in Japan. Although UAV is a very promising tool in 3D data generation for existing structures, the operation method for complex 3D structures is ad hoc, and there is no established methodology yet. While SfM (Structure from Motion) of photogrammetry process is a particularly powerful method of 3D digitization with a large number of photographs by aerial photography with UAV, the processing cost is very high, and reworking due to imperfections in aerial photography is a loss substantial. This paper proposes a method to monitor whether aerial photos are suitable for SfM by visual SLAM (simultaneous location and mapping) process in real-time. Visual SLAM is capable of tracking the camera's ego-motion from the captured image sequences, which also uses the photogrammetry principle. We arranged a UAV trajectory that guarantees overlap of aerial images with the shortest path, using mathematical programming. Specifically, for the model of bridge piers, an optimal flight plan is made to comprehensively shoot the subject with the minimum number of times of shooting, and experiments will be conducted to operate as planned while performing visual SLAM. We report on the reproducibility of the scheduled flight path and the evaluation of the indicator which shows the validity of the photography method at the time of the input image photography to SfM.*

KEYWORDS: *aerial photography, UAV (Unmanned Arial Vehicle), visual SLAM (Simultaneously Localization and Mapping), SfM (Structure from Motion)*

1. INTRODUCTION

In Japan, domestic social capital stock intensively developed during the period of high economic growth, and there is a concern that it will deteriorate rapidly in the future. Over the next 20 years, the proportion of facilities over 50 years after construction is expected to increase at an accelerating rate. It is required to maintain and update strategically the infrastructures which are aging all at once (Ministry of Land, Infrastructure and Transport, 2019). In this way, since efficient maintenance management for preventive maintenance is necessary to carry out strategic management and renewal under the constraints of severe financial conditions and lack of engineers, new technology must be introduced and actively used. The Ministry of Land, Infrastructure, Transport, and Tourism promotes the “i-Construction” initiative, aiming to improve productivity through the use of ICT (Information and Communication Technology) and 3D data in the construction, survey, design, planning, construction, and maintenance processes. Among these efforts, data acquisition of 3D terrain using UAV (Unmanned Aerial Vehicle) and SfM (Structure from Motion) is considered to be one of the most crucial technology for promoting ICT and efficiency in the construction industry (Youngjib et al. 2016).

In this study, we examine a method for confirming that the UAV aerial flight plan is capable of shooting suitable for SfM processing. In particular, we prepare a flight plan that captures the subject comprehensively for a pier and carry out the shooting. At this time, we consider a mechanism for checking whether the shooting situation is suitable for SfM in real-time by estimating the movement of the shooting viewpoint in three dimensions using continuously shot images.

2. RELATED WORK

2.1 Optimal flight planning of UAV for aerial photography in structural maintenance

Dan et al. Proposed an optimal UAV flight planning method to cover the target structure by aerial photography, assuming use in the maintenance of structures (Dan et al. 2018). This method consists of two stages. In the first stage, we set the shooting points that minimize the total number of shots while setting lower limits on the number of shots and the angular distance when shooting each wall of the target structure. In the second stage, the shortest route that goes around the shooting points obtained in the first stage is searched. When designing an optimal flight plan for UAV, it is necessary to consider the shape of the target structure and the points at which

UAV performs aerial photography in three dimensions. Dan et al. proposed an optimal flight planning method on a two-dimensional plane as a preliminary step in planning a flight plan in 3D space. This method is equivalent to drafting a flight plan that realizes comprehensive shooting of a vertical wall facing various directions at a constant height.

2.2 SLAM（Simultaneous Localization and Mapping)

Recently, SLAM has been introduced for UAV autonomous flight. SLAM is a technology that obtains information on the surrounding environment from sensors such as cameras and LiDAR, and simultaneously performs self-position estimation and environmental map creation and is often used in autonomous mobile robots. In the case of autonomous flight with conventional UAV, the method of moving by relying on GPS is the mainstream, but it is difficult to apply to the environments where GPS hardly function, such as densely packed structures and under bridges. However, using SLAM has made it possible to fly independently in a non-GPS environment (Alfredo et al. 2018). Engel et al. proposed LSD-SLAM that performs self-localization and environmental mapping on a CPU (Engel et al. 2014). Among Visual SLAM that simultaneously estimates the 3D information of the environment from the camera image alone and the camera's self-position and orientation at the same time, LSD-SLAM directly handles the brightness of the image pixels without using feature points, uses dense information of the image. Then, it is possible to acquire dense 3D point cloud of the scene and thus it is easier to visually confirm the 3D reconstruction results, as shown in Figure 1, comparing to Visual SLAM using feature points.

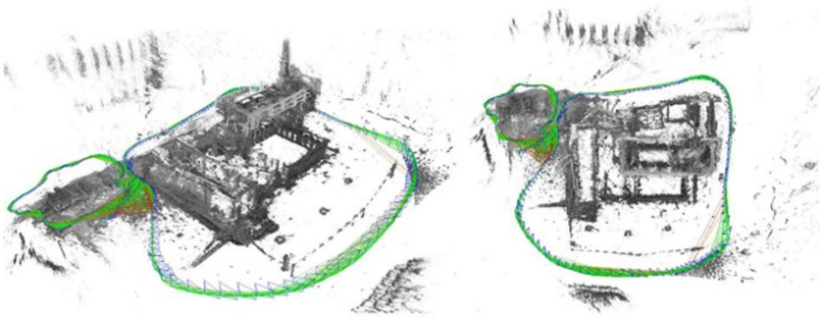

Fig. 1: Example of result during operating LSD SLAM; Gray points are the reconstructed 3D point cloud and green symbols are the estimated camera trajectory

3. METHOD

In this research, we prepare a flight trajectory of UAV aerial photography optimized by mathematical programming and monitor whether or not practical photography for SfM could be performed by visualizing the camera trajectory from Visual SLAM while performing aerial photography. For this purpose, we propose an index to judge the success or failure of UAV aerial photography suitable for SfM. The index is created based on the estimated aerial trajectory extracted from Visual SLAM during UAV aerial photography. Figure 2 shows the configuration of the proposed method. The shooting points and patrol routes planned in the past research 2) are used as a prior flight plan. When performing aerial photography, it is assumed that the UAV is flying while continuously capturing video or still images with the camera, and Visual SLAM for a monocular camera is implemented using the live video. Since Visual SLAM is capable of sequentially capturing the 3D point cloud of the subject during the flight, by performing SLAM processing in parallel with aerial shooting, it is possible to monitor the aerial shooting situation; the shooting point and the traveling route. Also, SLAM estimates the aerial shooting trajectory every frame (1/30 seconds), then the time variation of the trajectory is obtained. So, the collection of the speed variation gives a probability distribution of the speed of the camera motion as schematically shown in Fig. 3. Based on the causality between the motion speed and the 3D reconstruction quality, suitable motion speed can be an index for judging whether the UAV photo shooting is suitable for the 3D reconstruction by SfM or not.

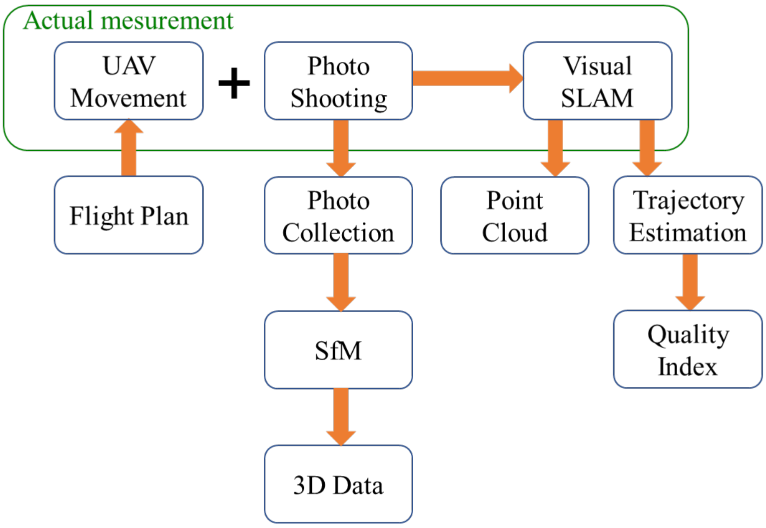

Fig. 2: Process overview of the proposed method

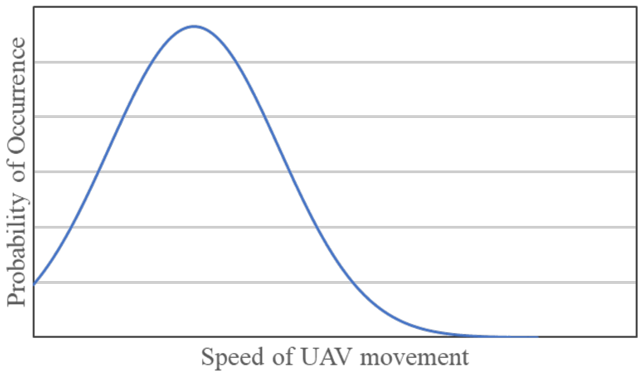

Fig. 3: Expected probability distribution of a UAV speed

4. PREMINARY EXPERIMENT

4.1 Outline

In this paper, as a preliminary step to applying to actual UAV aerial photography, a pilot study is conducted to formulate the index. We plan to shoot a small-scale cylindrical model (see Fig. 4) that looks like a pier, and manually perform monocular photography using a small Web camera according to the plan. When conducting the experiments, shooting is done in two ways: moving the camera at a constant speed and moving it at a variable speed. At the same time, running LSD-SLAM allows confirming the situation of the photographed subject real-time from the obtained 3D point cloud information. In this preliminary experiment, we record all of the SLAM behavior. Then, 3D reconstruction is performed with SfM using the images acquired from the video for each sequence with different speeds, and the relevance with the moving speed of the camera is confirmed. In consideration of the surrounding environment of the bridge pier, the ground around the cylinder was covered with a lawn texture printed (Figure 4 (left)).

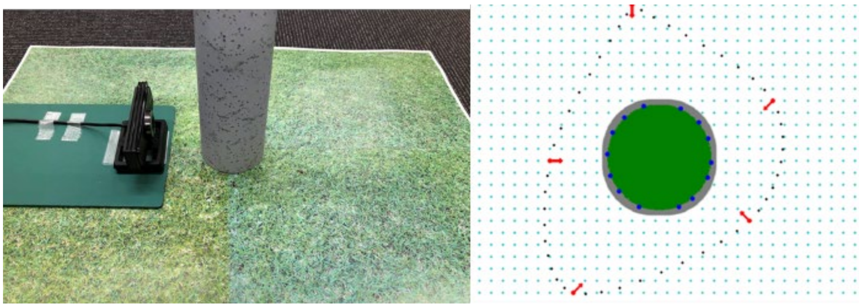

Fig. 4: Experimental setups (left) and prepared trajectory (right)

4.2 Experimental Environment

For the preliminary experiments, a laptop computer (OS: Ubuntu 16.04 LTS, CPU: Intel (R) Core (TM) i7-8750H, GPU: NVIDIA GeForce 1060 6GB, memory: 16GB) with LSD-SLAM3) mounted, USB camera (BUFFARO Inc., BSW200MBK, 2 million pixels, horizontal angle of view 120 °) Connect the camera manually to make it look aerial. The subject was a cylinder (diameter: about 7cm, height: about 21cm) printed on concrete-like texture image and viewed as a bridge pier (Fig. 4 (left)).

4.3 Results

Fig.5, Fig.6, and Fig.7 show the 3D point cloud and estimated shooting trajectory of the object output by LSD-SLAM during shooting. When shooting at a constant speed (Fig. 5 (left), Fig. 6 (left)), the 3D point cloud obtained from LSD-SLAM forms the outline of the subject, but the irregular speed When the image is taken (Fig. 5 (right), Fig. 6 (right)), it can be seen that the 3D point cloud does not form an outline. It can be seen from Fig. 7 that this is caused by failure to estimate the shooting trajectory. Fig.5, Fig.6, and Fig.7 show the 3D point cloud and estimated shooting trajectory of the object output by LSD-SLAM during shooting. When shooting at a constant speed (Fig. 5 (left), Fig. 6 (left)), the 3D point cloud obtained from LSD-SLAM forms the outline of the subject, but the case with variational speed (Fig. 5 (right), Fig. 6 (right)) show that the resultant 3D point cloud does not form any shape of the subject. Fig. 7 shows the failure case of estimated shooting trajectory. Figure 8 shows the model obtained as a result of 3D reconstruction by SfM using a series of captured images. In the model (Figure 8 (left)), which was photographed at a constant speed, the 3D shape of the subject was restored. Figure 8 (right) shows only a part has been restored because the number of input images used in SfM has decreased due to poor feature point extraction for matching between images. Therefore, we calculated the moving speed of the camera between imaging frames from the estimated shooting trajectory and created a histogram showing the distribution (Figure 10). According to this histogram, when moving at a constant speed, the frequency with a speed value close to 0 increases, and the frequency decreases with increasing speed, indicating stable movement. The graph shows that when moving at a variational speed the number of frequencies close to 0 is high, but the frequency does not decrease as the speed value increases.

5. VERIFICATION EXPERIMENT

Based on the results of this preliminary experiment, we created an index to evaluate the shooting trajectory based on the estimated shooting trajectory at the time of successful 3D reconstruction (at constant speed movement) using SfM. Fig. 11 shows the speed distribution obtained from the shooting trajectory when 3D reconstruction was successful. From this velocity distribution, we found that the speed value obtained from the shooting trajectory when 3D reconstruction was successful was included in the range of 0.0 to 0.02 at a rate of 99.999%. Therefore, if the speed value obtained from the shooting trajectory is 0.02 or less, the 3-D shape of the object restored by SfM from the camera frames can be stable. For the case with variational speed, the range of the speed distribution is enormous because a value of 0.02 or more often occurs.

Therefore, it was judged that SLAM would generally operate within the distribution range when 3D reconstruction by SfM was successful. Figure 12 (right) shows the result of the 3D reconstruction of the section where the speed of 0.02 or more occurred using SfM. The feature points could not be matched, and 3D reconstruction could not be performed. From these facts, the values obtained from the distribution created this time can be used as an index for determining the success or failure of UAV aerial photography suitable for 3D reconstruction by SfM.

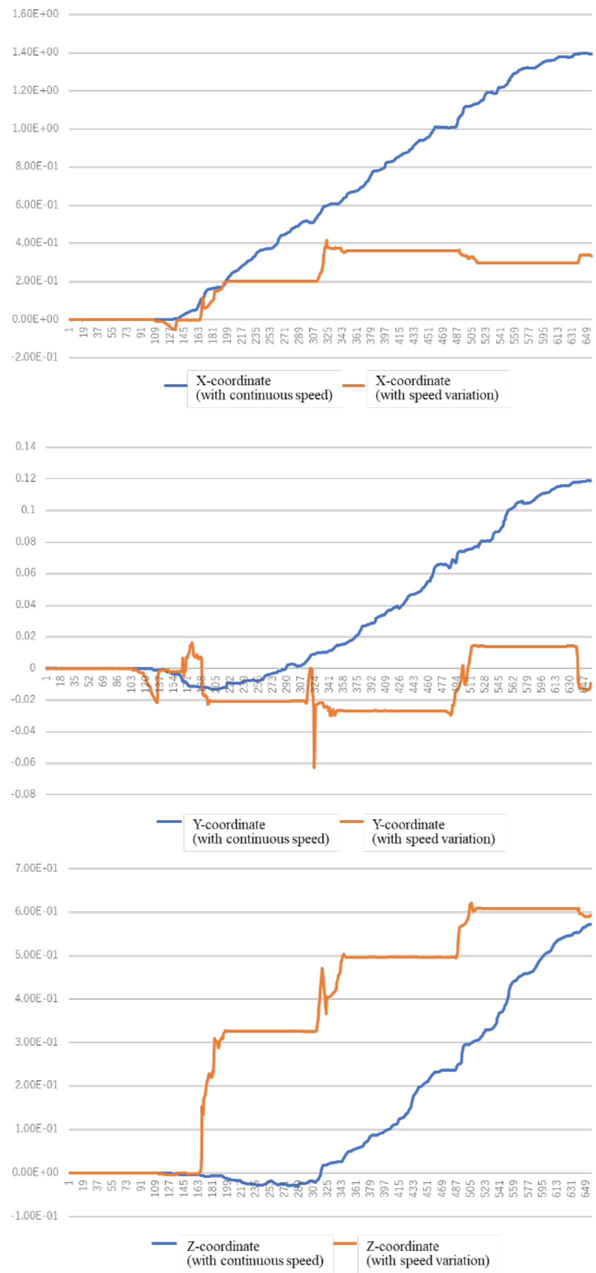

Fig. 5: Estimated camera motion by SLAM

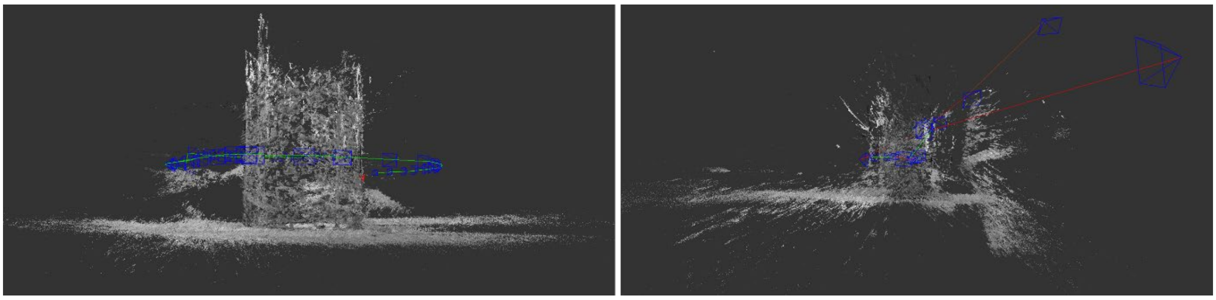

Fig. 6: Side view of the restored 3D point cloud: constant speed case (left) and variational speed case (right)

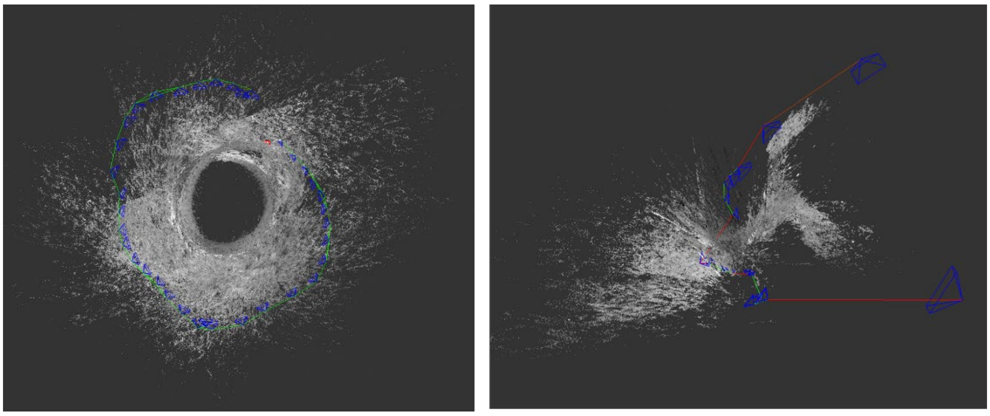

Fig. 7: Top view of the restored 3D point cloud: constant speed case (left) and variational speed case (right)

Fig. 8: Estimated camera trajectory: :constant speed case (left) and variational speed case (right)

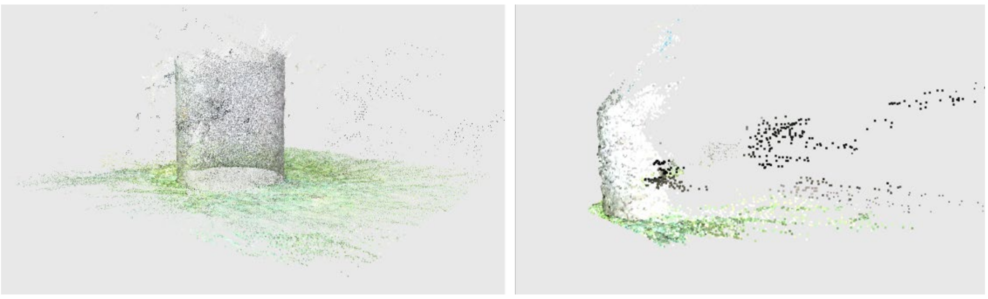

Fig. 9: 3D reconstruction results with SfM: constant speed case (left) and variational speed case (right)

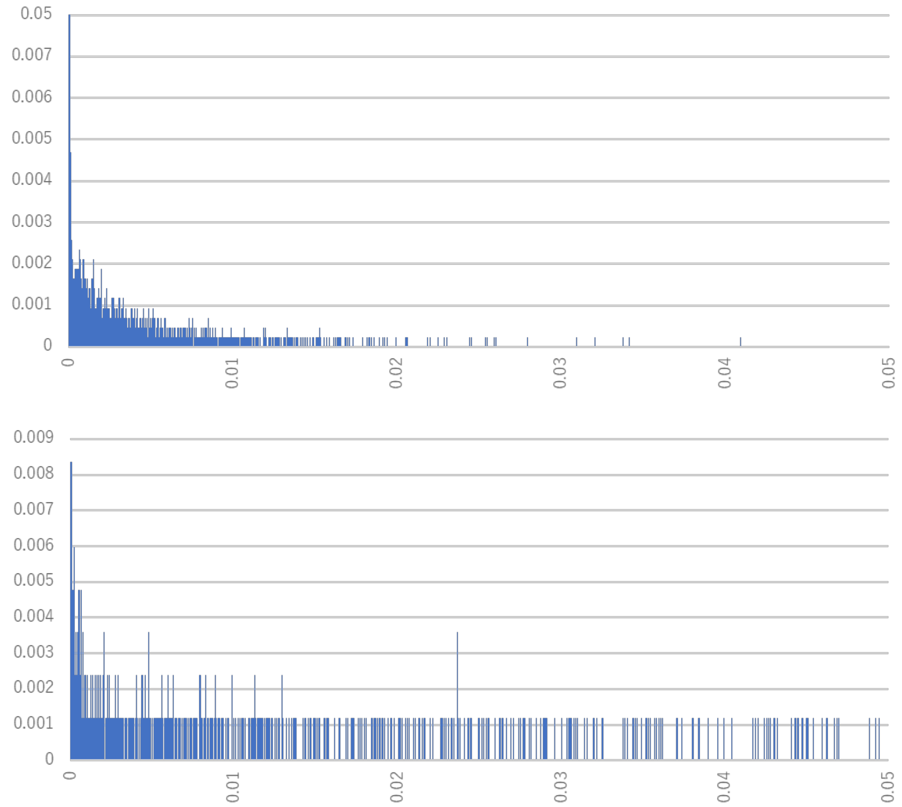

Fig. 10: Distribution of the camera motion speed: constant speed case (top) and variational speed case (bottom)

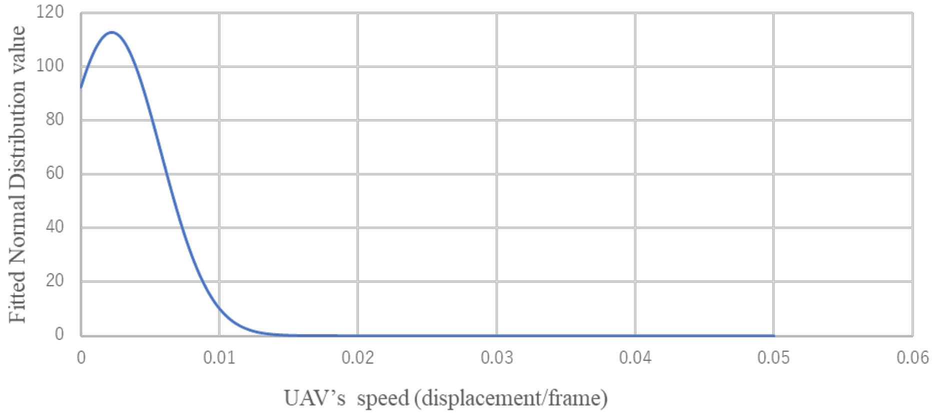

Fig. 11: Parametric representation for the distribution for constant speed case

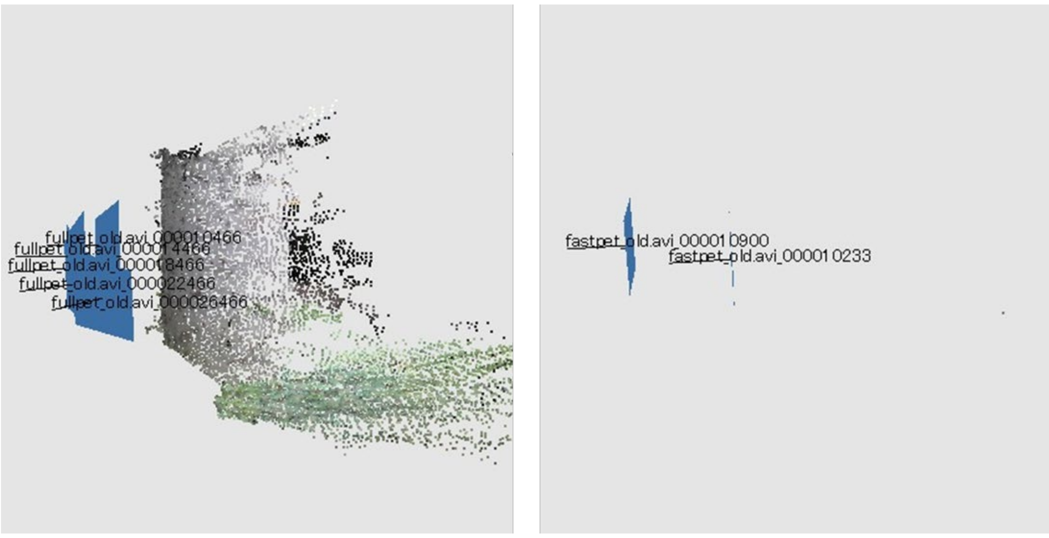

Fig. 12: Comparison of the 3D reconstruction with the same region of the shooting sequences
: constant speed case (left) and variational speed case (right)

6. CONCLUSION

In this study, a standard for evaluating the shooting trajectory in UAV aerial photography for SfM was created from the estimated shooting trajectory and the 3D point cloud information obtained from SLAM. The verification experiment shows that this criterion can be used as an index for evaluating the shooting trajectory. In the future, we will continue to investigate the allowable range of the index based on the data when the 3D reconstruction by SfM fails. Furthermore, we plan to evaluate the shooting trajectory using indices for actual structures.

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2D-3D AR Visualization of Physical Barrier for Wheelchair Users with RGB-D Sensing

Rio Takahashi, Hiroshige Dan, and Yoshihiro Yasumuro

Kansai University, Japan
ABSTRACT: *Since Japan is facing the issue of a rapidly aging society, the number of potential wheelchair users is overgrowing, as more and more seniors need long-term cares. The government has worked on prevailing the barrier-free environment by establishing a law regarding the promotion of smooth transfer for elderly and physically disabled people. Holding the 2020 Olympics is also a vital situation for infrastructure development in Japan. Barrier-free maps, for example, are prepared in many communities, but they cover only existences of facilities, e.g., lifts, slopes, and handrails, in major public institutions. Therefore, they miss the details of physical barriers, such as bumps and width clearances on the path, needed for the independent mobility of the wheelchair users. This paper addresses a method to find out physical barriers by using a depth camera to visualize them efficiently through augmented reality. A depth camera acquires 3D point cloud in the target space and checks the existence of interference between the environment and the volume of an actual wheelchair. The proposed system also performs back-projection of the detected barriers onto RGB color video frames for 2D AR representation. This paper verifies the achieved accuracy of the barrier check by the proposed system, as well as the implementation scheme.*

KEYWORDS: *Wheelchair, Barrier-free, Depth Camera, Point Cloud, Augmented Reality*

1. INTRODUCTION

In recent years, the aging of society has accelerated in Japan, and the proportion of older adults in the national population has increased. As of 2018, the number of elderly people is more than 35 million, and the aging rate is 28.1% (Cabinet Office, Government of Japan, 2018). Globally, the aging rate in the total population is expected to rise from 8.3% in 2015 to 17.8% in 2060, and the world's aging progress rapidly in the next half-century. Therefore, aging society measures must be regarded as a global issue. Also, In Japan, which has the highest aging rate in the world, since the outing rate of elderly is around 60%, it is necessary to improve the environment so that they can go out without hesitation (Ministry of Land, Infrastructure, Transport and Tourism, Japan, 2017). Physical barriers such as bumps and protrusions of equipment are obstacles to living in wheelchair movements that are often used by the elderly. As the new Barrier-Free Law was enacted nationwide in 2006, and now the Tokyo Olympics and Paralympics are ahead in 2020, the newly constructed structures, including public facilities, are becoming more barrier-free. The development of barrier-free maps in each local government is also widespread. On the other hand, barrier-free in existing facilities is difficult to proceed. In addition to the improvement of facilities such as handrails and toilets for the handicapped, expert verification and knowledge are required to discover and resolve detailed physical barriers around us. Therefore, it is difficult to obtain a comprehensive barrier-free map that covers the living environment of wheelchair users. Currently, there are four stages of implementation procedures for examining specific welfare living environment development by care managers (M. Sato, 2011). First, care managers fill out check-sheets to grasp the lifeline of the physically weak, then measure the desired repair location using graph paper or scales and create a floor plan from the measured data. Finally, they take a photo of the current situation not to overlook the checkpoints. This procedure costs a lot of labor and time every inspection. Therefore, barrier verification needs to be simplified for barrier-free promotion.

In this study, we propose a system that can quickly detect physical barriers in familiar environments that are difficult for healthy people to notice. The purpose of this study is to make it easier for facility managers to understand the actual situation and to create a comfortable environment for both wheelchair users and healthy people.

2. RELATED WORK

The authors' group created a 3D model of the space to be verified by using a depth camera to obtain a distance image of the real space as an alternative to taking out the actual wheelchair. By using the 3D information, the interference between the 3D volume occupied by the trajectory of the wheelchair and the target space can be verified on the 2D image projected on the floor plane (R. Takahashi, S. Matsushita, H. Dan, Y. Yasumuro, 2018). While this method can verify the interference between the wheelchair and the space model at high speed, preparation of the 3D model of the site requires high calculation cost, then barrier verification cannot be performed immediately on site. Also, the results of the detected barrier are not easily understandable. The authors proposed a system that detects the interference in realtime by directly using the 3D point cloud data of the real space acquired by a depth camera. In this method, the wheelchair model created in actual size is placed on the floor plane estimated from the point cloud data, and the interference is confirmed by checking the intersection between the volume of the wheelchair model and the point cloud. By moving the depth camera with the hand, highlighting the color of the point cloud of the interference location, the user can immediately confirm the location where the physical interference occurs with the virtual wheelchair. Since this system shows the interferences in a 3D view, precise grasp of the spatial narrowness became possible.

On the other hand, since the angle of view of the depth camera is limited, it is sometimes difficult to associate the range captured by the camera with the actual environment. So, it remains an issue to present the results in an easy-to-understand manner for users who are not familiar with depth cameras..

3. METHOD

3.1 Overview

Many depth cameras on the market are capable of both depth and color (RGB) imaging. They use either type of triangulation or TOF (time of flight) for depth imaging (R. Lange, P. Seitz, 2001). Both types of depth-imaging emit infrared lights and receive them with a camera device for the corresponding wavelength. In most cases, they provide a separate color camera that captures the same range as the depth image separately, and depth and color are associated in advance by pixel calibration. In any case, the depth and color angle of views are the same, or the color camera has a slightly wider angle of view for the specification, and the depth camera has a lower resolution.

This paper proposes a method for enhancing and visualizing the detected barriers against a background of wide-angle visual field and color information in real space for providing a barrier detection function that is easy to understand visually. The area which may be occupied by a wheelchair is focused on the 3D point cloud obtained by the depth camera, and the user virtually installs the wheelchair and moves the camera to determine the presence or absence of interference as a barrier in the 3D space. Also, a high-visibility color AR display is realized by projecting a barrier onto a high-resolution, wide-angle color image obtained from a color camera. Based on the coordinate system of the depth camera, as shown in Fig.1, a plane corresponding to the floor is estimated near the center of the camera field of view, to place a wheelchair model on it. By viewing such AR display of our system while walking with the camera, the user can expect to feel as if the user is pushing and steering the virtual wheelchair from the behind. The processing procedure of the system is as shown in Fig.2.

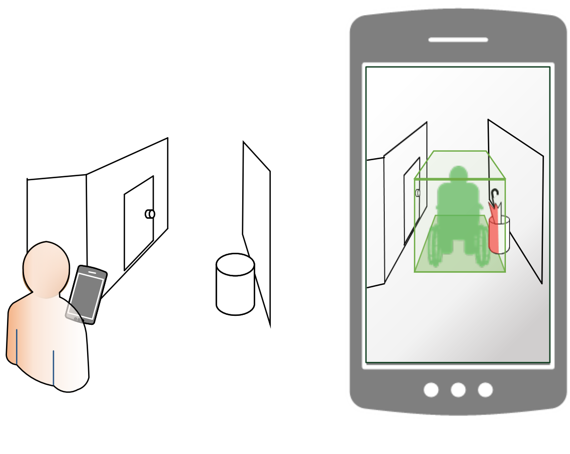


Fig. 1: Schematic image easy-to-use barrier inspection tool

First, the 3D point cloud of space is acquired by a depth camera, and the geometrical relationship between the camera and the floor is acquired by estimating the normal of the floor plane. Next, the system places a wheelchair model of real dimension created from the specifications on the estimated floor surface, and then the location of interference between the model and the point cloud can be detected as a barrier. Also, by taking the pixel correspondences between the color camera and depth camera prepared separately in advance, the barrier information is projected onto the color image in real-time, and finally the 2D AR display is performed with the barrier portion emphasized.

3.2 Process Chain

Using the range imaging by a depth camera, relative geometry of the floor can be captured from the camera's viewpoint in real-time. Instead of bringing a physical wheelchair, a volume model of a wheelchair can be placed on the floor plane. The wheelchair model is represented as a cylindrical shape with a rotation range based on the specifications of the wheelchair. The possible existence volume of the wheelchair is set by placing the cylindrical volume model along the normal on the floor, and the interference point with the 3D points in the real space can be checked by finding intersecting points into the cylinder. This result makes it possible to highlight and visualize the detected barrier part of the 3D points. Since the detected barrier points are associated with the pixels of the depth image, 2D-to-2D transformation, such as homography, enables mapping the barrier information into another image. By using the homography transformation, wide-angle camera frames can be used to 2D AR barrier visualization. The system process mentioned above is as shown in Fig.2.

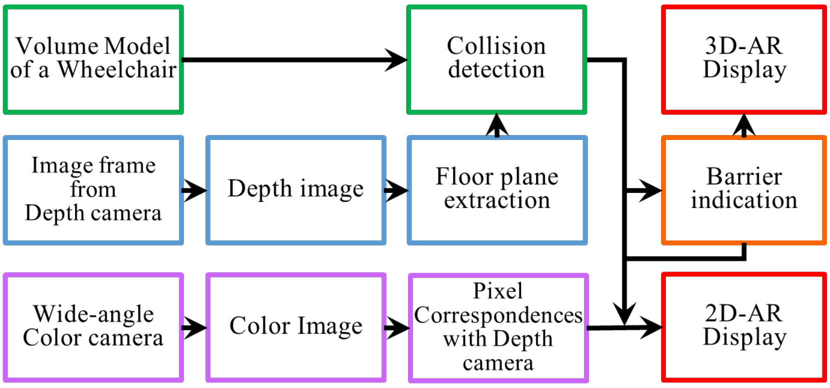


Fig. 2: Process chain

3.3 Floor Plane Estimation

By specifying a rectangular range of M points in length and width from the center of the depth image, the coordinates of the points that lie within this range are sampled for floor plane estimation. RANSAC (Random sample consensus) is employed because outliers in the sample significantly affect the results of the least square method (M. A. Fischler, R. C. Bolles, 1981). First, a plane approximation is performed on the point cloud within the sample range by the least square method, and the normal of the plane is calculated. Next, we randomly classify the sampled points into two groups as the inlier with a probability of n%, and others as the outlier. First, a plane approximation is performed on the point cloud within the sample range by the least square method, and the normal of the plane is calculated. Next, we randomly classify the sampled points into two groups as the inlier with a probability of n%, and others as the outlier. Then, the normal is calculated by plane approximation of the inlier point group, and the root-mean-square error is compared to the initial one. If the plane approximation is improved, current inlier points are adopted and updated. This process is repeated N times, while the points are randomly replaced between the inlier and the outlier points to acquire optimized the planar approximation with reliable inlier point samples. By this process, it is possible to selectively sample the point cloud data that lie on the floor surface, and other points can be treated as the ones lie on protrusions and steps on the floor. In this paper, we implemented with the parameters $M = 25$, $n = 15$, and $N = 1000$ respectively.

3.4 Color Barrier Verification

Fig. 3 shows the procedure for projecting the barrier information detected on the depth image onto the color image and performing AR display. First, we obtain a homography transformation matrix H for projective transformation from a high-resolution color image to the resolution of the depth image by taking multiple corresponding points in advance in the color image and depth image obtained from the color camera and depth camera. Next, each pixel of the depth image is mapped to the 3D space as a 3D Cartesian coordinate point to check whether the coordinate is inside of the wheelchair region. The 3D point that is judged as a barrier part is marked highlighted color with a pixel on the depth image. Then, the pixels corresponding to the barrier portion are highlighted (in red, for example) on the color image, whose size is adjusted to the depth image by applying the homography transformation H to the original wide-angle color image. Also, using the same color image as the background, the wheelchair model is superimposed and drawn with 3D CG to make it easier to grasp the positional relationship between the barrier detection location and the wheelchair model. The color AR image of the depth image size of this rendering result can be converted to a wide-angle color image coordinate system by inverse-homography transformation H, and the AR display is embedded in the wide-angle color image. In this way, 2D-AR display is realized by superimposing the barrier information detected by the 3D information obtained by the depth camera on the surrounding situation by a wide-angle color image.

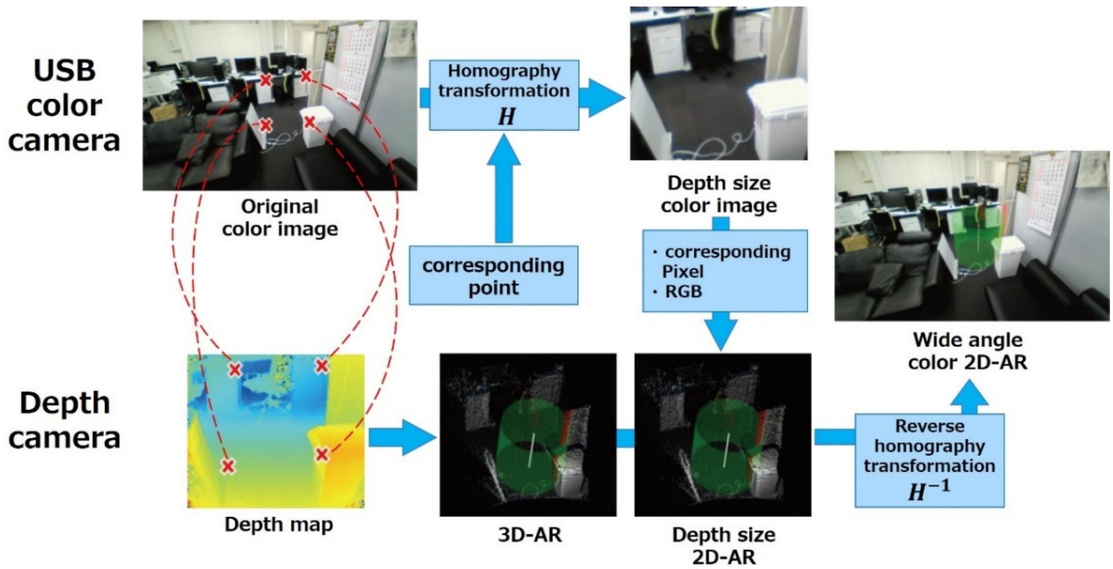


Fig. 3: Process flow for creating Color AR

4. IMPLEMENTATION

In this study, we conducted an experiment targeting indoor living spaces, assuming a barrier verification in the traffic flow of wheelchair users in daily life. We used a BSW200MBK (BUFFALO Inc.) for a color camera which captures 1920x1080 pixels at 30 fps with viewing angle of 120 [deg]. Software integration was done on Visual Studio 2015 (Microsoft), incorporating image processing modules from OpenCV and AR graphical display based on OpenGL library.

As shown in Fig. 4, the user can utilize the proposed system by holding a set of devices with a USB camera fixed on the depth camera, which is facing the floor of the verification target place and connected to the PC. For recording the sequences of the user's view, the verification was performed with the camera mounted on a movable table at this experiment.

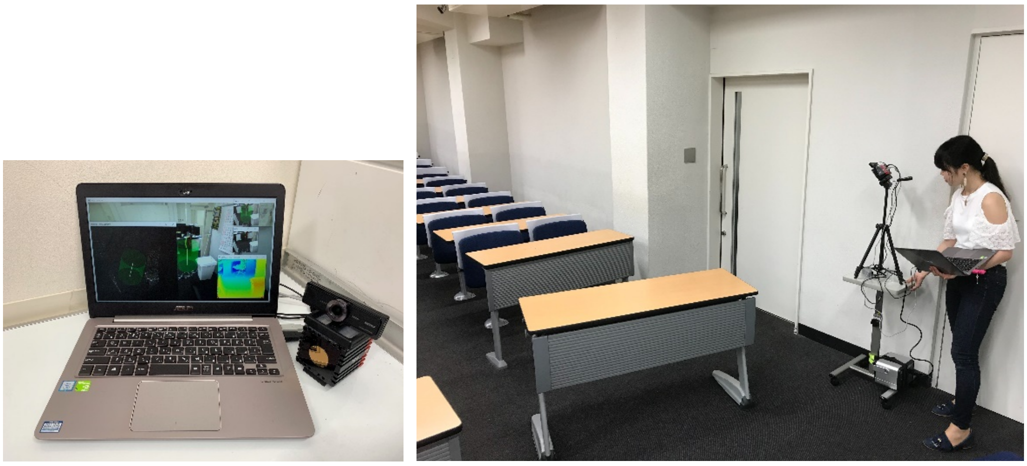


Fig. 4: Device used for implementation

The wheelchair model is a cylinder based on the standard of the Ministry of Land, Infrastructure, Transport and Tourism, and JIS (Japanese Industrial Standard) as shown in Fig. 5, with a height of 130 cm and a turning radius of 35 cm. The transmittance of the model color is set so that the red part of the barrier can be clearly detected in any direction. Besides, these numerical values can be changed immediately even during the verification, and by supporting the model drawing on / off, the number of barrier confirmation methods has been increased to assist the user in the verification method. This system is compatible with the size of the wheelchair user's physique, the type of wheelchair, and the range occupied by the movement.

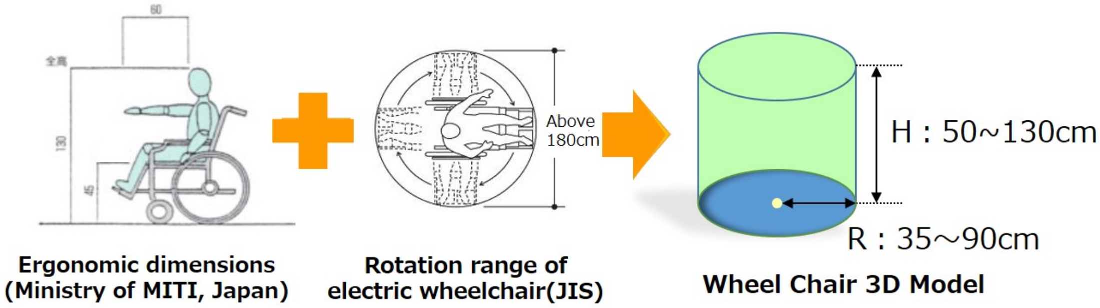


Fig. 5: 3D wheelchair volume model, considering an ergonomic dimensions and industrial standards

The experiment was carried out in the classroom of the university that some wheelchair users actually use. Verification was performed in the passage between the desks and around the desks prepared exclusively for wheelchair users. In each area, data were acquired with the three points ① to ③ as references on Fig. 6 and Fig. 7. Also, in order to consider the use of existing RGB-D cameras such as Kinect and Xtion, we used a USB-connected color camera UCAM-C750FBBK (ELECOM Corp.) with the same angle of view as the color camera built into these devices. The verification of Fig. 6 and Fig. 7 were performed under the same conditions as described above, and the narrow-angle field of view and wide-angle field of view were compared based on live color images. UCAM-C750FBBK obtains a color image with 1024 x 768 pixels, a frame rate of 30 fps, and a viewing angle of 66 [deg]. In the following, UCAM-C750FBBK is treated as a narrow-angle camera and BSW200MBK as a wide-angle camera. The verification results obtained are real-time display at 10 to 20 fps, a 3D barrier verification screen that allows checking the barrier while changing the magnification from an arbitrary angle with a mouse operation, and a two-dimensional display that reflects the results for color AR images are shown by the implemented system.

Fig. 6: Barrier verification area (left：case1, right：case2)

4.1 Passage between the desks

The target classroom is in a school building that is over 50 years old, and the area of the classroom has become narrower than the beginning of construction due to earthquake-proofing work. Currently, the passage between desks is designed not to allow wheelchair users to move, but it is desirable to be able to move in emergency cases. Therefore, the diameter of the wheelchair model was assumed to be an actual width (70cm) assuming that it would go straight, and the height of the model was verified to be 80cm considering the height of the desk. Figures 9 and 10 show the results obtained.

As a result, although traffic is possible, it is not easy to proceed without colliding with the surroundings. Besides, if the situation is an emergency panic, the progress will be even more severe.

Locations that interfered with the wheelchair model were highlighted in red as if they were colored on the actual object, and the positional relationship between the detected barrier and the object in the real space could be determined instantaneously. As shown in Fig.8, approaching to a desk for wheelchair users, the information around the passage is so limited that it is difficult to grasp the spaces between the desks and the chairs. On the other hand, with the wide-angle camera, it was possible to judge the barrier while confirming not only the vicinity of the wheelchair region but also the background of the traveling direction in the classroom.

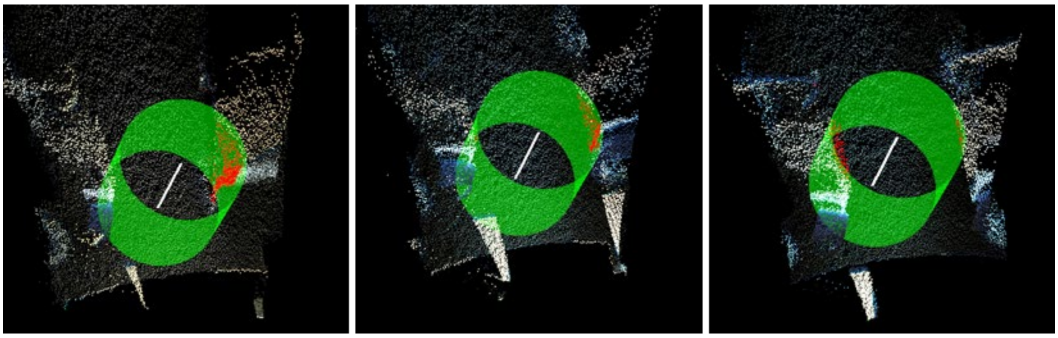
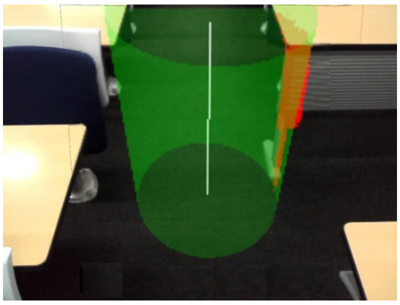
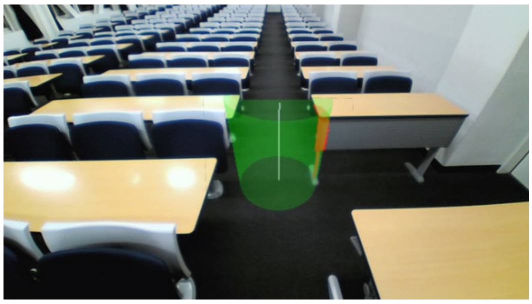
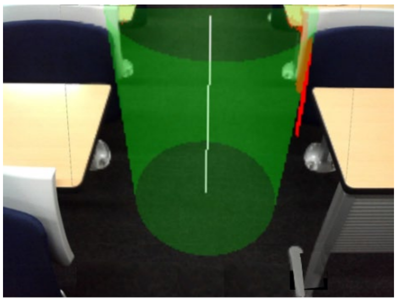
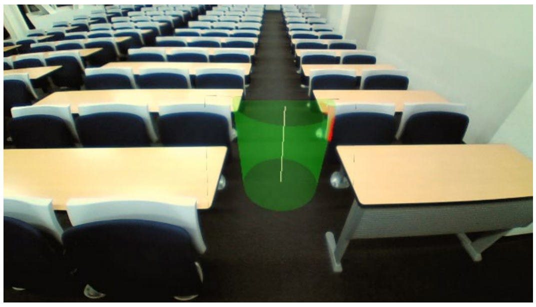


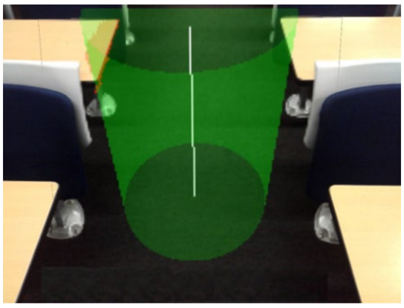
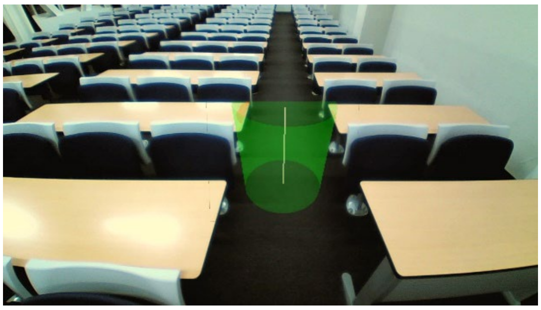
Fig. 7: Barrier check in 3D point cloud in Case 1
(left：position①, middle：position②, right：position③)

a) narrow angle camera：position① b) wide angle camera：position①

c) narrow angle camera：position② d) wide angle camera：position②

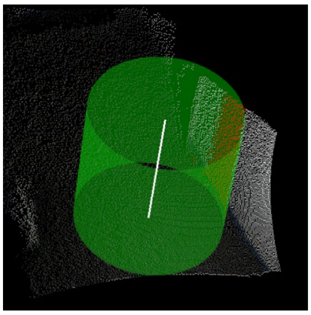
e) narrow angle camera：position③ f) wide angle camera：position③

Fig. 8: Examples of the results in physical barrier extraction around the wheelchair users table

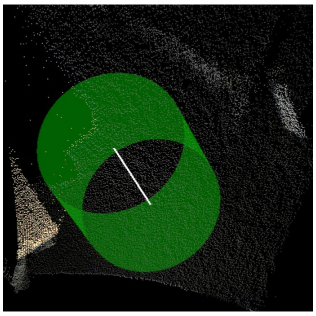
4.2 Around the wheelchair users table

In the classroom, there is a desk for wheelchair users at the closest position to the entrance door. Since this desk is not fixed on the floor, the installation position can be adjusted easily. When actually used, the surrounding healthy people often adjust the desk for wheelchair users. Assuming that a wheelchair user approaches this desk from the entrance, we set the desk inclined at a certain angle so that it was easy to go around the desk. In this case, considering the rotational motion when entering the desk, the radius of the model was set to 0.7m in the verification point ②. The height of the model was set at 0.8 m at three locations, taking into account the height of the desk. Fig. 9 show the results obtained.

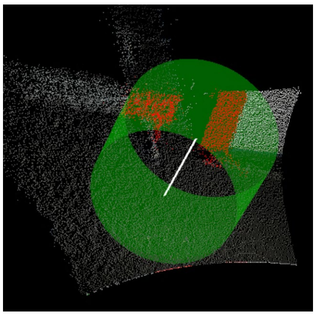
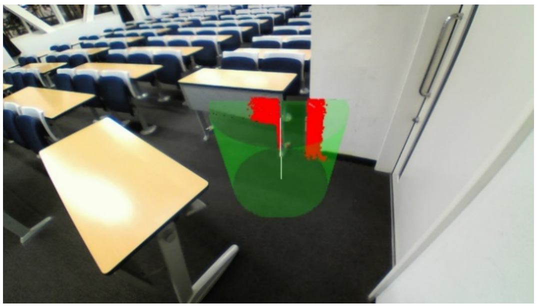
Even in this simple setup, we found complicated barriers to recognize, e.g., narrowing of the wall and the desks placed diagonally, the protrusion of the tops of the desks and f the legs. At the verification point ③, it seems that the front side of the desk-top is entering the wheelchair model, but they have a gap in depth-direction, and it is not a barrier. In such a complex spatial structure, it is essential to understand not only the barrier location but also the positional relations in space. While the AR display using a camera with a narrow angle of view has only a limited field of view centered on the floor, a wide-angle camera, the field of view expands in the height direction at 180 [deg] helps to understand the shape and the relationship between the target spatial characteristics and its barriers. Also, at the verification point ②, it was judged that the wheelchair model was in the back of the tabletop without interference. The real image of the desk partially hides the virtual model and expresses the context. This expression helps understanding not only the barrier location but also the entire space configuration.




a) Barrier check in 3D point cloud：position① b) wide angle camera：position①




c) Barrier check in 3D point cloud：position② d) wide angle camera：position②

e) Barrier check in 3D point cloud：position③ f) wide angle camera：position③

Fig. 9: Examples of the results in physical barrier extraction around the wheelchair users table

5. DISCUSSION AND CONCLUSION

In this study, we proposed an augmented reality display system that combines useful information such as 3D barrier verification and high visibility status display by correlating color images and depth images with different angles of view. The proposed system can provide a function for confirming the spatial narrowness in 3D space and the convenience of overlooking the positional relationship between the surrounding environment, including the flow line of the wheelchair and the verification location. As a result, it was confirmed that the barrier detection work that cannot be obtained with a general-purpose RGBD camera alone could be performed. Furthermore, the effectiveness of AR display can be enhanced by adding an occlusion effect that the virtual wheelchair model is concealed by the real object based on the depth information.

Since this system can interactively display the physical barrier in both 2D and 3D, it can be an easy-to-use tool even for the people who are not familiar with a PC without actually bringing a wheelchair in the site. So, a facility manager who does not have a care manager or specialized knowledge can easily find the possible barriers, which lead to improving the facility barrier-free environment.

In the future, by using SLAM (Simultaneous Localization and Mapping) technology (Durrant-Whyte, H. and Bailey, T., 2006), we will work on developing functions that dynamically estimate location information while performing barrier verification to map and aggregate the obtained barrier information for applying to In-situ verification.

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Construction and Usage of Three-dimensional Data for Road Maintenance Using Various Measurement Instruments

Satoshi Kubota, Kotaro Nishi & Chiyuan Ho
Graduate School of Kansai University, Japan

ABSTRACT: *In road maintenance, it is necessary to construct an environment that manages three-dimensional data and maintenance information for its effectivity and efficiency. The primary objective of this research is to support road maintenance work using three-dimensional data constructed by terrestrial laser scanning, unmanned aerial vehicles (UAV) with photogrammetry, and structure from motion (SfM) using compact camera. In this research, the use cases of three-dimensional data were organized and proposed. They are visualization of damage and inspection results and information and location management of damage, inspection, and landslide. Three-dimensional data were created for pavement, bridge, landform and tunnel. The upside of a landform is surveyed using a camera mounted on a UAV. Point cloud data for these objects are constructed using photographs with SfM technology. The constructed three-dimensional data of 2017 and 2018 were superposed for grasping the difference in temporal sequences. The difference was calculated and represented. A high-density measurement range of laser scanning is restricted to within an approximately 10 m radius, according to experimental results. It is necessary to perform several measurements for surveying wide-range pavement data. The three-dimensional data of road surface connected the thirteen laser scanning data of 10 m using the reference points such as trees and guard rails. Point cloud data for a bridge is combined UAV photogrammetry data and terrestrial laser scanning data. Point cloud data for a tunnel is constructed using camera fixed to the hand cart. SfM methodology was applied to create data using camera images. The three-dimensional data for the road structures could be used to develop a road maintenance management system that accumulates data and refers to the inspection results and repair information in three dimensions.*

KEYWORDS: *Point Cloud Data; Terrestrial Laser Scanning; Unmanned Aerial Vehicle; Road Maintenance.*

1. INTRODUCTION

The road consists of earthworks, bridges, and tunnels. According to the Ministry of Land, Infrastructure, Transport and Tourism of Japan (MLIT), the total length of roads in Japan is about 1,279,511 km (Ministry of Land, Infrastructure, Transport and Tourism, 2018). There are about 730,000 bridges. The proportion of bridges with a length of 2 m and more after 50 years of construction is 39% in 2023 and 63% in 2033. The number of tunnels is approximately 11,000, and the proportion exceeding 50 years after construction will be 27% in 2023 and 42% in 2033 (Ministry of Land, Infrastructure, Transport and Tourism, 2014). For road structures that have been operated for a long time after construction, there are no design drawings or completed drawings remaining, and the drawings are consistent with the current situation. This may cause problems in inspection and repair. In conventional maintenance management, two-dimensional data was used, but sufficient understanding could not be obtained among the parties involved in maintenance, and there was a possibility that the work period would be extended. To realize advanced maintenance management, it is useful to use three-dimensional data that is excellent in visual expression and enables information sharing.

MLIT has been promoting the "i-Construction" policy using three-dimensional data for improving efficiency and sophistication through computerization in every process from a survey, design, construction, and maintenance. Under this background, the mobile mapping system (MMS) is often used to acquire three-dimensional point cloud data of road structures. MMS is characterized by high accuracy and high-density point cloud data acquisition. However, it is difficult to apply on local roads because it takes time and cost. Also, since the laser scanner is mounted on the upper part of the vehicle, it cannot be used in places where the vehicle cannot run, or when the road itself becomes unusable due to landslide disasters or road depressions. Therefore, it is necessary to construct three-dimensional data with high accuracy by measuring with few work procedures.

The primary objective of this research, in order to realize advanced road maintenance management, scenes to utilize three-dimensional data in road maintenance management are proposed and terrestrial laser scanner, UAV and camera are used for constructing three-dimensional data in the on-site. Point cloud data is measured, and its applicability is examined.

2. USAGE OF THREE-DIMENSIONAL DATA FOR ROAD MAINTENANCE

The usage scenes of three-dimensional data in maintenance management of road structures are proposed for grasping the spatial position of structures and integrating and managing information, based on CIM model creation specification (Ministry of Land, Infrastructure, Transport and Tourism, 2015, 2016). Moreover, Development of the three-dimensional data model standard of the bridge which assumed the use by the maintenance (Yamaoka, 2015) was used. As a result, (A) visualization of invisible part and localization of buried object, (B) Confirmation of congestion area, workspace, route and inspection path, (C) visualization of inspection area and results, (D) visualization of the damaged situation and its degree, (E) unified management of inspection and damage information, (F) grasp of deformation of slope, (G) grasp situation by disaster on superposing three- dimensional data measured and constructed at different time, (H) explanation for citizens are extracted. The usage scenes (C), (D), and (E) are shown in Fig. 1. In this research, (C) to (G) in the usage scenes are targeted in order to measure the existing road structure from the outside by various measurement instruments.

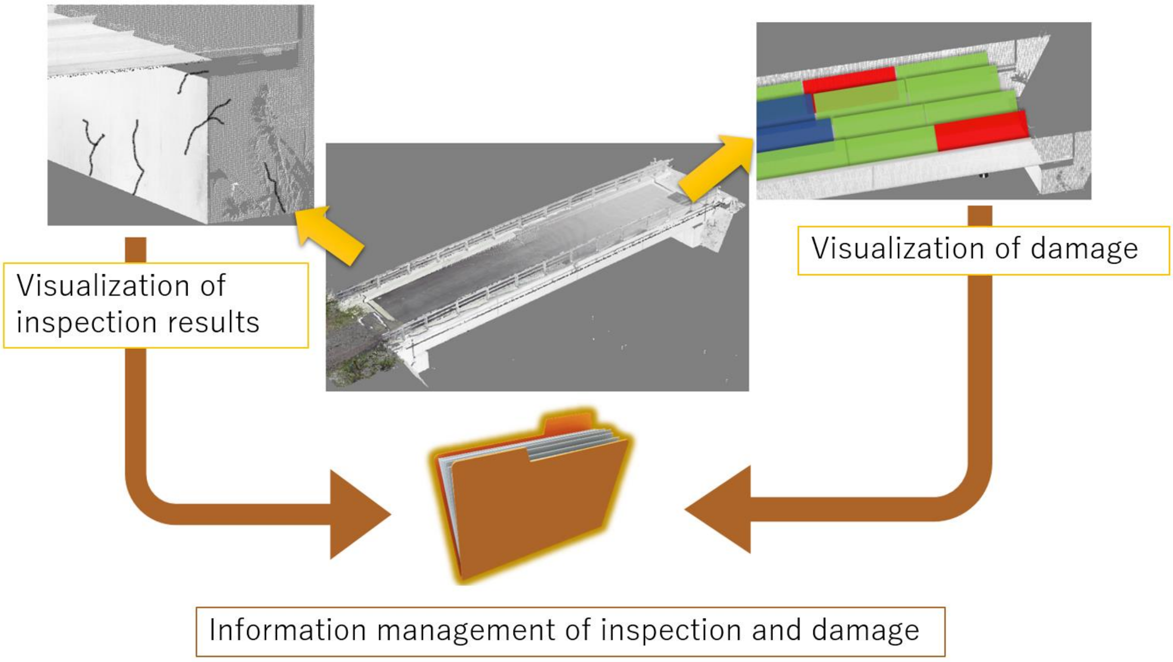

Fig.1 : Usage scenes (C), (D), and (E) of three-dimensional data

3. SURVEY AND CONSTRUCTION OF THREE-DIMENSIONAL DATA

3.1 Measurement Instruments

In this research, the terrestrial laser scanner (Ho, 2018), camera-mounted UAV, and SfM technology that generates point cloud data from images taken with the camera while walking on the ground are used Focus3D X 330 made by FARO as a terrestrial laser scanner, Inspire2 made by DJI as a UAV, ZENMUSE X5S mounted camera and GoPro Hero 6 Black as a camera used for walking are used. As for the pavement, the feature point for SfM processing cannot be obtained with the camera mounted on the UAV or the camera used for walking. The terrestrial laser scanner is used to measure the superstructure and lower parts of bridge, so the camera mounted UAV is taken the photographs of the superstructure of bridge for SfM. The tunnel is measured with a camera as it is impossible for UAV to fly and the traffic of people and vehicles is an obstacle for terrestrial laser scanner.

3.2 Construction of Landform Data

The upside of a slope or a landform is surveyed using a camera mounted on a UAV. In UAV photogrammetry, photos obtained from videos were SfM processed. We used PhotoScan(Agisoft) for SfM processing. The data constructed in 2017 and 2018 for Shiraito Highland Way of Karuizawa, Nagano prefecture were superimposed by the point cloud data editing software Cloud Compare to compare the cross-sectional shapes (Fig. 2). The constructed three-dimensional data can grasp the state of the upper part of the slope and can compare the past scale with the previous data when a disaster occurs. The landform data has a capability for using in the scene (F) and (G).

fig. 2 : Difference of cross section in temporal sequences

3.3 Construction of Pavement Data

The road pavement surface was measured using a terrestrial laser scanner in September 2018 in Shiraito Highland Way. Since FARO Focus 3D X 330 can measure the pavement surface with a high density of about 10 m, measurements were taken at 13 points at intervals of 20 m with a radius of about 10 m. Fig. 3 shows the result of combining the measured data. The constructed data has 205,375,900 points, and the pavement length is about 300 m. The software FARO SCENE was used to combine the measurement data. In order to combine multiple measurement data, feature points that can be recognized as identical among the data are necessary, but there are few feature points on the road pavement surface. The software combines the data using the characteristic points of the surrounding trees and the guardrails. We manually specified and indicated the same points of connecting data. In the measurement of pavement, it is necessary to devise to set up a signature stand which is a feature to reduce the burden of data combining work. The average error of the point-to-point distance at the connection point of 13 measurement data was about 3.700 mm. This is within twice of ± 2 mm, which is the accuracy of Focus3D X 330. It is considered that the accuracy of the combined data is satisfied with the accuracy of the equipment with consideration of the passing vehicles.

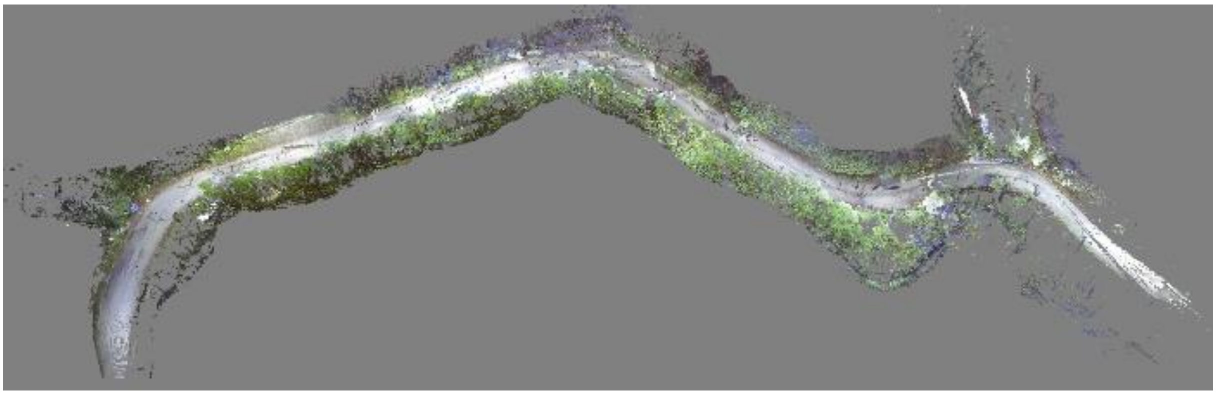

Fig. 3 : Three-dimensional data of road surface

3.4 Construction of Bridge Data

Measurements using a terrestrial laser scanner and a camera-mounted UAV were performed at Waraduhata bridge in Osaka Prefecture. In the measurement with the terrestrial laser scanner, feature points of multiple point cloud data measured from three locations were combined, and decimation processing was performed to make one data. SfM generated point cloud data was proposed using UAV photogrammetry. Three-dimensional data were created from two point cloud data of terrestrial laser scanner and a UAV data. The characteristic points of each data were selected and combined (Fig. 4). As a result, we constructed three-dimensional data, including bridge substructures that cannot be measured with UAV only. As a result of verifying the accuracy for the bridge length and width length of three-dimensional data, the bridge length of three-dimensional data is 22.212 m, the effective width is It is 4.019 m. The bridge length under design conditions is 22.200 m, the effective width is 4.000 m. Therefore, the error was 12 mm in bridge length and 19 mm in effective width.

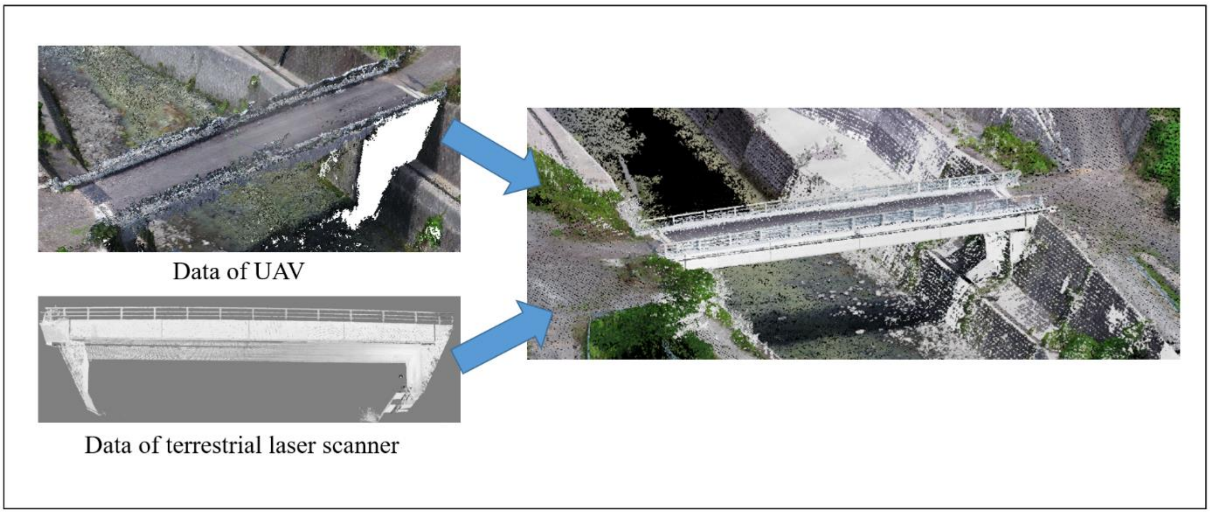

Fig. 4 : Data fusion of terrestrial laser scanning and UAV in road and bridge

3.5 Construction of Tunnel Data

The measurement of the tunnel was carried out in December 2018 near Waraduhata bridge. A tripod with a height of about 1.0 m was placed on the carriage, and the camera was fixed on the front with the camera facing forward (Fig. 5). In addition, the camera was fixed at 45 degrees to the right and 45 degrees to the right with an extension pole about 2.5 m high and reciprocated along the wall. The moving image was taken one round trip in the center of the tunnel. Table 1 shows each condition setting. In SfM processing, point cloud data was generated using measurement data of six patterns. The generation result of case 1 is shown in Fig. 6. Case 1 was able to construct three-dimensional data of the entire tunnel. Case 3 could not construct a tunnel shape (Fig. 7). This is thought to be because the camera turned to the right and images of similar shapes continued, so the feature points of the image in the tunnel could not be recognized, and the camera position could not be grasped.

The above three-dimensional data of pavement surface, bridge, and tunnel can visualize the inspection point and the damaged point. They can be unified managed by attaching that information to the constructed three-dimensional data. They can be used in usage scenes (C), (D), and (E).

Fig. 5 : Measurement scene

Table 1: Setting measurement conditions for tunnel

	Camera direction	Camera height	Direction
Case 1	Front	1.0 m	Outward way
Case 2	Front	1.0 m	inward way
Case 3	45 degrees to the right	1.0 m	Outward way
Case 4	45 degrees to the right	1.0 m	inward way
Case 5	45 degrees to the right	2.5 m	Outward way
Case 6	45 degrees to the right	2.5 m	inward way

Fig. 6 : Point cloud data for case 1

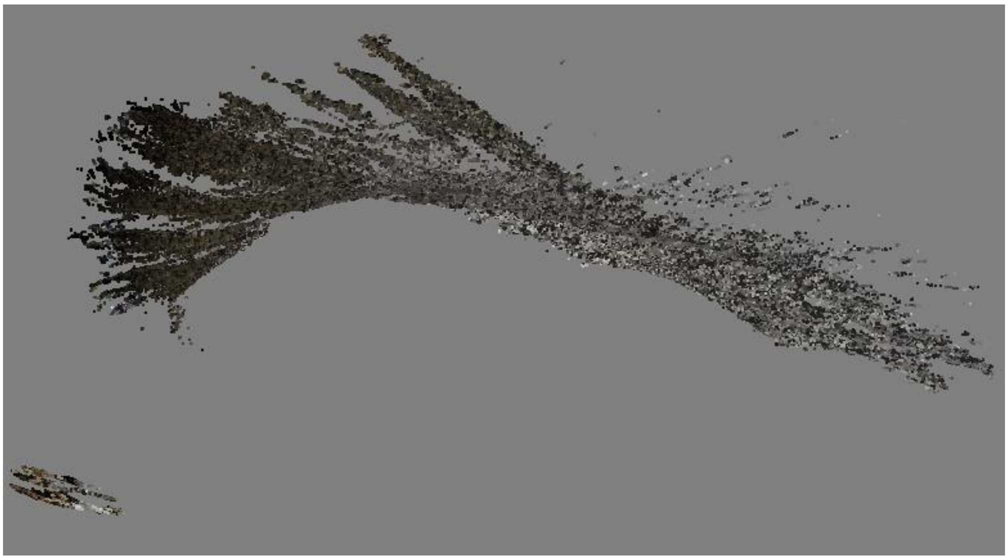

Fig. 7 : Point cloud data for case 3

4. CONCLUSION

In this research, we proposed the usage scenes of three-dimensional data in the maintenance of road structure and constructed landform, bridge, pavement, and tunnel data by using a terrestrial laser scanner, camera mounted UAV, and compact camera. As a result, it suggested the application of three-dimensional data in the point of attention to process the data and the utilization situation. In the future, we will consider a method to construct three-dimensional data by applying Simultaneous Localization and Mapping (SLAM) technology to data obtained from a small and portable laser scanner (LiDAR: Light Detection and Ranging, Laser Imaging Detection and Ranging).

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A QUANTITATIVE EFFECT EVALUATION OF THE UNWANTED FEATURES REMOVAL OF INFRASTRUCTURE DIGITAL IMAGES

Natthapol Saovana, Nobuyoshi Yabuki, and Tomohiro Fukuda
Osaka University, Japan

ABSTRACT: *Structure from Motion (SfM) is a photogrammetric technique that utilizes an algorithm called the feature detector and descriptor to automatically detect and match numerous suiting attributes from intersections between images to construct a model. SfM has been implemented with numerous topics such as geoscience, surveying, and historical architecture. However, the image matching is usually complex when it comes to the infrastructure domain because of the disordered surroundings, for instance, boulders, plantation, unrelated buildings, etc. These extrinsic features can complicate the matching and lead to the unsatisfactory output of the interested infrastructure. Consequently, some studies advised to remove these unwanted features beforehand to raise the quality of the matching but no studies have focused on the quantitative effect of the unwanted features removal for infrastructure images. This study proposed the quantitative effect evaluation of the unwanted features removal from various infrastructure digital images. Firstly, 50 original image pairs were manually removed the unwanted features to form two datasets of original and unwanted features removed images. Then, both datasets were processed through feature detector and descriptor algorithms to find the number of matching both inside and outside of the region of interest (ROI) and the computational time of each process. Finally, the number of matching and computational time for each corresponding image pair of before and after unwanted features removal were compared. The result showed that removing the unwanted features of infrastructure digital images can decrease 72.30 percent of the computational time. Although the number of matchings decreased by 77.65 percent, these matchings were 13.18 percent more focused on the interested infrastructure instead of the unwanted features, which could increase the quality of the 3D infrastructure model. This research serves as the evidence that removing the unwanted features beforehand can benefit the feature matching of infrastructure digital images.*

KEYWORDS: *Unwanted features removal, infrastructure digital images, feature detector and descriptor algorithms, quantitative effect evaluation, image matching*

1. INTRODUCTION

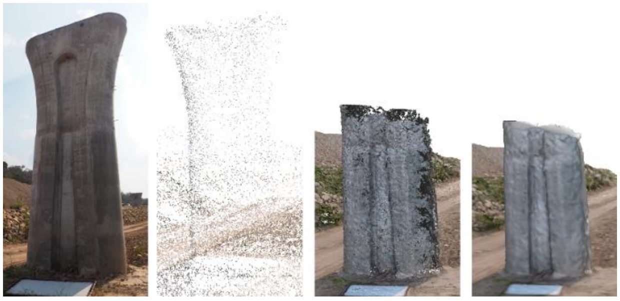
Currently, construction digital images are utilized to visualize the construction progress and calculating for the quantity of work (Zhang *et al.*, 2009; Hamledari *et al.*, 2017). These images can be transformed into a model by implementing Structure from Motion technique or SfM. Due to its easy utilization and cost-effectiveness, it has been applied with various types of work in civil engineering, for instance, a field (Carbonneau and Dietrich, 2017), a building (Musialski *et al.*, 2013), a pile of embankment (Wrózyński et al., 2017), and a river bank (Micheletti et al., 2015).

SfM utilizes an automatic algorithm, which is called feature detector and descriptor, to find the features inside images and match these features across different images to form the point cloud of the interested structures. Then, this point cloud can be further processed into a model. Fig. 1 shows the sample output from each SfM process. These images are captured from Agisoft Photoscan software.

a) b) c)

Fig. 1: Sample output of each SfM process: a) The feature detected in the input images, b) The generated dense point cloud from the previous features, and c) The final mesh.

However, feature matching is very delicate and prone to error, particularly when there are unwanted features or noises in the images, for example, the background has been proven to be one of the factors that can affect the matching process (Oron *et al.*, 2018). The difference between pixels from the background can lead to the false matching, especially for infrastructure images that usually consist of textureless or smooth planar in the region of interest (ROI) surrounded with complex color pixels such as boulders, plantation, and unrelated structures in the same image. This circumstance can complicate the matching algorithm to focus on the disordered parts more than the ROI and deceive the separation between good and bad matchings (Bian *et al.*, 2017). Consequently, the algorithms have to sacrifice numerous correct matchings to ensure the quality of the overall process (Lin *et al.*, 2018). The less amount of matching can affect the following process such as 3D triangulation to be less effective. Fig. 2 shows the SfM process of a column which had some difficulties with the final product. These images are captured from Agisoft Photoscan software. It can be seen from Fig. 2b) that there are some matched features detected by the software. However, the generated point cloud in Fig. 2c) lacks the point cloud at its top part which resulted from the lower confidence in matchings around this area and got filtered out (Agisoft LLC, 2018). Therefore, the final model in Fig. 2d) results in the incomplete structure, different from the original image in Fig. 2a).



a) b) c) d)

Fig. 2: Sample problem of SfM process: a) The original image, b) Matched features from the system, c) The point cloud generated from the software, and d) The final mesh from the software.

By removing the uninterested features, the quality and confidence of the matching could be improved as the feature detector and descriptor algorithms can better focus on the ROI. Therefore, there is a need for the evaluation of the quantitative effect of the unwanted features removal with the feature matching of infrastructure digital images, which has yet to be seen. The objective of this research is to evaluate the effect of the unwanted features with the feature matching for infrastructure digital images. The samples for the evaluation were separated into two types, the original images and the images which unwanted features were removed.

2. LITERATURE REVIEW

Previous research related to this study were reviewed and are presented in this section. They are separated into 4 topics; 1) Feature detector and descriptor algorithms and SfM, 2) feature detector and descriptor algorithms in the civil engineering domain, 3) performance evaluation on feature detector and descriptor algorithms, and 4) effects of unwanted features removal.

2.1 Feature detector and descriptor algorithms and SfM

The feature detector and descriptor algorithm is one of the key innovations in computer vision (Musialski *et al.*, 2013). They were invented in the 1980s (Westoby *et al.*, 2012). These algorithms try to detect the features or keypoints in a set of images and match these features between images, which is called *Image Registration* (Tareen and Saleem, 2018). When features are obtained, they can be further managed into photogrammetry techniques such as SfM to create models. SfM was first mentioned around 1990 by the research in computer vision expertise (Westoby *et al.*, 2012). It has been proved that it is compatible with various type of photo and video capturing devices, for instance, cameras (Fathi and Brilakis, 2013), action cameras (Raoult *et al.*, 2016), unmanned aerial vehicles (UAVs) (Carbonneau and Dietrich, 2017), and mobile phones (Wrózyński *et al.*, 2017).

The procedure of SfM utilizes these detected features and processes into the bundle adjustment to minimize the reprojection error between the location of the camera and features, which is called 3D triangulation (Wrózyński *et al.*, 2017). The output from this method are the parameters, for example, poses of cameras in 3D environment and focal length. These parameters affect the quality of the model from photogrammetric techniques such as SfM greatly (Musialski *et al.*, 2013). The final result of the process is the point cloud data that can be further transformed into a model by using techniques such as Poisson Surface Reconstruction (Kazhdan, Bolitho and Hoppe, 2006).

There are many feature detector and descriptor algorithms available, for instance, Scale Invariant Feature Transform (SIFT) (Lowe, 2004), Speeded Up Robust Features (SURF) (Bay *et al.*, 2008), Oriented FAST and Rotated BRIEF (ORB) (Rublee, Rabaud and Konolige, 2011), and Binary Robust Invariant Scalable Keypoints (BRISK) (Leutenegger, Chli and Siegwart, 2012). These algorithms are very well known for their easy utilization from OpenCV (Bradski, 2000) and robustness in image distortion, for example, rotation, and affine deformation.

2.2 Feature detector and descriptor algorithms in civil engineering domain

Digital images with feature detector and descriptor algorithms in the civil engineering domain have been studied for a decade, for instance, Zhu and Brilakis (2010) proposed the use of SIFT to extract the feature inside concrete column images for simple detection. Fathi and Brilakis (2011) utilized SURF to match features inside two video frames from two calibrated cameras and then, calculated the 3D coordination of these features using 3D triangulation technique to generate the point cloud of a building. Hui, Park and Brilakis (2014) developed a system to calculate the amount of bricks in an image. They used Feature from an Accelerated segment Test (FAST) (Rosten and Drummond, 2005) to detect features from bricks inside the ROI. Finally, Rashidi, Brilakis and Vela (2015) proposed a new method to generate the point cloud precisely by using a cube for outdoor environments and a paper for indoor environments in order to calibrate the position of the point cloud. Their system utilized SURF to detect features in the background. However, these studies only evaluated system performance. Feature detector and descriptor algorithms in these studies were not focused and evaluated beforehand.

2.3 Performance evaluation on feature detector and descriptor algorithms

Although there are numerous available feature detector and descriptor algorithms, each algorithm has their own advantages and disadvantages over separated expertise. In order to use the suitable feature detector and descriptor algorithms with new expertise, they should be tested before use (Rusinol *et al.*, 2015). Işık and Özkan (2014) tested several algorithms on the Oxford dataset. They recommended the usage of ORB that was able to perform well with this image dataset. Hietanen *et al.* (2016) evaluated various feature detector and descriptor algorithm on Caltech (Fei-Fei, Fergus and Perona, 2006) and ImageNet classes (Deng *et al.*, 2009). They evaluated that the combination of a detector with SIFT descriptor was able to outperform other algorithms. Tareen and Saleem (2018) appraised algorithms with numerous image datasets such as Oxford, MATLAB, and OpenCV. Their result showed that ORB was able to perform well, especially when the user specified ORB to detect up to 1,000 feature points so that it could decrease the low confidence features and be able to match these features rapidly. In conclusion, ORB and SIFT have recommendations when the public image dataset is utilized as the sample of the implementation.

On the other hand, when the topic came to more specific expertise, their recommendations did not go along with the recommendation from the public image dataset domain. Mouats *et al.* (2018) argued that most of the studies about performance evaluations were mainly focused on clear and bright images. Therefore, they proposed the evaluation of feature detector and descriptor algorithms on night goggle images, which is blurry and dark. Their result demonstrated that SIFT had very high performance with images with noises. They suggested that SIFT was very slow and might cause problems when the computational time is considered. Rusinol *et al.* (2015) evaluated the performance of these algorithms with thousands of document images and the result revealed that SIFT had extraordinary high performance within this domain. Its accuracy and computational speed were high. Moreover, BRISK and ORB also displayed promising performance having slower decimal speed level than SIFT. Cowan *et al.* (2017) utilized videos from UAVs to let the users choose the area where they want the UAVs to land. Their result showed that BRISK was able to perform well with the videos which were taken from UAVs. Finally, Saha *et al.* (2018) assessed the performance of feature detector and descriptor algorithms with retinal images and found that SIFT and SURF were able to execute comparatively well.

It can be seen that there are different kinds of recommended algorithms depending on the topic of the dataset. Therefore, there is a need to evaluate the feature detector and descriptor algorithms before the actual utilization.

2.4 Effects of unwanted features removal

Carrivick, Smith and Quincey (2016) explained that there are various advantages from discarding uninterested data or noises from the input, such as, reduced computational time, reduced file sizes, and better quality output for the ROI. By increasing the matching inside ROI, there will be more point cloud inside which can prevent the void inside the final model. Furthermore, if there are some outliers in the matching, the surface of the model might not be smooth. The curvature might also not reflect the real structure (Carrivick, Smith and Quincey, 2016).

However, there were also concerns with the unwanted features removal. Rahal *et al.* (2018) suggested that camera positions might be miscalculated due to the less matchings. Furthermore, less matchings might also affect the quality of the overall matching because good matchings cannot contain the false matchings. Therefore, the elimination of false matchings might not be done effectively (Lin *et al.*, 2018).

3. PROPOSED METHOD

The proposed method was separated into five parts, which were shown in Fig. 3. The first process was data acquisition and preparation. Infrastructure digital images that were taken from a camera were utilized as the input of the system. The camera which was used in this study is Olympus EM-10 Mk III. The total of one hundred images, for instance, roads, bridges, dams, tunnels, and waterways, were formed into fifty image pairs for image matching. These images were also processed into image editing application to be manually removed the unwanted feature to form the ROI of each image. Therefore, there were fifty image pairs for both original and modified dataset, which had no unwanted feature. Moreover, the rims of the images that their backgrounds were removed were used as the boundary of the ROI for the evaluation in the further stage. All of fifty images pairs from both sets can be found in https://drive.google.com/drive/u/1/folders/14OZO6dQ3mIYLCjBQHRNCsJeA81x7yLZE

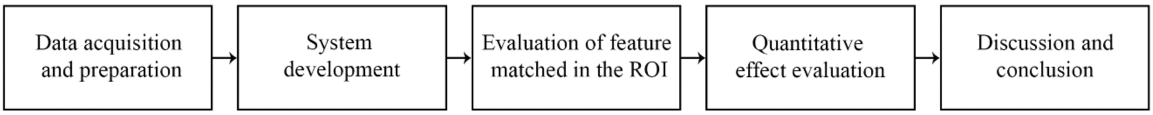
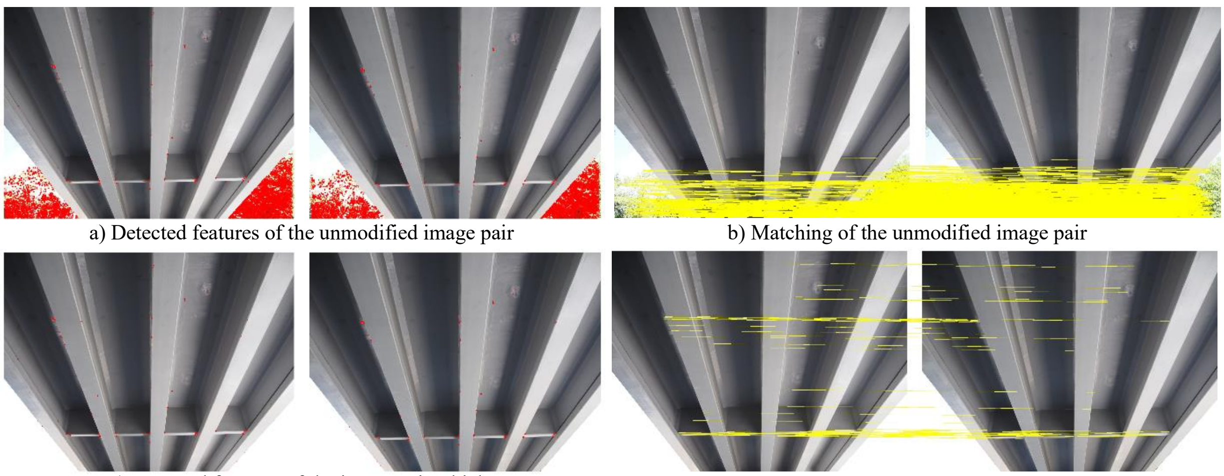


Fig. 3: Our proposed method

The system for evaluation was developed using Spyder with OpenCV 3.4.2 to detect features and do the matching. The specification of the programming computer was Intel(R) Core(TM) i5-8400 CPU @ 2.80GHz and 8.00 GB RAM. Feature detector and descriptor algorithms that were tested in this study were SURF (64-Floats), SURF128 (Extended SURF, which used 128-Floats), ORB, and BRISK. These algorithms were chosen because they had high performance with infrastructure domain in our previous study (Saovana, Yabuki and Fukuda, 2019). Moreover, they also had both feature detectors and feature descriptors that could be easily utilized in OpenCV. The output of the system were the images with red dots showing the detected features in each input image and yellow lines showing the matching between two input images. Fig. 4 shows the detected features and matching results from one of the image pairs, both with and without unwanted features.



a) Detected features of the unmodified image pair

b) Matching of the unmodified image pair

c) Detected features of the image pair which unwanted features were removed

d) Matchings of the image pair which unwanted features were removed

Fig. 4: Samples of the detected features and matchings by ORB.

Then, these images with red dots were processed through Photoshop CS2 to calculate for the number of feature matc hed inside the ROI. In this process, the boundary for the ROI was obtained from the rim of the corresponding image without unwanted features. For example, Fig. 5 shows images of a pedestrian crossing bridge which is the 4th sample in the dataset. Fig. 5a) is the unmodified images. Fig. 5b) is the Fig. 5a) that was removed the unwanted features. Fig. 5c) shows the boundary that used the rim of the middle pair for the ROI coverage evaluation. This boundary was utilized to calculate for the number of feature matched in the ROI for the unmodified images. Next, the numbers of feature matched inside the ROI of each original image pair were compared with their corresponding image pair that unwanted features were removed. The result of the comparing was the different percentage between number of matches before and after unwanted features were removed. However, if there are no matchings inside the ROI before the unwanted features removal but instead have matchings after that, the different percentage will be infinity because the divisor is zero. Therefore, samples that fell into this case must be removed from the averaged data and presented in the total number of case instead. After that, the average total number of features and matchings with their computational time in each step were processed and compared between each algorithm to verify the effect between modified and unwanted features removed images. The data was further analyzed to find the different percentage of each algorithm and concluded.

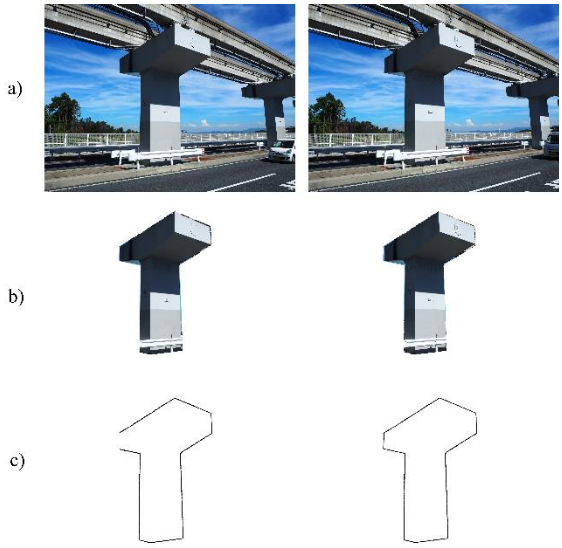


Fig. 5: The example of a sample image pair from the dataset: a) The original images, b) Images which unwanted features were removed, and c) The boundary of the ROI for this sample image pair

4. RESULTS

The results of the study were separated into two parts, which were the comparison between number of matching inside ROI and the quantitative effect of the unwanted features removal.

4.1 Number of matching inside ROI

The result of this part was shown in Table 1. However, please be noted this table only shows the final result of this procedure. The entire result of each sample and each algorithm can be found in the appendix of this study in the same link with all of the image samples in chapter 3. In addition, abbreviations in Table 1 were utilized in the table in the appendix. The total of fifty image pairs of various infrastructure digital images were processed through our system with different feature detector and descriptor algorithms. The result showed that unwanted features removal could support every feature detector and descriptor algorithm in order to match the features inside the ROI. They were able to detect all of the ROI in every sample. Moreover, ORB gained the biggest benefit from unwanted features removal because it could match 22.6% more features inside the ROI. Meanwhile, other algorithms in the study detected about 7 to 12% more features inside the ROI and the overall average was 13.18%.

Table 1: The evaluation of the effect from unwanted features removal

Feature detector and descriptor algorithms	Average percentage of increasing matchings inside the ROI after unwanted features removal (%)
BRISK (B)	10.82
ORB (O)	22.60
SURF128 (S128)	7.36
SURF (S)	11.94
Average	13.18

4.2 The evaluation of the effect on performance

In this part, the result was separated into two sub topics, which were the detected features and matchings and computational time.

4.2.1 Detected features and matchings

The result in this part was separated into three tables as shown in Table 2 to Table 4. Table 2 shows the number of detected features and the matchings of the dataset that had only unmodified images. Meanwhile, Table 3 shows the number of detected features and the matchings of the dataset that had unwanted features removed. Finally, Table 4 shows the difference percentage between the data before and after the unwanted features removal. It can be seen that be removing the unwanted features, the features that could be detected was decreased by about 68% (69.16% for the first images in each image pair and 67.58% for the second images in each image pair). Moreover, the matching was also decreased 75.36% and 77.65% for both before and after outliers elimination by RANSAC, respectively.

Table 2: Detected features and matchings from the original image dataset

Feature detector and descriptor algorithms	Detected features of the 1st image (points)	Detected features of the 2nd image (points)	Matched features (pairs)	Matched inliers (pairs)
SURF	20,882	20,425	3,369	2,721
SURF128	15,147	14,889	2,405	1,940
ORB	80,014	78,263	7,140	5,845
BRISK	28,603	27,779	3,182	2,595

Table 3: Detected features and matchings from the unwanted features removed image dataset

Feature detector and descriptor algorithms	Detected features of the 1st image (points)	Detected features of the 2nd image (points)	Matched features (pairs)	Matched inliers (pairs)
SURF	7,523	7,607	970	700
SURF128	5,264	5,358	678	500
ORB	21,898	22,457	1,429	1,048
BRISK	7,215	7,709	686	518

Table 4: Different percentage of detected features and matchings between two datasets

Feature detector and descriptor algorithms	Detected features of the 1st image (%)	Detected features of the 2nd image (%)	Matched features (%)	Matched inliers (%)
SURF	63.97	62.75	71.21	74.28
SURF128	65.25	64.01	71.81	74.24
ORB	72.63	71.31	79.99	82.06
BRISK	74.77	72.25	78.43	80.03
Average	69.16	67.58	75.36	77.65

4.2.2 Computational time

Subsequently, the computational time that was used according to the work process in the previous sub topic was demonstrated in three tables from Table 5 to Table 7. Table 5 shows the computational time that was utilized in each step, namely features detection of both images, feature matching, outliers rejection, and time in total, for the dataset that contained only original images. Next, Table 6 shows the computational time of the same topics as Table 5 but with the dataset that unwanted features were removed. Lastly, Table 7 shows the different percentage of the time used to process between both datasets. From the result tables, the biggest amount of time that could be decreased was the time for features matching. It was diminished about 82% if the unwanted features removal was implemented. For the total amount of time spent for the entire process, it was decreased to the average of about 72% which ORB and BRISK were the top two algorithms that can gain the most benefit from unwanted features removal. The time used for algorithms to detect features was also reduced for all of the algorithms. The average of the decreased time was about 46% for the entire image dataset (46.98% for the first images in each pair and 45.70% for the second images in each pair). Finally, the time that RANSAC spent to eliminate the outliers was also reduced by 55.38%.

Table 5: Computational time in each process of the original image dataset

Feature detector and descriptor algorithms	Time for detected features of the 1st image (μSecond)	Time for detected features of the 2nd image (μSecond)	Time for features matching (μSecond)	Time for outliers to be rejected (μSecond)	Total time (μSecond)
SURF	13.389	13.178	48.882	0.342	75.791
SURF128	6.024	5.947	26.645	0.267	38.883
ORB	6.093	5.955	315.989	0.634	328.671
BRISK	12.194	11.839	83.873	0.327	108.233

Table 6: Computational time in each process of the unwanted features removed image dataset

Feature detector and descriptor algorithms	Time for detected features of the 1st image (μSecond)	Time for detected features of the 2nd image (μSecond)	Time for features matching (μSecond)	Time for outliers to be rejected (μSecond)	Total time (μSecond)
SURF	8.941	8.829	9.871	0.165	27.807
SURF128	3.876	3.937	5.268	0.142	13.223
ORB	2.426	2.434	54.370	0.203	59.432
BRISK	5.016	5.105	13.566	0.148	23.836

Table 7: Different percentage of the computational time in each process between two datasets

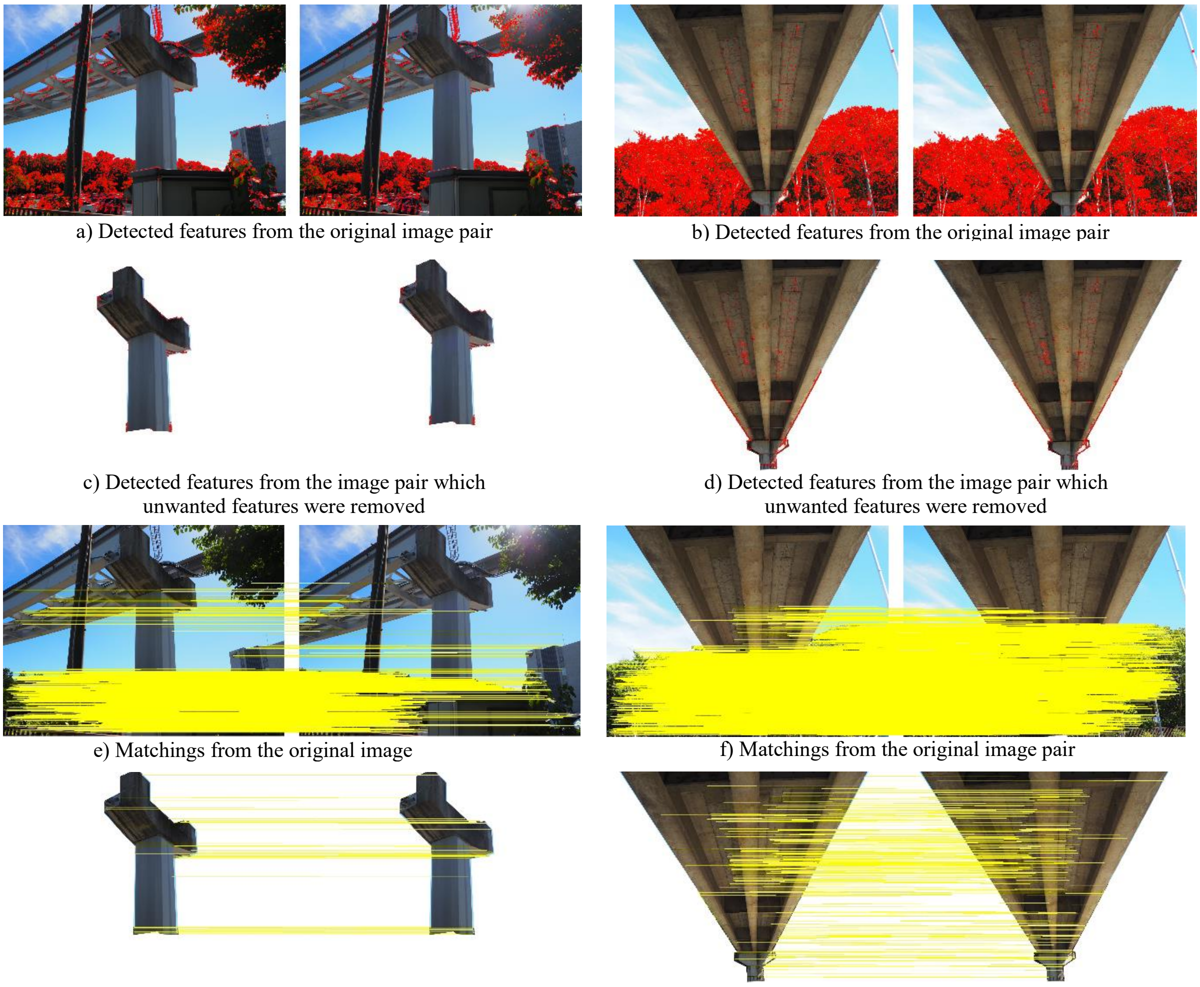
Feature detector and descriptor algorithms	Time for detected features of the 1st image (%)	Time for detected features of the 2nd image (%)	Time for features matching (%)	Time for outliers to be rejected (%)	Total time (%)
SURF	33.22	33.00	79.81	51.74	63.31
SURF128	35.65	33.81	80.23	46.95	65.99
ORB	60.18	59.12	82.79	68.05	81.92
BRISK	58.86	56.88	83.83	54.76	77.98
Average	46.98	45.70	81.66	55.38	72.30

5. DISCUSSION

The evaluation of the effect from unwanted features removal was tested with one hundred infrastructure digital images (fifty image pairs) in two datasets, original and unwanted features removed. The result showed that by removing unwanted features, it was able to help the feature detector and descriptor algorithms to focus more on the ROI and hence, had more matching inside the ROI. The reason behind this situation was the algorithms had lower confidence to match the features inside the ROI so, it instead matched the features that it had more confidence. Although the distance between image taking positions is only a centimeter away, this problem can still occur. Fig. 6 shows the samples that an algorithm was not able to match features inside the ROI greatly when using the original images (The matching of 32nd sample (Monorail pier) and 40th sample by BRISK (Bridge girder)). The algorithm was able to detect some features inside the ROI (The red pixels inside Fig. 6c and 6d). However, it matched the uninterested features such as buildings, rails, and trees instead of the ROI (Figure 6e and 6f). By removing unwanted features, it assisted these algorithms to shift their matchings into the ROI directly (Figure 6g and 6h) thus, the following process such as 3D triangulation could gain benefits from these matchings inside the ROI. Based on Table 1, the average percentage of the increasing matching inside the ROI was 13.18%. Furthermore, ORB gained the biggest benefit from this method. It was able to match 22.60% more matchings inside the ROI after the unwanted features removal.

For the quantitative performance evaluation, the features that each algorithm could detect were about 68% decreased. The matchings were also decreased to the average of 75.36% and 77.65% for both before and after RANSAC implementation, respectively. These results might affect the overall matching because the number of good matches may be too few to suppress the bad matchings (Lin *et al.*, 2018). Therefore, it should be further analyzed to know the quality of the output model whether it is affected.

Anyway, removing the unwanted features out of the input images had great advantage for the computational time. The required time for features detection was about 46% decreased or nearly half of the original images procession time. Moreover, the matching time was also 81.66% reduced and due to the less amount of matchings, the outliers rejection by RANSAC also spent 55.38% less amount of time. Finally, the total average time for the entire process was 72.30% decreased.



a) Detected features from the original image pair

b) Detected features from the original image pair

c) Detected features from the image pair which unwanted features were removed

d) Detected features from the image pair which unwanted features were removed

e) Matchings from the original image

f) Matchings from the original image pair

g) Matchings from the image pair which unwanted features were removed

h) Matchings from the image pair which unwanted features were removed

Fig. 6: The sample matching results that their matching performance of the ROI were better after unwanted features removal

6. CONCLUSION

This study presents a quantitative performance evaluation of the unwanted features removal with four feature detector and descriptor algorithms, which were SURF, SURF128, ORB, and BRISK. These four algorithms were chosen because they performed well with the infrastructure digital images based on our previous research (Saovana, Yabuki and Fukuda, 2019). There were also easy to be utilized and robust to image distortions. The evaluation was conducted on various infrastructure digital images such as roads, bridges, and dams. The results of this study showed that although unwanted features removal decreased about 68% and 75% of detected features and matchings respectively, it was able to increase the matchings inside the ROI by 13.18% and reduce the total computational time by 72.30%. Moreover, ORB gained the biggest benefit from unwanted features removal by having 22.60% more matching inside the ROI and 81.92% less computational time. This study can be implemented as a proof that by removing the unwanted features out of the input images, it can increase the matchings inside the ROI and reduce the computational time in order to process these images.

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Potential Use of Big Data and Artificial Intelligence for Delay Problem Resolution by Construction Management Consultancy Services in Thailand

Noppadol Jaisue
PHD. Student, Department of Civil Engineering, Faculty of Engineering, Chulalongkorn University, Thailand, 10330

Vachara Peansupap
Assist.Prof.Dr., Department of Civil Engineering, Faculty of Engineering, Chulalongkorn University, Thailand, 10330

Tanit Tongthong
Assoc.Prof.Dr., Department of Civil Engineering, Faculty of Engineering, Chulalongkorn University, Thailand, 10330

ABSTRACT: *Construction management consultancy services become indispensable for project delivery. The services include resolving problems of delay which is a chronic problem in global manner. The delay does not only result in cost overruns and poor quality but also greater disputes, even total abandonment and protracted litigation by a project owner and contractor. Therefore, delay problem resolution is very important and requires certain data to start with. The data in construction industry have high volume, variety and velocity which are natures of the Big Data. However proper use of the Big Data in construction management consultancy services for delay problem resolution has not been found. One of the reasons is due to human's inefficiency in dealing with the natures of the Big Data even with ordinary computers. To overcome this problem, we propose using artificial intelligence (AI) to process the Big Data. The study aims to show potentials of using Big Data and AI applications for delay problem resolution by the construction management consultancy services in Thailand. It starts with literature review to identify and filter causes of delay. The filtered causes are then presented in questionnaires to thirteen experts for importance ranking. Results from the experts are analysed into Relative Importance Index (RII). Causes with RII more than 50% are then selected to be included in an online Daily Delay Report (DDR) which is to be completed and submitted by more than twenty projects in Thailand. Data from DDR are then processed by Big Data and AI applications to recommend resolutions to each project every working day. Such projects can consider and then action on the resolutions as appropriate. We also propose Delphi method to verify the results. After adjusting until consensus threshold of 75% is achieved, the results are then concluded and fed back to DDR for the next round of process. This study forms a basis of applying Big Data and AI for delay problem resolution by construction management consultancy services globally. It is also recommended that further research about objective measurement of resolution's influence and impacts from other project characteristics beyond type should be conducted.*

KEYWORDS*: Artificial Intelligence; Big Data; Construction Management Consultancy; Delay*

1 INTRODUCTION

As an emerging business sector, construction management consultancy services offer professional services to clients/owners or on their behalf in managing the construction process. The services become indispensable underpinnings for project delivery (Qi Wen, Maoshan Qiang, & Nan An, 2017). This definitely includes resolving problems of delay.

In construction, delay could be defined as the time overrun either beyond completion date specified in a contract or beyond the date that the parties agreed upon for delivery of a project. To the owner, delay means loss of revenue through lack of production facilities and rentable space or a dependence on present facilities (Nurul Sakina Mokhtar Azizi, Elizabeth, & Huemann, 2015). Construction delays do not only result in cost overruns and poor quality but also greater disputes, even total abandonment and protracted litigation by the parties (Toor & Ogunlana, 2008). Notwithstanding its proven significance, most of the construction projects (both in developing and developed countries) faced schedule delays, which makes it a chronic problem in global manner. Therefore, delay problem resolution is very important in construction management consultancy services. In addition, the resolution requires certain data to start with.

The volume of data generated by the construction industry has increased exponentially following an intense use of modern technologies. The data explosion thus leads towards the big data phenomenon which is envisioned to revolutionize the construction like never before (Ismail, Bandi, & Maaz, 2018). Big data fundamentally means datasets that could not be perceived, acquired, managed and processed by traditional technologies within a reasonable time (Lněnička, 2016). It has a complex nature that requires powerful technologies and advanced algorithms (Oussous, Benjelloun, Ait Lahcen, & Belfkih, 2018).

Artificial Intelligence (AI) is defined as the capability of a machine to imitate intelligent human behavior. It is being utilized in the construction industry in equipment, administration, construction methodology, and post-construction (Kinshuk, 2014). This study provides insight of applying AI to process the big data for delay problem resolution by construction management consultancy services in Thailand.

2 PROBLEM STATEMENT

Delay problem resolution by construction management consultancy services nowadays are normally based on methods proposed mainly by responsible project manager. Unfortunately, a single project manager does not have all experiences and this leads the resolution to be not fully efficient. He therefore should have most similar and updated experiences from other project managers.

Most construction has so many causes of the delay problem happening daily and each cause has many possible solutions. A project manager cannot follow all resolutions because of time constraints. He needs to know priority so that the most proven successful and updated resolutions can be firstly considered and so on. The priority should be analyzed from patterns of many conditions. The patterns grows on a number of days and projects, and analysis of the patterns becomes beyond capacity of human.

3 OBJECTIVES

This study aims to fulfil the following objectives:

1. To explore issues related to delay problem resolution practices by construction management consultancy services worldwide
2. To apply big data and artificial intelligence for delay problem resolution by construction management consultancy services in Thailand

4 LITERATURE REVIEWS

4.1 Construction Management Consultancy Services

Hu, Xia, Ye, and Skitmore (2016) addressed that construction management services (CMS) offer professional services to clients/owners or on their behalf in managing the construction process. In addition to well-recognized services such as construction supervision, project bidding, and quantity surveying, CMS in general embrace all other consulting activities that are related to construction management with the intention of achieving predefined project goals. They mentioned that the field of construction project management more explicitly addresses project management related to the construction of facilities; most importantly, it assumes and advocates the integration of all phases from conception to completion and argues that this integration is essential on behalf of the client. Today construction managers act on behalf of clients mainly in the design and/or production phase of a construction project. According to Qi Wen et al. (2017), the professional consultancy services provided by construction management consultants (CMC) are important supplements to clients' management of project execution. The professional managerial and technical services by construction management consultant—CMC, engineer in FIDIC (Fédération lnternationale Des lngénieurs Conseils) contract, in project execution become indispensable underpinnings for project delivery. With their professional expertise and capabilities, CMCs have long been assuming various responsibilities in construction projects. Shi et al. (2014) highlighted that Construction management consultancy is an integral part of construction professional services (CPS) that are created by a set of knowledgeable consultants including architects, engineers, engineer-contractors, architect-engineers, engineer-architects, environmental, planners, geotechnical engineers, and landscape architects. Meanwhile, the sizeable urbanization as well as the emergence of numerous construction projects characterized by complicated technologies and management challenges has yielded tremendous opportunities for CMCs to prosper. These studies raised importance of construction management consultancy services.

4.2 Construction Delays

According to Assaf and Al-Hejji (2006), delay could be defined as the time overrun either beyond completion date specified in a contract, or beyond the date that the parties agreed upon for delivery of a project. It is a project slipping over its planned schedule and is considered as common problem in construction projects. To the owner, delay means loss of revenue through lack of production facilities and rent-able space or a dependence on present facilities. In some cases, to the contractor, delay means higher overhead costs because of longer work period, higher material costs through inflation, and due to labor cost increases. Completing projects on time is an indicator of efficiency. However, it is rarely happen that a project is completed within the specified time. It was mentioned by Durdyev et al. (2017) that delay may also be defined as act or event, which extends required time to deliver work of the contract, manifests itself as additional days of work. Construction project delay has been a research topic for decades and several studies have investigated causes of delays in countries. However, most of those studies are area specific. The research findings in other countries and in different project types may not be completely applicable to the nature and scope of this research, as the socio-cultural, regulatory, legislative environment and project specific issues may vary from country to country and from project to project. Nurul Sakina Mokhtar Azizi et al. (2015) addressed that completing projects on time is an indicator of efficiency. It was highlighted by Ogunlana et al. (1996) that construction delays impact the time and cost of projects. A survey of the delays experienced in highrise building construction projects in Bangkok, Thailand, was undertaken and the result compared with other studies of delays and overruns around the world to determine whether there are special problems that generate delays for construction in developing economies. Resource supply problems were by far the most acute problems of the Thai construction industry in the boom years. The results of the study support the view that construction industry problems in developing economies can be nested in three layers: (a) problems of shortages or inadequacies in industry infrastructure (mainly supply of resources); (b) problems caused by clients and consultants and (c) problems caused by contractor incompetence/inadequacies. Conclusions recommend the need for focused effort by economy managers and construction industry associations to provide the infrastructure needed for efficient project management. Oliveros and Fayek (2004) stated that delays in the completion of construction projects are often an unavoidable circumstance. According to Tafazzoli (2017), delays in construction projects is a global problem that causes considerable losses for many economies. Due to the complexities in standardizing construction projects, efforts to mitigate risks of delay have not been adequately successful. A rudimentary step to prevent delays involves identifying the main potential causes, which may be different in each region. Requiring any time more than what is actually needed to complete a project, should be considered as a delay. However, in field conditions many tasks cannot be completed in the minimum required time due to unpredictable events, the interconnectivity of tasks, and other factors. Although the deterrent factors of the smooth progress of a project are, to some extent, taken into consideration in scheduling, the statistics indicate that a considerable amount of construction projects fail to finish on time. Delays during construction is a global phenomenon that has imposed immense costs on the construction industry. Some of the consequences of delay in construction projects are lawsuits between house owners and contractors, exaggerated prices, loss of productivity and revenue, and contract termination. It should be noted that late completion also indirectly causes such costs as the late opening of projects, and the losses may not always be easy to claim and compensate. Also, aggressive schedules, which are used as a common remedy to get back on track, are costly; they may affect the quality of work by increasing disturbance of work and loss of productivity. Since the construction industry is one of the most important elements of the economy in most countries, losses caused by construction delays can affect the whole economy. Therefore, it is essential to come up with ways to minimize construction delays. Toor and Ogunlana (2008) mentioned that studies in various developed as well as developing countries have shown that construction delays are common and one of the most recurring problems in construction projects. According to all studies above, delays have been happening in most, if not all, construction projects and causing very wide and large negative impacts. Resolution of the delays is therefore of very great importance.

4.3 Big Data in Construction

Lněnička (2016) stated that big data fundamentally mean datasets that could not be perceived, acquired, managed and processed by traditional technologies within a reasonable time, which indicates that efficient tools and platforms together with suitable methods have to be developed to analyse and process big data. According to Oussous et al. (2018), developing big data applications has become increasingly important in the last few years. Big Data has a complex nature that require powerful technologies and advanced algorithms. Provost and Fawcett (2013) addressed that big data mean datasets that are too large for traditional data processing systems, and that therefore require new technologies. Ajayi et al. (2018) studied on using the big data frameworks for designing a robust architecture for handling and analysing (exploratory and predictive analytics) accidents in power infrastructure. Big and Can (2018) concluded that construction firms are now using data to make better decisions, increase productivity, improve jobsite safety and reduce risks. Bilal et al. (2016) stated that there is currently no comprehensive survey of big data techniques in the context of the construction industry. Big data has three defining attributes (a.k.a. 3V's), namely (i) volume (terabytes, petabytes of data and beyond); (ii) variety (heterogeneous formats like text, sensors, audio, video, graphs and more); and (iii) velocity (continuous streams of the data). The 3V‘s of Big Data are clearly evident in construction data. To understand the subtleties of big data, we need to disambiguate between two of its complementary aspects: Big Data Engineering (BDE) and Big Data Analytics (BDA). Xi Chen et al. (2018) stated that big data is a collection of data sets so large and complicated that it becomes difficult to process using traditional data management tools. Likewise, Schönberger and Cukier (2013) proposed big data as "things one can do at a large scale that cannot be done at a smaller one, to create a new form of value". It adopts an inductive, qualitative case study method whereby the empirical data is collected using an ethnographic–action-meta-analysis research approach and triangulated with data from literature, ongoing debate, and other sources. The paper offers some insights on big data acquisition, storage, analytics, implementation, and challenges. X. Chen and Lu (2018) stated that the construction industry is responsible for undertaking some of the biggest and most expensive projects where huge volume of data concerning the resources and works throughout the life cycle of a facility. Therefore, data generated from construction activities is not an exception to the pervasive digital revolution in this industry. Many considerations have been given to the labors and objects involved in construction activities, such as construction safety, productivity and efficiency, and competitive advantages. Ismail et al. (2018) stated that the volume of data generated by the construction industry has increased exponentially following an intense use of modern technologies. The data explosion thus lead towards the big data phenomenon which is envisioned to revolutionize the construction like never before. Like any other technologies, big data is a disruptive paradigm and inevitably will give impact to the construction industry. As the industry is refocusing towards an improved productivity, the appeal to embrace big data is certain given the value it offers. This certainly will benefit construction akin to the manufacturing and the retail industry alike. Nevertheless, a review of the literature suggested a limited coverage on the potential application of big data in construction as compared to other industries. This limits understanding of its potential, where the industry is seemingly unaware thus could not relate and extract its real value. Hence, this study aims to draw insights on the specific areas of construction big data research. The research objectives include: (1) to analyse the current extent of construction big data research; (2) to map out the orientation of the current construction big data research; and (3) to suggest the current directions of construction big data research. This resulted in the theoretical orientation which was conceptualized as: (1) project management; (2) safety (3) energy management; (4) decision making design framework and (5) resource management. Martínez-Rojas et al. (2012) stated that Construction is an extremely information-dependent industry in which a project's success largely depends on good access to and management of data. Effective project management requires the characterization of its challenging issues and the use of appropriate tools for data handling. For this purpose, the construction industry is increasingly adopting the use of information and communication technologies (ICT) in recent years. Given the acknowledged potential of ICT to bring about improvements in other industries, many initiatives have been undertaken to develop appropriate tools to support various tasks during the construction project lifecycle. This paper focuses on the proposals that use ICT to provide access to the data and take advantage of this access to manage crucial issues within project management such as costs, planning, risks, safety, progress monitoring, and quality control. The authors will demonstrate that suitable data handling facilitates and improves the decision-making process and helps to carry out successful project management. Motawa (2016) stated that with the rapid development in the internet technologies, the applications of big data in construction have seen considerable attention. While many industrial sectors such as the health and transport sectors have started to use big data resources, the construction sector is still behind. Safa and Hill (2019) stated that capital construction projects generate massive amounts of data throughout the course of their project lifecycles. Ordinarily, this data is collected and stored in databases providing a historical record of the project. Similar construction projects can be used to compare the data taken from each and better predict the cost, time, and efficiency for future projects. By using data mining, big data analysis can potentially save hundreds of hours planning, organizing, and assigning projects by using data that has already been recorded. To allow for a quick and efficient construction site, managers use big data to organize the construction site and plan when the construction will take place based on data from outside factors such as traffic and the weather. You and Wu (2019) stated that with the advent of big data era, the construction industry has focused on processing large quantities of engineering data and extracting their value. However, inaccurate manual entries and delayed data collection have created difficulties in making full use of information. They proposed a big data infrastructure called the enterprise integrated data platform (EIDP) for use by construction companies. Zhang et al. (2015) stated that with the improvement of companies' information technology application and the advent of big data era, the project cost-related data can be completely and systematically recorded in real time, as well as fully utilized to support decision-making for construction project cost management. In this paper, a system for tender price evaluation of construction project based on big data is presented, aiming to use related technique of big data to analysis project cost data to give a reasonable cost range, which contributes to obtaining the evaluation criterion to support the tender price controls. The paper introduced the data sources, data extraction, data storage and data analysis of the system respectively. The before-mentioned studies indicate that big data application in construction is very scarce and one for delay problem resolution does not exist.

4.4 Artificial Intelligence in Construction

Ai et al. (2019) stated that Relative to banking, finance or healthcare, construction is still a small market for artificial intelligence. They classify the major applications for artificial intelligence in construction and building under the following categories: (1) Planning and Design (2) Safety (3) Autonomous Equipment (4) Monitoring and Maintenance. J. H. Chen and Hsu (2007) expressed that a hybrid Artificial Intelligence (AI) model, the Hybrid ANN-CBR Model (HACM), is developed utilizing the AI branches of Artificial Neural Networks (ANN) and Case Based Reasoning (CBR). It can be concluded that it is feasible to link ANN and CBR together to provide a tool with a relatively high rate of prediction accuracy and a conceptual model to solve potential severe disputes caused by change orders. Kinshuk (2014) stated that through his paper, he explore the ways in which AI can assist in the goal of making construction sites safe. Artificial Intelligence (AI) is defined as the capability of a machine to imitate intelligent human behavior. Artificial Intelligence is being utilized in the construction industry in equipment, administration, construction methodology, and post-construction. Klashanov (2016) mentioned that in construction one of the important factors of the effective development of the construction production is improving the methodology of management, as an economic entity. This became especially possible in view of the rapid development of computer technology and logical-linguistic methods. Active application of information and computing technology allows you to select economically feasible methods of management based on reliably grounded methods of artificial intelligence. Labonnote et al. (2017) stated that Artificial Intelligence is demonstrating new possibilities in the way computers can inform and actively interact with the design process. Ok and Sinha (2006)'s study develops and compares two methods for estimating construction productivity of dozer operations (the transformed regression analysis, and a non-linear analysis using neural network model). It is the hypothesis of this study that the proposed neural networks model may improve productivity estimation models because of the neural network's inherent ability to capture non-linearity and the complexity of the changeable environment of each construction project. The comparison of results suggests that the non-linear artificial neural network (ANN) has the potential to improve the equipment productivity estimation model. Yakhchali et al. (2016) stated that the artificial neural network approach is employed to predict the rates of probable time and cost claims in the projects. It is observed that AI application in construction industry, especially for delay problem resolution, is very limited and not found respectively.

5 METHODOLOGY

This study is conducted as shown in Fig. 1 and separated into 5 stages as follows:

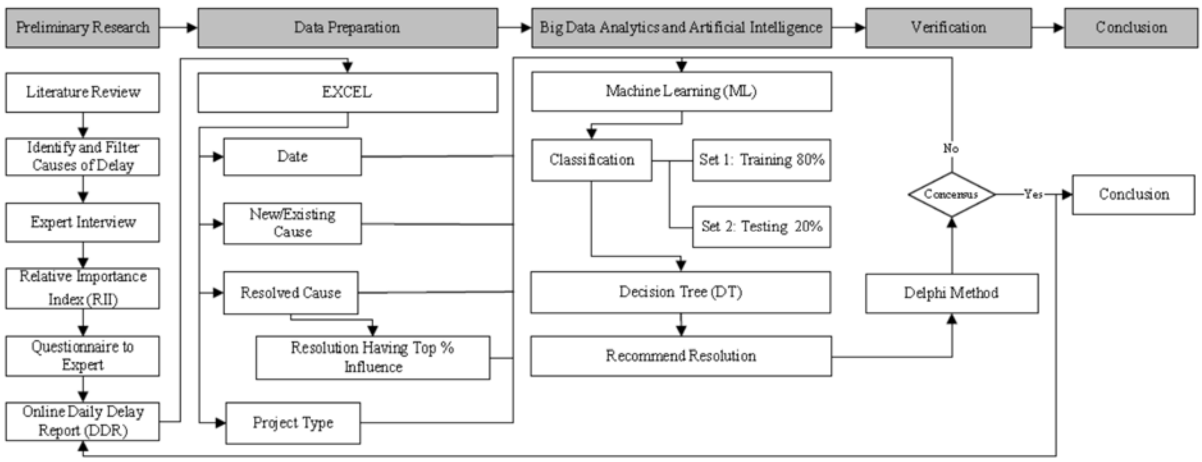

Fig. 1: Methodology

5.1 Preliminary Research

This stage starts with reviews of related literatures in order to explore meaning, importance and causes of delays in construction projects. The causes are then identified and filtered to eliminate duplication and inconsistency. The filter process provides a shortlisted causes for the next step which is expert interviews. Twelve experts are interviewed and asked to rate importance of each cause based on the LIKERT scale as well as to recommend solution(s) of each cause. Results of the interviews were then analyzed for Relative Importance Index (IRR). The causes with IRRs of more than 50% are selected to be included in an online Daily Delay Report (DDR). The report also includes recommended resolution(s) of each cause. Twenty projects are selected to daily complete and submit the report. Data of the report are then processed to the next stage.

5.2 Data Preparation

EXCEL is used to receive, store and process the required data which are date, new/existing cause, resolved cause, resolution having top % influence, and project type. Such process is to prepare the data of each day of each project so that they are ready for the next stage.

5.3 Big Data Analytics and Artificial Intelligence Application

This stage involves using Machine Learning (ML) to process the data from the Big Data Storage. ML is a combination of Big Data Analytics and Artificial Intelligence as shown in Fig. 2 and it has five techniques as shown in Fig. 3 including Classification which is used in this study. Classification is further divided into seven algorithms and Decision Trees (DT) is one of them and is used in this study. Data from the last stage are randomly split into 80% and 20% for training and testing of DT respectively. This stage will result into recommendation of problem resolution.

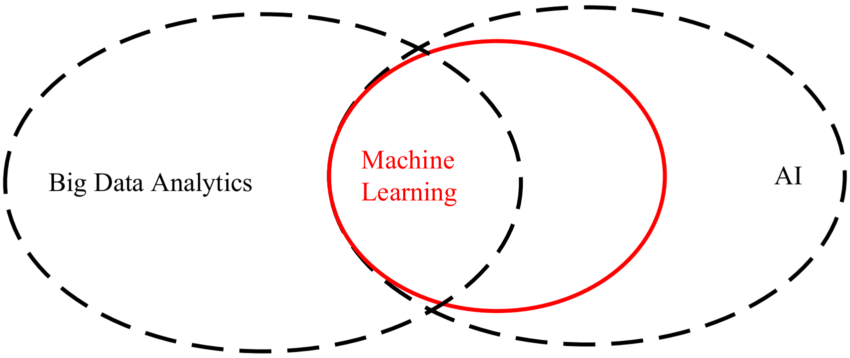

Fig. 2: Multidisciplinary nature of Machine Learning (Adapted from Bilal et al. (2016))

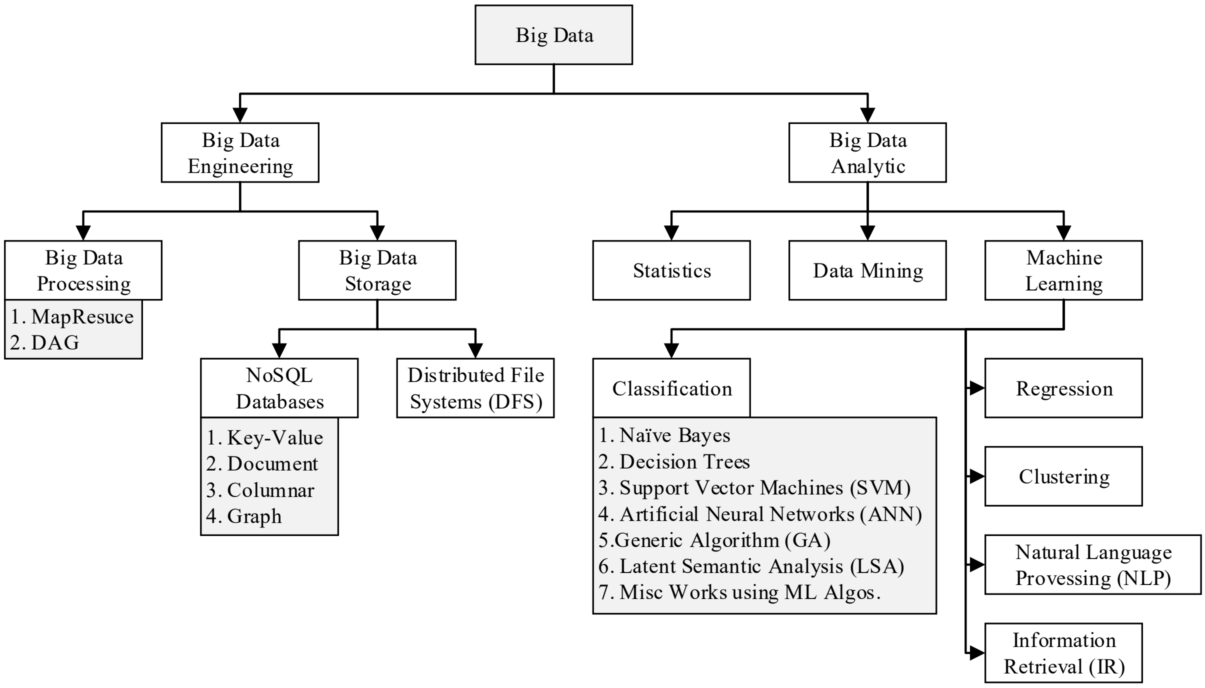

Fig. 3: Structure of Big Data (Bilal et al., 2016)

5.4 Verification

In this stage, Delphi method is used to verify whether the recommended resolution meets the 75% consensus threshold. If so, the recommendation is fed back to the DDR so that a concerned person can consider and make decision on how to apply the recommendation. Vice versa, the experts' opinions are sent back to ML for re-training and re-testing. This process is repetitive until the threshold is achieved.

5.5 Conclusion

After meeting the consensus threshold, the study is concluded and further recommendation is reviewed and then provided.

6 RESULTS

6.1 Causes of Delay

Nineteen literatures as shown in Table 1 are found related to this issue. From all of them, total one hundred seventeen causes of delay are extracted and identified as shown in Table 2. However, some of the causes are found to be subset of others. We therefore filter them out and find remaining forty eight causes to be outstanding. Relative Importance Index (RII) of LIKERT scale by experts results into forty four causes having RII of more than 50%. Resolutions to these causes are recommended by experts via questionnaires.

Table 1: Nineteen literatures regarding causes of delay

	Author(s)	Year	Location	Organization	Type of Project	#Resp	Respondents	Analysis Method
1	Assaf and Al-Hejji (2006)	2006	Saudi Arabia	Public and Private	-	57	Client, Contractor, Consultant	Importance Index, Spearman
2	Odeh and Battaineh (2002)	2002	Jordan	Public and Private	Building, Roads,Water and sewer	100/50	Contractor, Consultant	RII,Spearnan
3	Owolabi et al. (2014)	2014	Nigeria	-	Residential, Office, Industrial, Civil, Institutional	90	Client, Contractor, Consultant	Mean Index Score
4	Sambasivan and Soon (2007)	2007	Malaysia	Public Works Department of Malaysia	Building, Infrastructure, Mechanical and electrical	150	Client, Contractor, Consultant	RII,Spearnan, Correlation
5	Haseeb et al. (2011)	2011	Pakistan	Government, Private and Semi Government Organization	-	120	Client, Consultant, Contractor, Subcontractor	Likert Scale, Mean, Mode
6	Aziz (2013)	2013	Egypt	Private, Public and Local General Construction Firm	Wastewater projects	2700	Consultants, Managers, Engineers, Contractors	RII
7	Fugar and Agyakwah-Baah (2010)	2010	Ghana	-	Building	130	Client, Contractor, Consultant	RII,Spearnan
8	Orangi, Palaneeswaran, and Wilson (2011)	2011	Australia	Linear Construction Project	Pipeline Project	-	Project Managers	Scale
9	Kazaz, Ulubeyli, and Tuncbieki (2012)	2012	Turkey	TCA (Turkish Contractors Association)	-	71	Contractor	RII
10	Ogunlana et al. (1996)	1996	Thailand	Resident, Office, Hotel, Hospital	9-52 Stories Building	30	Designer, Client, Contractor, Consultant	Percentage Respones
11	Sunjka and Jacob (2013)	2013	Nigeria	Niger Delta Region.	Infrastructural and Utilities Projects	83	Client, Contractor, Consultant	Factor Analysis, ANOVA, T-Test
12	Santoso and Soeng (2016)	2016	Cambodia	Public and Private	Rroad Construction Projects	153	Contractor, Consultant	Likert Scale, Importance index
13	Abd El-Razek et al. (2008)	2008	Eygpt	-	Building	74	Client, Contractor, Consultant	Likert Scale, Importance index
14	Songer, A. D, et al.(1997)	1997	US	Public-Sector Selection of Design-Build	Building, Industrial, Heavy & Highway	88	Client, Experts	AHP
15	Odeyinka and Yusif (1997)	1997	Nigeria	-	Housing	95	Client, Contractor, Consultant	Scales, Index
16	Toor and Ogunlana (2008);	2008	Thailand	Suvarnabhumi International	Airport	76	Designer, Client, Contractor, Consultant	Likert, ANOVA
17	Shahsavand, Parvaneh et al. (2017)	2017	Iran	Iranian construction industry	-	175	Client, Contractor, Consultant	RII, ANOVA, Pearson
18	Mohammadsoroush, Tafazzoli (2017)	2017	US	50 States	Building, Highway, Infrastructure	219	Designer, Client, Contractor, Consultant	RII
19	Pittayaporn and Jakrapong (2018)	2018	Thailand	-	Oil and Gas	134	Contractor, Supplier	Likert, Spearman, CFA

Table 2: One hundred seventeen causes of delay

	Causes of Delay	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
1	Unrealistic project scheduling	■	■								■	■					■	■	■	■
2	Frequent breakdowns of construction plant and equipment		■	■	■						■		■			■		■		
3	Late payment by the owner for the completed work				■	■				■		■	■				■	■	■	■
4	Poor site management	■	■		■	■			■	■	■	■	■				■	■		■
5	Delay by subcontractor	■			■													■		
6	Conflicts in subcontractors schedule	■																■		
7	Rain effect on construction activities		■	■									■				■	■		
8	Price fluctuations			■			■	■			■		■				■	■		■
9	Imported materials										■									
10	Type of construction contract	■	■		■		■	■				■					■			
11	Legal disputes		■					■									■		■	
12	Bad weather conditions	■	■	■				■				■		■	■		■	■		
13	Rework due to the construction errors		■		■				■									■		
14	Poor labor productivity	■	■				■						■				■	■		
15	Shortage of materials on site	■	■		■	■		■	■		■	■				■		■		
16	Unskilled equipment operators										■		■					■		
17	Accidents due to poor site safety						■	■						■	■			■		
18	Project size													■	■					
19	Poor communication and coordination	■	■	■	■			■	■			■	■				■	■	■	■
20	Unavailability or delay of utilities in site	■					■										■	■		
21	Poor ground conditions	■	■					■					■				■	■		
22	Complexity of project													■	■			■	■	
23	Delays in obtaining permit from municipality							■							■			■	■	
24	Lack of labor supervision						■										■			
25	Construction method		■					■				■	■				■	■	■	
26	Labour absenteeism						■					■	■	■			■			
27	Lack of high-technology mechanical equipment		■	■	■	■							■			■	■	■		
28	Late delivery of material	■					■	■			■					■		■		
29	Effect of social and culture factors	■							■									■		
30	Design changes	■	■		■			■					■				■	■	■	
31	Personal conflicts among labors	■					■					■						■		
32	Confusing and ambiguous requirements																■			
33	Improper project feasibility study																■	■		
34	Lack of owner's representative																■		■	
35	Lack of clear bidding process																■	■		
36	Slow responses from the client organization																■			
37	Low constructionability of design																■			
38	Over-design incresing the overall cost																■			
39	Errors and omission in design documents																■		■	
40	Lack of standardization in design																■			
41	Lack of involvement during construction stage																■			
42	Inadequate experience of consultant staff																■	■		
43	Slow responses from the consultant																■	■		
44	Failure to utilize tools to manage the project symmetrically																■			
45	Poor leadership on part of the project manager																■			
46	Lack of timely decision and corrective action																■		■	
47	Large number of participants of project																■			
48	Involvement of several foreign designers and contractors																■			
49	Poor project planning and control																■			
50	Bureaucracy at the workplace																■			
51	Lack of top management commitment																■			
52	Lack of project manager experience																■			
53	Unreasonable risk allocation																■			
54	Lack of competent subcontractors/ suppliers																■			
55	Contractor's financial difficulties																■	■	■	
56	Unavailability of local labour unions																■			
57	Severe overtime and shifts																■			
58	Hign interest rate																■			
59	Increased cost due to high inflation during the project																■			
60	Shortage of funding																■			
61	Poor contract management																■		■	
62	Legal issures arising due to local government rules and regulations																■	■		
63	Lack of cooperation from local authorities																■			
64	Incomplete contract documents																■	■		
65	Inappropriate method of dispute resolution																■			
66	Unclear lines of respoensibility and authority																■			
67	Lack of coordination among project team members																■			
68	Lack of IT use for indormation, coordination and interface management																■			
69	Inaccurate site investigation																■			
70	Poor site access or availability																■			
71	Site polution and noise																■			
72	Poor site shortage capacity																■			
73	Difficult site terrain to work																■			
74	Poor site management and slow clearance																■			
75	Poor safety conditions on site																■			
76	Force majeure and acts of God																■	■		
77	Non-value added works																■			
78	Poor quality control over project																■		■	
79	Fraudulent practices and kickbacks																■			
80	Unverestimation of cost of projects																	■		
81	Delay to furnish and deliver the site to the constractor by owner																	■	■	
82	Late in revising and approving design documents																	■	■	
83	Type of construction contract																	■	■	
84	Suspension of work by owner																	■		
85	Ineffective delay penalties by owner																	■	■	
86	Unavailability of intensives for contractor for finishing ahead of schedule																	■		
87	Delay in approving shop drawing and sample materials																	■		
88	Poor supervision																	■		
89	Low bid																	■		
90	Delays in inspection and testing of work																	■		
91	Inadequate contractor experience																	■	■	
92	Frequent change of subcontractors because of their inefficient work																	■		
93	Inflexibility (rigidity) of consultant																	■		
94	Unclear and inadequate details in drawings																	■		
95	Misunderstanding of owner's requirements by design engineer																	■	■	
96	Inadequate design team experience																	■	■	
97	Changes in material types and specifications during construction																	■		
98	Delay in manufacturing special building materials																	■		
99	Late procurement of materials																	■		
100	Late in selection of finishing materials due to availabilitity of many type in the market																	■		
101	Escalation of material prices																	■		
102	Unqualified workforce																	■		
103	Shortage of labors																	■		
104	Low productivity and effiiciency of equipemnt																	■		
105	Traffic control and restriction at job site																	■		
106	Inadequate definition of substantial completion																	■		
107	Unnescessary interference by the owner																		■	
108	Contractor inefficiency (in providing the labour, equipment and material and handling sub-contractors)																		■	
109	Inadequate site assessment by the designer during design phase																		■	
110	Financial difficulties with the designers																		■	
111	Lack of safety rules and regulation																			■
112	Defective materials and mistakes during construction																		■	■
113	Late delivery of materials and equipment																		■	■
114	Supply of low quality materials																			■
115	Supply of unqualified and unskilled workers																		■	■
116	Late supply of workers																			■
117	Supply of low effeciency equipment																			■

6.2 Online Daily Delay Report (DDR)

The forty four causes and experts' recommended resolutions from above are used to develop online DDR as shown in Fig. 4. MACRO functions and spreadsheets of EXCEL are utilized for the purpose. Twenty projects use DDR to daily report and submit.

Fig. 4: Online DDR

6.3 EXCEL Data

MACRO functions and spreadsheets of EXCEL are also used to receive, store, process data from DDR. Data processed by EXCEL are date, new/existing cause, resolved cause, resolution having top % influence, and project type.

6.4 Resolution from Decision Trees (DT)

We adopt RapidMiner software with DT function to process the data from BDS. Accuracy of results are getting better and better with more and more daily data available. 90% accuracy is expected before passing recommended resolution to process Delphi.

6.5 Delphi Consensus

After passing the expected accuracy from ML, the recommended resolution is verified by Delphi method. 75% consensus threshold is to be met.

7 CONCLUSION

Potential use of Big Data and Artificial Intelligence for delay problem resolution by construction management consultancy services in Thailand is proven. Creation of online DDR enables convenient report and collection of data required for the system. The data then grow quickly and BDE application such as BDS can handle them. The data require efficient analysis, process and recommendation. AI can facilitate such requirement effectively due to its intelligent natures. It can be seen from this study that Big Data and AI applications provide comprehensive and real-time resolution to delay problem thus responsible person can consider and take appropriate action accordingly. This enhances decision making with prompt and rapid analysis of all relevant and available data.

The authors expect that this study forms a basis of applying Big Data and Artificial Intelligence for delay problem resolution by construction management consultancy services in other countries around the world. In addition to the regional issue, it is also recommended that further research about objective measurement of resolution's influence and impacts from other project characteristics beyond type should be conducted. Such research definitely improves comprehensiveness and thus efficiency of the resolution recommendation.

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How can Virtual Reality and Augmented Reality Support the Design Review of Building Services

Meinhardt Thorlund Haahr
Department of Technology UCN, Denmark

Kjeld Svidt and Rasmus Lund Jensen
Department of Civil Engineering Aalborg University, Denmark

ABSTRACT: *Cost overrun, failure and defect in civil engineering are known problems, which among other things are caused by increased complexity, more rigorous requirements for the building services, indoor environment and building energy performance. Existing design and design review are primarily based on 2D drawings and descriptions and less on 3D models, which places demand on human interpretation. Virtual reality (VR) and augmented reality (AR) are technologies that allow a user to experience a computer-generated environment or add virtual models and information as a layer on top of the physical world. These technologies make it possible to inspect building design proposals as intuitively as in a real building and with minimal need for interpretation. Research from the manufacturing industry shows that the quality and productivity can increase significantly with the aid of VR and AR. The aim of this study is to identify possibilities for new VR and AR supported design review processes, that potentially can improve the quality of building services. This paper reports an interview-based qualitative study, where five representatives from different parts of the Architecture, Engineering and Construction (AEC) industry in Denmark were asked to go in to detail about 1) failure and defects, 2) traditional design review and VR and AR supported design review. This study showed that VR supported design review can potentially replace a physical mock-up and be suitable in the design phase, especially when reviewing constructability. Furthermore, AR supported design review clearly has a potential in the construction phase. It is suggested that the VR and AR supported design review take place in the existing design review processes. Furthermore, an information filtering process in the VR and AR setup, that is controlled by the project's type, complexity and users, is suggested.*

KEYWORDS: *Augmented Reality, Virtual Reality, Design Review, Building Services, Failures and Defects, Information Filtering.*

1. INTRODUCTION

A construction project is considered successful if the construction is done on time, at agreed price and quality, and achieves a high degree of customer satisfaction. Unfortunately, there are many examples of this not being achieved (Akin, 2011; Shirkavand, Lohne and Lædre, 2016). It is the impression of the authors, as well as Shirkavand et al. that problems with delays, failure and defects are, among other things, due to increased complexity and increasing demands from the building services, indoor climate and energy performance. The purpose of this paper is to identify new processes for design review, based on VR and AR, that can improve the quality of building services.

In 2008-2012, an examination of the constructional documentation regarding 100 buildings in Denmark was carried out, which showed that the average fulfilment of requirements was 43% (Hansen and Aagaard, 2013). At the same time, failures and defect is estimated to account for up to 10% of the total costs in the Danish construction sector (Statens Byggeforskningsinstitut, 2004). Shirkavand et al. find that defects related to building services is the area with most frequent negative deviations. Furthermore, they find that the main reason is incomplete or poor design (Shirkavand, Lohne and Lædre, 2016). Inadequate or improper execution of building services entail, that they cannot maintain the desired indoor climate, or they will provide the desired indoor climate with a considerably higher energy consumption than intended (Construction Products Association, 2016).

For decades, analyses of the AEC industry have uncovered low productivity development compared to other industries and other countries. Among other things, the Danish Ministry of Higher Education and Science points out the need for research in manufacturing processes and cooperation between the parties involved as a solution to lack of growth in the AEC industry (Schrøder, 2016). Design and planning of buildings and especially their building services is a complex process, since buildings are unique, the parties are many and different from project to project. In addition, several of the parties, such as users and building owner, are not necessarily building professionals. The current design, design review and execution processes are largely based on 2D drawings, descriptions and to a lesser extent on 3D models, which is inadequate (Thuesen and Ryesgaard, 2018) and a demanding cognitive load (Hou, 2013). When using VR and AR it is possible to obtain a more natural and intuitive design review, like that performed in constructed buildings. These years access to VR and AR is moving from a narrow professional market to the wide consumer market. This transformation creates an accessibility and development that makes a broad use in the AEC industry, natural even for smaller companies. Experience from the manufacturing industry shows that quality and productivity can be significantly enhanced by these technologies (Hou and Wang, 2013; Rios *et al.*, 2013; Richardson *et al.*, 2014; Hou, Wang and Truijens, 2015; Wolfartsberger, 2019).

Based on the manufacturing industry's positive results, the question is raised, whether this can also be achieved in design review processes of building services. However, due to a building project's long, interdisciplinary and complex process, it is not obvious if, when or how VR and AR can provide value to the design review process of buildings. Resent research have investigated the potential of the technologies in the AEC industry, which indicate that they have a potential of enhanced productivity, shortened project duration, reduced conflicts, improved project collaboration, and reduction of rework (Bademosi and Issa, 2018). Nevertheless, one of the main risks is the extent that the technology is ready to be used in the AEC industry (Heinzel and Azhar, 2017).

This paper reports an interview-based qualitative study, where five representatives from different parts of the AEC industry in Denmark were asked to go in to detail about 1) failure and defects, 2) traditional design review and 3) VR and AR supported design review. The aim is to identify new VR and AR supported design review processes, that potentially can improve the quality of building services. This knowledge is important to target the development of methods and tools that gives value to the AEC industry.

2. METHOD

The aim of this study is to identify new possibilities for VR and AR supported design review processes. To clarify this research domain, a series of semi-structured interviews were conducted, which can uncover rich descriptive data on the personal experience of the participants (Zorn, 2008). Furthermore, the information gathered can move the process from a general topic (domains) to more specific insights (factors and variables). Following William C. Adams guidelines (Adams, 2015), the design of the semi-structured interviews was based on an inductive approach, where the questions were open and investigating, following the three following topics:

- Topic 1: Failure and Defect in the AEC Industry
- Topic 2: Traditional Design Review of Building Services
- Topic 3: Virtual- and Augmented Reality based Design Review of Building Services

The interviews were conducted in connection with The Digital Days (DD), which is a 3 days convention within AEC that focuses on digital collaboration, -technologies and -communication (De Digitale Dage, 2018). During DD, students from UCN and Aalborg University create digital construction projects with guidance from experts from the Danish AEC industry. Out of all the participating experts only a few had experiences with building services, which was crucial for this study. Furthermore, the experts' knowledge and experience within AR and VR was diverse. Therefore, prior to the interview, the experts were introduced to the technologies. They were presented to a simple student 3D model in VR, see Fig. 2, and were shown an introduction video of AR, see Fig. 1.

In spite of the fact that the experts' knowledge and experience within AR and VR technologies in some cases were at a novice level, they were able to provide a practice-oriented knowledge within traditional and new possibilities for design review processes, which is the main purpose of the study. Five of these participants were selected for the interview, see Table 1, which, in our opinion, was sufficient to give an idea of how VR and AR can support design review of building services. However, a larger number of interviewees would increase the generalizability of the study and improve the validity of making general conclusions.

The interviews where first recorded and later transcribed. The transcribed interviews were then condensated into sub-topics emerging from the data on three different levels, following a grounded theory approach (Strübing, 2007). 1) Open coding: Going through each sentence and marking keywords and sentences, in which clearly illustrates the expert's opinion in relation to the problem area. 2) Axial coding: Common features from the different experts is identified and categorized. 3) Selective coding: Generalizing the identified categories into themes.

Table 1: Background of the interviewed participants. Scale: Novice, Advanced, Competent, Skilled and Expert

No	Background	Present occupation	VR	AR	Building Services	AEC industry
1	M.Sc. in CMBI[1]	Developer	Skilled	Skilled	Advanced	4 y
2	P.Ba. in ATCM[2]	Eng. Consultant	Competent	Advanced	Advanced	7 y
3	P.Ba. in ATCM[2]	Contractor	Novice	Novice	Competent	10 y
4	P.Ba. in ATC[2]	Eng. Consultant	Competent	Advanced	Advanced	6 y
5	M.Sc. in CE[3]	Eng. Consultant	Novice	Novice	Expert	15 y

[1] CMBI: Construction Management and Building Informatics
[2]ARCM: Architectural Technology and Construction Management
[3]CE: Civil Engineering

3. RESULTS

This section consists of three subsections, which present the results from the semi-structured interviews with the experts from the AEC industry. The sections summaries the prevailing answers and main tendencies from the interviews, in relation to the three themes mentioned above. The interviews are also summarized in Table 2.

Table 2: Summarization of the interviews, where Axial codes and selective code based on the open codes

Open code	Building services; Routing; Installation room; Project complexity; Poor execution; Poor design; Lack of time; Interdisciplinary collaboration; Non-disciplinary	Design phase; Construction phase; BIM; 2D drawings; Mock-up; Interdisciplinary collaboration; Non-disciplinary; Regular meetings; Collision control; Coordination	Comprehend ability; Constructability; Intuitively observation; Abstract level; Accessibility; Information level; User type; Complexity; Information management; Traceability
Axial code	Failure and defect	Traditional design review	AR and VR supported design review
Selective code	Improving design quality of building services in AEC industry		

3.1 Failure and Defect in the AEC Industry

As stated in the introduction, failures and defects in the AEC industry are well-known problems. In this subsection, the experts were asked to comment on this problem in relation to their own practice as well as in general.

3.1.1 To what degree are failures and defects actual problems?

The five experts agree that failures and defects in the Danish AEC industry are genuine problems. As a matter of fact, four experts directly state that it is a huge problem. The issue has existed for a long time and has not decreased over time, according to expert no. 5. On the contrary, he states that the problem has especially increased in public projects.

The experts also agree that the problem is often related to the building services. The experts appoint installations room, shafts, suspended ceiling and branch points in general as being typical places of attraction. When asked, to what degree are failures and defects an actual problem, expert no. 3 replied:

"A big problem. I have been involved in projects where building services clash in the suspended ceiling, which is the primary place where things go wrong"

Especially in complex building projects where there are few repetitions, the amount of failures and defects increases. It is implicit that with unique complex buildings, the above-mentioned building services also become more complex. As opposed to simple apartment buildings, were building services is monotonous with many repetitions. Expert 3 explains:

"In student apartments, where the setup is fairly simple, the risk for defects is not particularly high, because when you have built one apartment, you have already defined the rest of them"

3.1.2 Why do failures and defects arise?

It is important to note, that failures and defects arise both during the design phase and the construction phase. In some cases, mistakes are made in the project material by the design team, where in the worst-case failures and defects are first discovered in the construction phase. As in other cases, mistakes are made in the construction phase, even though the project material is correct. In general, the experts agree that the overall reason for failures and defects is lack of time. In this subsection, both failures and defects are investigated more thoroughly.

It is important to note that in a turnkey contract, which is the most commonly used contract form in Denmark at the time, the subcontractors are not known until the project material is defined. It's on the very basis of this project material that the subcontractors make an offer. In most cases, the turnkey contractor will pick the lowest bidding, in order to save money. In some cases, the turnkey contractor will stick to the engineering consultant's project material, in that way failures and defects in the design, if any, are not his responsibility. In other cases, the turnkey contractor will give the subcontractor a certain freedom to carry out his work, in that way the contractor will get the cheapest solution.

Generally, all experts agree that one of the main reasons that failure and defect arise, is the lack of collaboration between the different parts of the AEC industry as well as interdisciplinary collaboration between the different disciplines within building services, such as heating, ventilation, plumbing etc. In the design phase it is common for the designer to focus his work within his own discipline, e.g. ventilation. Expert no. 2 explains a typical situation:

"When designing cable trays, one is not typically looking at ventilation channels, which results in a collision"

Expert no. 2 continues explaining, that when a designer does not know how to solve a routing problem, he will intentionally create a collision, because he knows it will be solved later in a collision meeting. The drawback is that it can be time consuming to rectify the flaws.

In relation to the construction phase, expert no. 4 mentions that especially in shafts and in suspended ceilings, where cored-out openings in concrete elements define the routing for building services, the first subcontractor (e.g. ventilation) interprets this as the fastest and cheapest for himself, which later makes a challenge for the other subcontractors. Similar tendencies are also described by the other experts.

With the exception of major contractors, the design review and execution processes in construction phase is based on 2D drawings, even though the building is designed in 3D by the use of Building Information Modelling (BIM). Two of the experts argue, this entails loss of information as well as requires increased knowledge of building services of the persons involved. Furthermore, in order to keep the drawing simple, such a 2D drawing will typically only contain information on one discipline, making it difficult to coordinate in relation to other disciplines.

Coring-out concrete elements for building services routing is time consuming. Today it is common that cored-out openings in concrete elements is done in the production, saving a lot of time on the construction site. However, due to the long waiting list and production time of the concrete elements, these openings need to be fixed quite early in the designing phase, which appears to be very difficult.

3.2 Traditional Design Review of Building Services

In the AEC industry it is common practice to go through design reviews in both the design and construction phase. There are many aspects of design review, such as an informal review of the ventilation system by the designer himself, internal design review of the whole and/or parts of the building service systems as well as design review of the whole building service systems by all/different parts of the AEC. In this subsection traditional design review methods are investigated.

3.2.1 How is design review in the design process performed?

Today the majority of design teams, such as architects and engineering consultants, design buildings in 3D by use BIM as opposed to computer aided design. To a degree, depending on the level of information, BIM allows the designer to create a digital copy of a building.

Typically, when a designer, e.g. ventilation engineer, designs the ventilation system, he will only relate to his own discipline, since anything else will be difficult to comprehend. This especially applies in complex buildings. This often result in defects such as collisions between various parts of the building services. Today it is common that the design team organizes regular meetings, typical weekly, where these collisions are solved. In a turnkey contract, it is common that the contractor attends these meetings if and when needed. According to expert no. 4, it is often at these meetings most failures and defects in the design is discovered.

Design reviews is based on the 3D model as well as the information the model contain. Expert no. 4 finds that collisions are typically found automatically by software, such as Solibri, and attended to at the above-mentioned meetings. However, expert no. 2 points out that constructability is not solved by this software. He states:

> *"Collision contlrol software is not more intelligent than the person sitting behind the screen, in that way a person could easily model something that is not constructible, without it being detected by the software"*

3.2.2 How is design review in construction phase performed?

As mentioned in subsection 3.1.1. most contractors perform design review on the basis of 2D drawings. Typically, the contractor arranges design review meetings on a regular basis, where the consulting engineer and subcontractor(s) participate. Here they coordinate workflow so that everyone knows how and when an agreed task is executed.

In order to perform a thorough design review, expert no. 3 mentions that they build a physical mock-up of the problematic rooms, e.g. installations room etc. In that way they can get a spatial understanding as well as review a com plex solution. The expert underlines that this is an expensive solution, however, he also states that it is an efficient method to achieve constructible solutions.

During the construction phase the engineering consultants also go through a design review of the building services in the construction phase. This is to make sure that the building services are installed according to the design.

3.3 Virtual Reality and Augmented Reality supported Design Review

As described in the section METHOD, the experts where introduced to AR, se Fig. 1, as well as experienced VR, se Fig. 2. In this section, a VR and AR supported design review is investigated, followed by the section DISCUSSION, where a suggestion to how VR and AR can support the design review of building services.

Fig. 1: (Left) AR view of ventilation system in a meeting room. (Right) Viewpoint of the user. This picture is a screen shot from an AR demonstration video from a student project at Aalborg University

3.3.1 Can VR and AR supported design review be of value for the AEC industry?

All the interviewed experts agree that VR and AR technologies have great potential, however the problem is to identify how these technologies bring value. As expected, the experts fully agree that VR has its potential in the design phase, since most projects today are already designed in a fully compatible digital model. Furthermore, the experts agree that AR has its potential in the construction phase, since AR makes it possible to display the digital model augmented on the real building.

Expert no. 2 and 4 argue that designing and design review in 3D is an efficient method to reduce failures and defects. However, they do not entirely agree that VR would be better suited than a traditional design review in a BIM software, such as Revit. They present 3 main arguments: 1) Collision control is already done automatically, 2) it's important to work in 3D view and simultaneously keep track of ones position in a 2D plan and 3) during the weekly interdisciplinary meetings of the design team, it is important to be able to see the same view on the screen and have eye contact when discussing solutions. Although, expert no. 2 clarifies that when the question of general accessibility as well as accessibility in relation to building services arises, existing design reviews is shortcoming.

Based on 2D drawings it is difficult to comprehend the constructability, according to expert no. 1. With a VR view of the building site it is easier to see how the work should be executed. Furthermore, a BIM model contains a large amount of information, which is lost in a 2D drawing. He states:

"With a 3D model one can see, how the design of building service system is intended"

Among other things the job descriptions as a project manager for the contractor, includes overall responsibility as well as design review. However, the project manager does not always hold knowledge of the various disciplines within building services, which can make it difficult to completely understand the intended design. For example, Expert no. 3 mentions that it is quite common for him to think, that there is enough space available for the ventilation system, but later he finds outs that there isn't, because he didn't focus on the different discipline, e.g. where the electrical engineer has placed the lighting units. He continues and adds, that VR makes it possible to observe the building services intuitively as in the real world, which gives him an ocular proof.

As an example, during the VR walk through a student's digital model, see Fig. 2, he noticed that a ventilation duct is modified from circular to rectangular, which is designed in order to keep the suspended ceiling at a certain level. Straight away he commented, that solution is way too expensive in the real world. Furthermore, he states that VR would make it possible to make a digital mock-up as an alternative to a physical mock-up, which is costly.

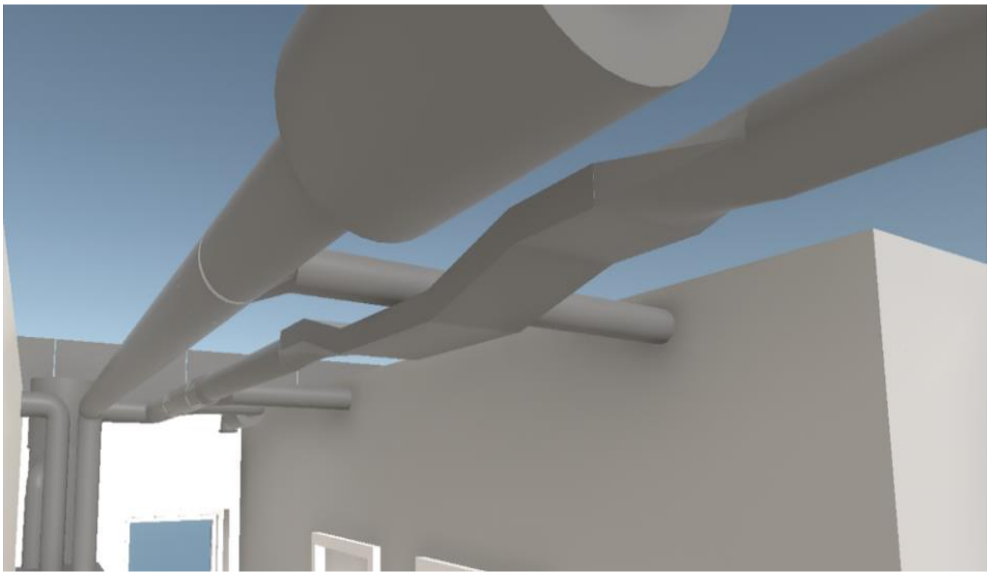

Fig. 2: VR view of a ventilation system proposal in an apartment. The proposal is designed by a team of AEC students during the convention, The Digital Days, in Aalborg (De Digitale Dage, 2018).

3.3.2 Which functionalities beneficial for a AR and VR setup?

A VR and AR setup makes it possible to access information from BIM. However, as the experts argue, an overflow of information makes it difficult to comprehend and understand a design. The key word is to keep it as simple as possible. Therefore, it is important to limit the amount of information to the appropriate level, in that way the user does not get disturbed.

Expert no. 4 argues that the information needed will vary depending on the user. E.g. when a contract manager uses the VR or AR technology, in contrast to the ventilation fitter, he does not need to know what type of hinge is used and the distance between the them. Therefore, it would be beneficial to include a user type, where type of information accessible is predefined based on who uses it.

Expert no. 3 argues that the level of information will also vary depending on the complexity as well as the type of the project. E.g. when building a hospital in contrast to a university faculty, different information is needed. Furthermore, when buildings are certified in according to a sustainability assessment standard, such as DGNB, additional requirements are set to the building services. In such a case expert no. 3 mentions, that he, as a project manager, would benefit from more specific information, such as information regarding the building automation system. Therefore, it would be beneficial to customize the amount of information, depending on the project as well as the user.

In the earlier mentioned design review meetings, between the different parts across the AEC industry, the failures and defects can be managed and taken care of in real time. However, in other cases, e.g. when a contract manager identifies failures and defects on site, it is important to manage them in a useful and intelligent way. For example, expert no. 3 mentions one should be able to take a picture in the virtual environment including a message describing the problem. Furthermore, the message should also include the position in relation to the 3D model, so that the receiver knows where the issue is. The problem should be appointed to a specific user, who then will get a notification. According to expert no.1 traceability, as described above, in the information flow is the key to good management

4. DISCUSSION

The results show, that failure and defects in the Danish AEC industry are genuine problems, which is also emphasized in existing studies (Akin, 2011; Hansen and Aagaard, 2013; Aagaard, Brunnch-Nielsen and Hansen, 2014). Furthermore, it shows that defects and failure is often related to building services, which is also concluded by others (Shirkavand, Lohne and Lædre, 2016; Thuesen and Ryesgaard, 2018). Moreover, complex buildings increase the complexity of building services. This entail more failures and defects, which also is the impression of Shirkavand et. al.

The experts agree that both VR and AR have the potential to improve the design review processes, which is also estimated by Bademosi and Issa (Bademosi and Issa, 2018). VR makes it possible to experience the 3D model of the building in scale 1:1 long before it is constructed. Furthermore, AR is a similar technology that overlays virtual 3D models and information on the physical world. This gives completely new opportunities to show where and how the building services should be placed in the carcass. As described in 3.3.1. two of the interviewed experts argue that an existing design review in 3D is an efficient method to reduce failures and defects in the design phase. However, significant failures and defects are still a well-known problem in the AEC industry (Akin, 2011; Thuesen and Ryesgaard, 2018). Furthermore, a study by Shikavand et al. imply that incomplete and poor design is the main reason for defects in building services (Shirkavand, Lohne and Lædre, 2016). Moreover, Lin et al. find that a virtual environment based discussion in the AEC industry, is more effective than traditional. Therefore, the authors suggest VR supported design review in the design phase and AR- in the construction phase, see Fig. 3. Seeing that existing design review involve regularly coordination meetings and quality control at the end of design and construction phase, it is suggested that VR and AR technologies are put in to use here (Lin *et al.*, 2015). It is also suggested that VR supported design review is used instead of a physical mock-up and to evaluate the constructability of building services.

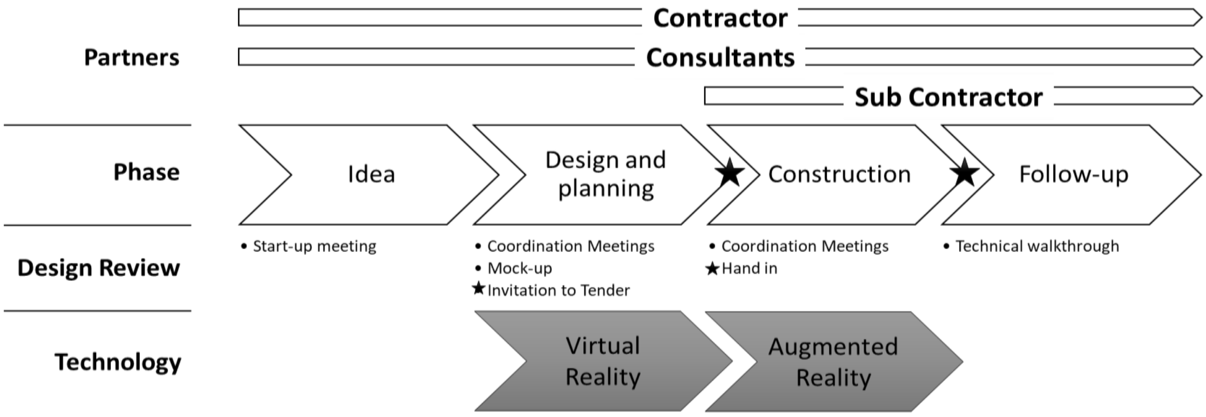

Fig. 3: Overview of a turnkey contract, showing which and where the identified, traditional design reviews are located and where VR and AR could be introduced.

An overflow of information can make it difficult to comprehend and understand a design. The results of this study indicate, that the information needed in an AR and VR supported design review will vary depending on the user and the complexity as well as the type of the project. BIM-based collaboration between experts of different disciplines, that requires appropriate model views that match their specific needs, is a known problem. Windisch et. al. suggest a filtering framework, that enables generation of various model views for a wide range of domains, tasks and applications in a consistent manner (Windisch, Katranuschkov and Scherer, 2012). This study suggests a similar information filtering process for the AR and VR setup, that is controlled by the identified parameters, see Fig. 4

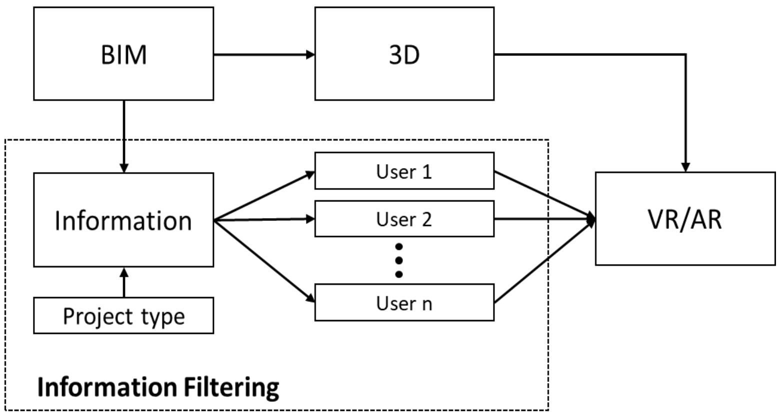

Fig. 4: An initial overview of an information filtering process in the VR and AR setup, that is controlled by the identified parameters.

5. CONCLUSION

The aim of this study was to identify possibilities for new VR and AR supported design review, that potentially can improve the quality of building services. The study was based on a qualitative study with semi-structured interviews of five representative experts from the AEC industry in Denmark. The main findings where:

- *Failures and Defects*: As indicated in existing research, the experts acknowledge that failures and defects in the AEC industry is a genuine problem. The more complex the building is, the bigger risk for mistakes. The problem often lies with building services, the experts appoint installations room, shafts, suspended ceiling and branch points. Furthermore, the experts agree that failures and defects arise both in design- and construction phase.

- *The Cause*: The failures and defects are often caused due to lack of collaboration between the different parts of the AEC industry, as well as lack of interdisciplinary collaboration between the different disciplines of building services. Furthermore, majority of contractors and subcontractors still use 2D drawings on site during the construction phase, which makes it difficult to comprehend.
- *Traditional Design Review*: Design review takes place during all phases. This could be individually or collaboratively between the different disciplines of building services as well as other parts of the AEC industry. This could be regularly coordination meetings as a part of an internal quality control or quality control before a handover. In the design phase, design review is typically carried out directly in BIM, whereas in the construction phase design reviews is typically carried out on the basis of 2D drawings.
- *VR and AR supported Design Review*: The experts agree that both VR and AR have the potential to improve design review of building services. Particularly, AR supported design review in the construction phase arouse an interest for the experts, since the technology is able to show virtual models and information on top of the physical world, which makes it possible to show how and where building services are to be placed in the carcass. On the other hand, two of the experts were less convinced about VR supported design review, since existing tools automatically detect collisions. However, if it's a question of constructability, such VR supported design review might come in handy. Furthermore, VR can potentially replace physical mock-ups.

This paper suggests a VR supported design review in the design phase and an AR supported design review in the construction phase, which takes place in the already existing design review, such as regular coordination meetings. Furthermore, an information filtering process for the VR and AR setup that is controlled by the project's complexity, type and user, is suggested.

Based on a semi structured interview, this study aims to identify new VR and AR supported design review processes. The interviews were conducted during DD, which entail that the selection of participants for the study was limited to experts from the Danish AEC industry. Due to the following reasons the conclusions given in this paper should not be seen as general, but rather indicative, as 1) the study is based on 5 interviews; 2) respondents consist of experts form the Danish AEC industry and 3) experts participating at a convention, such as DD, may in general be in favor of new technologies, such as VR and VR. Furthermore, our results especially in relation to the VR and AR shows an indication, as 1) the expert's knowledge within VR and AR was diverse and 2) the expert were asked to relate to the potential of VR and AR supported design review.

In our opinion, this study achieves to identify how VR and AR can support design review of building services. However, based on the limitations, future work should include a study of a more conceptualized VR and AR supported design review, that is based on a mix of qualitative and quantitative study. This could lead to a more in-depth understanding of how such a design review should work in practice as well as the effect of such an approach.

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EXPLORING DIFFERENT DESIGN SPACES – VR AS A TOOL DURING BUILDING DESIGN

Mattias Roupé, Mikael Johansson, Elke Miedema, Saga Karlsson, Lin Tan, Göran Lindahl and Christine Hammarling
Chalmers University of Technology

ABSTRACT: *During the design process of a building different medias are often used to depict the design. Traditional media, especially 2D requires high spatial skill and cognitive demand on the designers. For inexperienced designers, this process can be demanding, be difficult and can cause potential biased design perceptions that are significantly different from the reality. However, studies have also shown that different media and representation facilitates different cognitive reasoning processes about the design. Immersive Virtual Reality (VR) is assumed to give another level of understanding and perception of design space from an egocentric perception than 2D plan drawings or bird-eye views, which have been argued to provide opportunities for better pattern and object recognition that is suitable when studying spatial organization in an allocentric reasoning process. This paper investigates, the different design medias and spatial space explorations further, by studying how students used the different representations and medias (e.g. sketches, 3d-models and VR) during their design process. By combining and using both of these two design space representations, (e.g. egocentric and allocentric) in the design process, it gives a possibility to achieve a more developed design outcome. The methods used in this study were observations and un-structured interviews during the design process and a follow up questionnaire at the end of the design project. The result show, by combining and using both VR and traditional design sketching tools that it is possible to support the two design space representations together and give the designer the possibilities to explore, understand, discuss and work with the design in a more elaborate way from both an egocentric and allocentric perspective. The paper also presents in what way VR can contribute to the Evidence Based Design (EBD) criteria and how the students used different design spaces representations for design and spatial reasoning about the healthcare design of the psychiatric facility they were designing.*

KEYWORDS: *Virtual Reality, VR, Evidence Based Design (EBD), Design process, Design Space*

1. INTRODUTION

The design process of a new building is often recognized as a complex and creative process where different artifacts, requirements, and functions are established and then designed, reviewed, analyzed and decided upon during the process (Chan, 1990). For inexperienced architectural students, this process can be demanding and the ability to interpret information and interpolate it into the spatial reasoning about the design could be challenging (Granath et al., 1996). The most common representations in these processes are documents, descriptions, sketches, 2D-drawings, pictures, 3D-models and physical scale models. However, these representations can be difficult to interpret and understand and place high cognitive demands on the designers' ability to transform the information into a self-made mental image of the project. The self-made mental image could also be misinterpreted and differ depending on the individual's background education, experience, and interest. Studies have shown that different representations facilitate different reasoning processes about the design (Coburn, 2017). For instance, flat 2D plan drawings or bird-eye views have been argued to provide opportunities for pattern and object recognition, which is suitable when studying spatial organization, relationship between space and objects, and orientation of different objects e.g. allocentric reference (Coburn, 2017). In addition, other studies have shown that 2D representations, such as floor plans or engineering drawings, are less intuitive for laymen (Granath, 1991; Hardie, 1988; Ingram, 1984; Lawrence, 1982). Ingram (1984) further argues that designers require lot of training and practice before they can efficiently use 2D drawing techniques as a primary design tool. During this process the designer must have the cognitive ability to mentally transform two-dimensional objects into a 3D-view to understand the design space e.g. called *Spatial visualization*. Another cognitive process related to the design process is the *Spatial orientation,* which is the ability to imagine an object or scene from other perspectives. These two parallel cognitive processes are a very demanding and can influence understanding and discussion about the design, as the different individual's could interpret design artifact differently. Bertel et al. (2008), argued that this type of mental design representation significantly differs from the reality i.e. the actual built building. In this context, studies have showed that immersive Virtual Reality (VR) can provide another level of understanding and perception of space, which is hard to experience using other type of visualizations and medias (Coburn, 2017; Roupé et al., 2016). To understand how information is decoded and interpreted it is necessary to explain how the human brain processes visual information into mental imagery and spatial perceptions. During this process the mind tries to create an understanding of the visual space within two parallel systems: the self-centered egocentric reference frame and an environment-centered allocentric reference frame (Burgess, 2006; Klatzky, 1998). Both systems interact during this processing and retrieval of spatial knowledge (Plank et al., 2010). In the egocentric reference frame, the viewer compares him/herself with the object in 3D space. During this self-to-object process, the distance and bearing to the object are processed independently of the global environment. As the viewer navigates through the environment, egocentric parameters have to be constantly processed and updated with each view change in 3D space and therefore it is seen as a viewpoint dependent reference frame. By contrast, the allocentric reference frame is built up by comparing object-to-object or environment-object relationships and is a global reference frame associated with the visual environment. Furthermore, Immersive VR gives the user the opportunity to compare themselves and their bodies with the environment in a view-dependent process i.e. egocentric reference. Research also suggests that using the physical-human rotation and movement Immersive VR provides a better understanding and spatial perception (Paes et al., 2017; Riecke et al. 2010; Roupé et al., 2014; Ruddle and Lessels 2009). In recent years, new Head Mounted Display (HMDs) technology released help support better stereoscopy, higher resolution of the display, wider Field-of-view, physical-human rotation and movement. Recent studies have shown that space perception in the HTC-Vive start to be comparable to real world space and distance perception, but still the virtual environment feels compressed (Buck et al., 2018; Kelly et al. 2017; Paes et al. 2017).

The work presented in this paper investigate the different design media and spaces further, by studying how masters level architectural students used the different representations (e.g. sketches, 3d-models and VR) during their design process. During this process the students/designer elaborate on various alternative solutions to a given task in the *architectural design problem space* (Chan, 1990; Goel and Pirolli 1992). Within the scope of this paper we define this problem space as a rational search process that elaborate on various alternative design solutions to a given problem through spatial reasoning and problem exploration of the design in 2D and 3D space. This spatial reasoning and problem exploration process is done both in egocentric and allocentric frame of reference. As mentioned, the allocentric theory suggests that flat 2D plan representation such as drawings/sketches or bird-eye views support better reasoning about the design when it comes to studying spatial organization, studying relationship between spaces and objects and orientation of different objects and functions (e.g. allocentric spatial reasoning). In comparison, VR supports another level of understanding and perception of space from a self-centered view-dependent process i.e. egocentric perception where the user can experience the design in scale 1:1. By combining and using both of these two design space representations in the design process, it gives a new possibility to achieve a more appropriate project outcome. To explore this design method and process, we have implemented it in the masters course Healthcare Architecture Studio. One of the key course objectives was to actively incorporate Evidence Based Design (EBD) principles in the architectural design process (Ulrich, Zimring, and Zhu 2008). Founded in research, EBD within building design for healthcare demonstrates processes for how the built environment can provide optimal conditions that support health, productivity and healing process. Furthermore, VR gives the student/architect/designer the possibility to analyze the design from a patients and nurses point of view (e.g. egocentric spatial reasoning), which could facilitate the EBD process. In this context, the aim of this research is to explore and describe in what way VR can contribute to the above mentioned design criteria and how the students used different design space representations for design and spatial reasoning about the design of the psychiatric facility that was the case in the course.

2. METHOD

The study was conducted with masters level architectural students (i.e. 4 year) students (n=24) at Chalmers University of Technology, 2018. The respondent groups were part of Healthcare Architecture Studio with the assignment of designing a 15 000 sqm psychiatric facility. An EBD approach was one of the key course objectives and was used during the design process (Ulrich, Zimring, and Zhu 2008). In this context, EBD bases the design decisions concerning the built environment on validated research to achieve the best possible outcomes of the design regarding health, productivity and healing process. Additionally, health promotion, reduced treatment time, decreased medication, and stress reduction are some examples of studied outcomes related to design based on the EDB approach.

Clear functional objectives connected to the architectural program for psychiatry are as follows:

- ***Clear and visible sightlines*** between staff and patients. Facilitate unobtrusive observation of patients. Visible and central placement of staff team stations. No hidden corners where patients can hide.
- ***Protect patient privacy***. Orientate and place windows so that patient rooms and communal areas are not exposed to overlooking.
- ***Views and connection to nature***. Avoid long narrow corridors and create breaks in the facade to allow in daylight and views.

The students were introduced to VR and how they could use it as a tool during their design process in the fourth week of their design project. By then they hade had done the pre-design of the Psychiatric Facility, where the students had done sketches and 2D-drawings of the layout and studied relationship between functions and spaces. In the following week five and six the students worked with more detailed design and room layout. It was in week 5-6 the students had VR workshops, where they used VR for group discussion and design review meetings, see Fig 1. During these design review meetings, at least one teacher was present for observation, tutoring and feedback. The VR system that was used was HTC Vive together with the software BIMXplorer (Johansson, 2016). The creation of the 3D-models was done in Rhino, Autodesk Revit, or SketchUp and imported directly into BIMXplorer through the 3ds-file format or as a plugin in Revit. During the design review meetings/group discussions, the groups used the HTC-Vive together with a big screen display, see Fig 1.

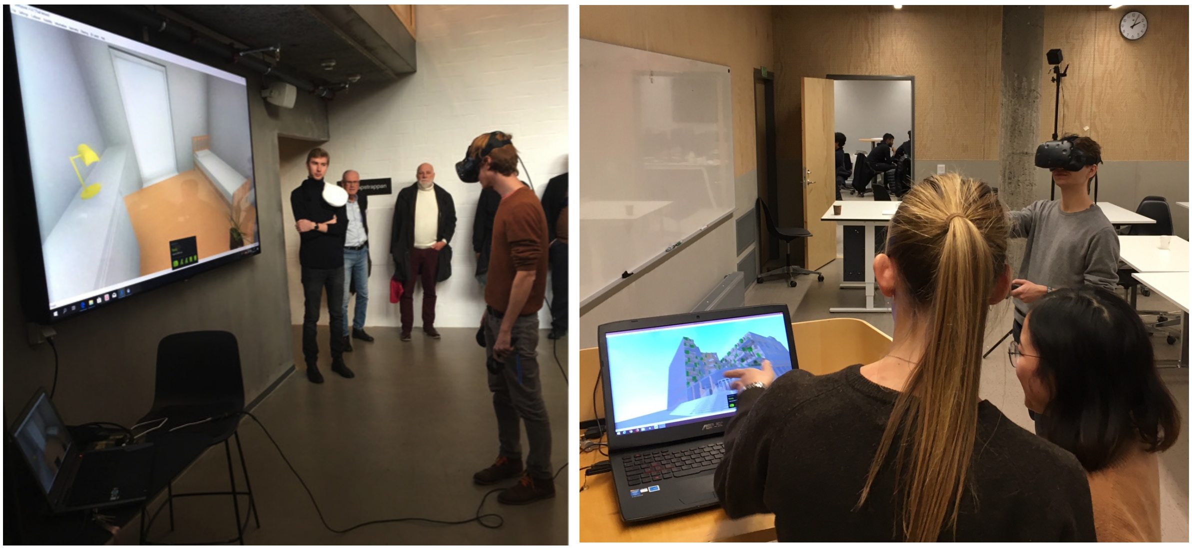

Fig 1: Design review meetings the groups used the HTC Vive together with a big screen display during their group discussions.

The methods used in this study were observations and un-structured interviews during the design review meetings and the design process. The main focus during the observations and un-structured interviews was to explore and to investigate how the students explored and used VR during the design process. From these observations and interviews a follow-up questionnaire was created, which was conducted by the students at the end of the project/course. The questionnaire included in total 22 variables and questions. The questionnaires contained questions that were answered by marking five-step scales and some questions were open-ended. The open-ended questions results were analyzed and categorized. The questions was related to; *-design changes due to VR and what type of changes, -new insights about the design space using VR, - were there any advantages of using VR during the design process, - what the individual student thought about work with VR in design process in comparison to work with for example physical models, drawings and sketches.*

3. RESULT

The following result section presents the results from the open-ended questions, which has been analyzed and categorized. Some of the citations from the open-ended questions are also used to highlight the essence and meaning of the different categories. In the end of the result section the quantitative questionnaire results are presented.

3.1 Design changes due to VR design review

In table 1, we present the results from the question related to if the students made any design changes due to experience the design in VR and what type of changes they made.

Table 1. Reported comments relating to: *Did you make any design changes due to the VR design review? If so, what type of changes?*

Category	**Number of responses (n=21)**
Changes related to perception of room size and space	13 (61.9%)
Too large space/rooms	12
Widths of the corridors	9
Height of the ceiling	2
Changes related to floor plan	4 (19.0%)
Size of rooms and spaces	4
Wayfinding	2
Changes related to sightlines	5 (23.8%)
Sill-height and placements off windows	5
Corridors and rooms	2
Changes related to design errors, such as stairs, windows etc.	3 (14.3%)

As can be seen in table 1 and also observed during design reviews in VR, most of the discussions and design changes were related to the size of rooms and corridors (e.g. width and height) in the building due to the better understanding and perception of the designed space. Other changes were related to the floor plan due to; -recognized difficulty during wayfinding and navigation in the building, -the ambition to accomplish clear and visible sightlines between staff and patients in corridors and rooms and the visibility and central placement of staff team stations. Furthermore, some students recognized more general design errors and some groups used VR for evaluating different sizes and placements of windows and views connected to the experience of nature in the patient rooms.

3.2 New insights about the design space using VR

Table 2. Reported comments relating to: *Can you give one (or several) example(s) where VR gave you new insights about the design (that you weren't fully aware of before doing the VR review).*

Category	**Number of responses** (n=21)
Another understanding and perception of room size and space	13 (61.9%)
Walk around and analyzing orientation and wayfinding in the building	3 (19.0%)
Materials	2 (19.0%)

As can be seen in table 2, the students also here mention that they got another understanding and perception of room size and space of their design compared to the other traditional design medias. Also, by having the possibility to walk around and analyzing orientation and wayfinding in the building it also gave an insight about their design. One student mentioned that: *"It´s hard to see the dimensions in just a 3D model or drawing, it is way easier to see and feel it in VR"* another student comment was: *"VR helped to better grasp how the spaces that we draw in plan view would feel like"*. Another mentioned, *"I felt that the scale of the patient rooms wasn't as big as I feared, that was good. Also we saw that the corridors could be smaller."* One student comment related to analyzing orientation and wayfinding was: *"One example is the wayfinding. On paper and in 2D it seemed to work but when we walked* *around in the building we figured out that it was really hard to find the right places. We got lost."*

3.3 Advantages of using VR during the design process

In table 3, the result from the question related to what the advantages of using VR during the design process was.

Table 3. Reported comments relating to: *What were the advantages of using VR during the design process?*

Category	**Number of responses** (n=21)
Better understanding of the design	19 (90.5%)
Better understanding of spaces and the scale	18 (85.7%)
Experience of being in the building/designed project	10 (47.6%)
Discussion about the design	5 (8.3%)

The result in table 3 indicates that the participant's thought that the biggest advantages in using VR during the design process was related to better understanding of the design and that they got an better understanding of space and scale compared to other media and tools. They also mentioned that VR gave them another experience of being in the building/designed project. Some student mentioned that VR helped them during discussion about different design opinions and concepts. One student mentioned that: *"Easier to understand the design of the project than just plan- and section-view or even 3D model. It is also exciting to see how our ideas turned out in 'reality '"* another student comment was: *"that it is hard to see the dimensions in just a 3D model or drawing, it is way easier to see and feel it in VR"* Another student mentioned: "*We realized that the space was too large and not giving the feelings we wanted to provide. So VR is good for understanding the spatial qualities you want to achieve in your design and VR could really work as a design tool"*. Furthermore another student highlighted that VR helped the design process during the experience and analysis of architectural design problem space, e.g. *"How big the patient room look like in 'reality' and what effect our curved bathroom wall gave to the room, how good overview the staff would have of the patient."* One student mentioned that VR helped during discussion and analysis about the design, e.g. *"To see it together with your team you find both the positive and negative things of our design, and create a common frame of reference for discussion."*

1.4 Working with VR during the design process in comparison to physical models, drawings and sketches

In table 4, the result from the question related to: What the student thought about working with VR during the design process in comparison to working with, for example, physical models, drawings and sketches.

Table 4. Reported comments relating to: *Make a short reflection of how it was to work with VR during the design process in comparison to working with for example physical models, drawings and sketches?*

Category	**Number of responses** (n=21)
New experience of the design space by "brining it to life"	14 (66.7%)
Better understanding of space and the scale	7 (33.3%)
More accurate feeling of scale	6 (28.6%)
Simulate the movement and wayfinding in the design/building	2 (9.5%)

As can be seen in table 4, the students mention better understanding of space and scale as one of the most positive effects of using VR compered to physical models, drawings and sketches. But the most positive effect was that they felt that VR gave them a new experience of the architectural design problem space by "*bringing it to life*". Related to this, one student mentioned that: *"Exciting to see the result of analogue and 3D work, ideas coming live almost"* Another student mentioned: *"The VR offers a reality to the project, brining it to life and making it feel big, important and realistic and the virtual perspective can't be compared to smaller physical models, drawings etc. VR offers a new important dimension to the design process"*. Furthermore another student's reflection was: *"When* *working with VR you can get a very realistic feeling. When working with physical models, plan and sketches everything seems smaller than it is"*. Another student mentioned: *"Physical models and drawings don't take you inside of the building. Physical models are better for understanding the volume from above."*

Observations during the VR design reviews also identifies the above-mentioned categories. Some groups used VR to analyse the design from the patients and nurses point of view by trying to sit on the chair or lie on the bed in the patient room and experience how the future patients would experience the room. One group analyzed their designed *curved bathroom wall* from the staff security point of view, e.g. if the staff could enter the patient room by seeing the whole room from the window in the door which is vital for psychiatric patients rooms for safety and assault reasons.

Fig. 2 displays the frequency and rating from the last quantitative questions related to how the students used and perceived VR during their design process.

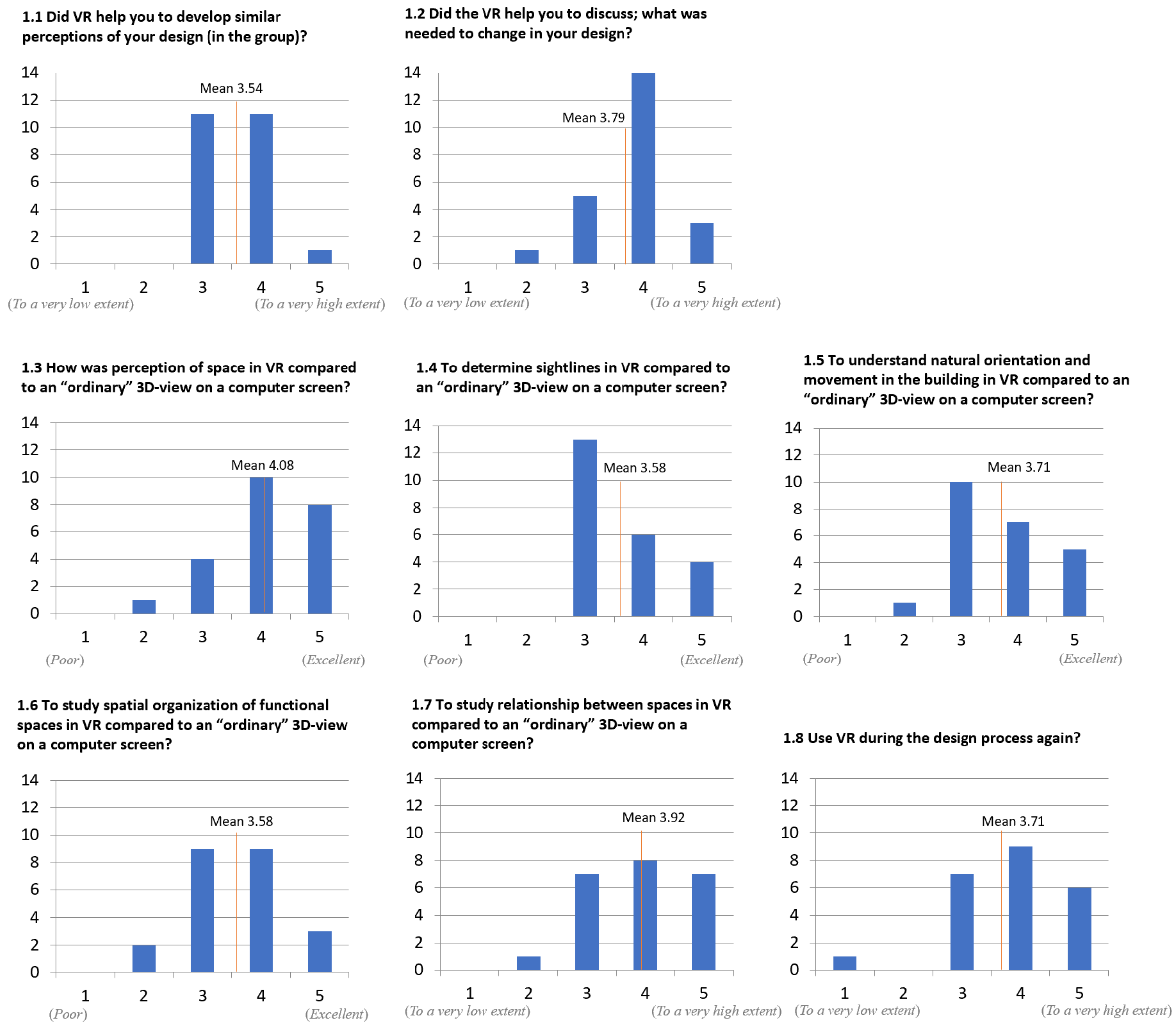

Fig 2. Frequency and rating for the last quantitative questions related to how the students used and perceived VR during their design process on a scale from 1 (*To a very low extent*) to 5 (*To a very high extent*). (n_{tot}=24)

As can be seen in Fig. 2, the results from the quantitative questions are aligned with the results from the qualitative questions in table 1-4 and the observations. The participants thought that VR helped them during discussion about what was needed to change in their design and that they wanted to use VR again during their design process. Furthermore, the participants perceived that VR gave them a better perception of space and some of them believed that VR gave them the ability to study relationship between spaces and natural orientation and movement in the building (i.e. how you would naturally navigate in the real building).

4. DISCUSSION AND CONCLUSIONS

The design of a new building or healthcare environment is recognized as a creative and complex process, where different artifacts, requirements and functions are designed, reviewed, analyzed and decide upon. For inexperienced architectural students, this process can be demanding and the ability to interpret information and transform it into spatial reasoning about the design could be challenging. However, as the result of this study show, VR support the students/designers in understanding and how they perceive the designed spaces from a self-centered view-dependent process compared to other medias. Furthermore, VR gives the student/architect/designer the possibility to analyze the design from other stakeholder's perspectives, e.g. nurses and patients. Either by including them or by simulation of these users from a self-centered view-dependent process. This facilitate an EBD approach in building design as it complements the use of validated research with a tool to develop understanding of context and specific user requirements – all aspects of an EBD decision making process. As mentioned before, EBD within healthcare building design strives to accomplish a built environment that has a positive effect in the healing process and healthcare productivity. As this study shows, the students analyzed and tried to understand how the future patients would experience the patient room by sitting in the chair or lie on the bed and experience how the views connected to out door nature would be. Also the security point of view was tested e.g. if the staff could enter the patient room by seeing the whole room from the window in the door. Furthermore, analyses of unobtrusive observation of patients and natural orientation and movement in the building was also enabled by VR. In this study it is recognized by the participants that VR is a good tool to use during the design process as it gives a new experience of the architectural design problem space by "*bringing it to life*" and *"that it is hard to see the dimensions in just a 3D model or drawing, it is way easier to see and feel it in VR"*. In this context, VR could be argued to bring a pedagogic effect to the design process, as it gives the student the possibility to experience their design from an egocentric perspective in scale 1:1, which is not possible in other medias. Other media can be difficult to interpret and understand and place high cognitive demands on the designers' ability to transform the information into a self-made mental image of the project. Furthermore, the self-made mental image could also be misinterpreted and differ depending on the individual's cognitive spatial capabilities. Bertel et al. (2008) has also agued that this can cause potential design biases and that this type of mental design representation can significantly differ from the reality e.g. the actual built building environment. Furthermore, by using VR the designers' get a feedback loop that their cognitive spatial and mental image (e.g. *Spatial visualization and orientation)* of the design is accurate or not. As the result from this study showed, the students used VR as a tool for understanding space and to explore the design and analyze the design from the above-mentioned EBD design criteria's. They used VR for design review and to examine their design and if they had decoded and interpreted their design correctly during the sketching process. As the result show, most of the student groups implemented several design iterations after they used VR as they found design errors and misinterpretations of spaces and sightlines, which were hard to find using traditional design medias such as sketches, 2D-drawings, pictures, 3D-models. By combining and using both VR and traditional design sketching tools it is possible to support the two design spaces together and give the designer the possibilities to explore, understand, discuss and work with the design in a better way from both an egocentric and allocentric point of view. As the observations showed during the project, the student used sketches and 2D-drawings initially to create the first draft and studying relationship between spaces in 2D from bird-view perspectives. This type of reasoning process can also be seen in other studies related to the design process. For instance, Brösamle & Christoph (2007) found that during the pre-design analysis in 2D of pathways, navigation and orientation and visitor flows, the designers reason from an allocentric view about axis, flows and paths and missed to consider more location factors that are used during actual navigation and orientation in an building. It could be argued that these type of allocentric representation and design process support better reasoning about the design when it comes to studying relationship between spaces and objects and orientation of different objects and functions (e.g. allocentric spatial reasoning). However, as the results in this study show, VR supports another level of understanding and perception of space from a self-centered view-dependent process e.g. egocentric perception where the user could experience the design in scale 1:1. In this context the participants thought that VR gave them ability to study relationship between spaces and how the future patients and staffs would actually experience, orientate and navigate in the building. By combining and using both of these two design spaces in the design process, it gives a new possibility to achieve a better outcome of the building design when it comes to perception, orientation and navigation. Furthermore, the result from this study exemplifies that this type of analyses is most efficient in VR.

Additionally, the study also shows how the student used HMD-VR in their design process connected to EBD. As mentioned before, EBD principles in healthcare has very high focus on the patient's and nurse's perspective and experience of the self-centered view-dependent process, it could be agued that design review in HMD-VR is very suitable in this context. Besides, as the result shows, the designers analyzed and tried to understand how the future patients and staff would experience the healthcare facility from both a healing process and from a security and productivity point of view as mentioned above. In this context, VR could be argued to be a great EBD tool for design reviews and decision and to overcome potential design biases imposed, which is not as easy in other medias.

More importantly, VR require the designers to leave the traditional drawing board and become reflective and aware of their own practical experience of elaborating on various alternative solutions to a given task in the architectural design problem space. It could be argued that the immersive VR system facilitated a self-centered egocentric reference frame and reflection space and where the user had the opportunity to consider, reflect, validate and confirm the design. Traditional media, especially 2D, which modern day designers use most in design processes, are more static and designers might require greater cognitive spatial capability to work with it. VR has the possibility to provide much more dynamic visual-spatial feedback than traditional media does. This might lower the threshold of some cognitive spatial capabilities such as spatial orientation and spatial visualization for designers. It potentially shifts the attention from the creation of objects that define space to the creation of space itself and shifts the direction of the design process from outside-in perception (such as traditional design medias, sketches, 2D-drawings, physical models) to inside-out perception (such as 3D models/BIM together with VR). Looking forward, VR applications are likely to support even more integration and interaction thru sketching and editing directly in immersive VR. This will open up new possibilities where support for self-centered egocentric reference frame and reflection space will have more focus and possibly will change how the future design process will be conducted.

Additionally, many studies has claimed that VR should be used as an communication media between different stakeholder and specialists, but as this study show it is also important to use VR during the creative design process by the designers as an reflection space to get another level of understanding and perception of the architectural design problem space and the artifact.

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APPLICATION OF VIRTUAL REALITY BASED REMOTE COLLABORATION SYSTEM IN CONSTRUCTION

Sunseng Tea & Kriengsak Panuwatwanich
Sirindhorn International Institute of Technology, Thammasat University, Thailand

ABSTRACT: *The geographically distributed working environment and multidisciplinary stakeholders of the fragmented construction industry have been one of the most critical issues in construction project delivery contributing to the indispensable digitally collaborative working environment. In practice, sharing a common understanding during conceptual design among remote key project participants is a barrier to a profitable project. However, the recent development of virtual reality (VR) makes it a solution for interactive visualization of design, construction, and maintenance. This paper presents an integration of collaborative VR in construction through a proposed multiuser VR-based system whose client application will be deployed on Windows and displayed by HTC Vive, and its server will be hosted on Amazon Web Services (AWS). The main purpose of the proposed research is to develop a VR-based remote collaboration system to facilitate the collaborative environment and improve the understanding between project participants during the conceptual design. As a case study, the proposed system will be developed for a chosen part of a newly constructed laboratory in a university campus and tested for usability. The study will result in a practical and user-friendly system in terms of fast consensus between remotely located project stakeholders. Further studies need to be conducted to enrich the functionalities and capabilities of the proposed system pertaining to collaborative tasks in construction.*

KEYWORDS: *application, virtual reality (VR), remote collaboration, visualization, Amazon Web Services (AWS), Building Information Modeling (BIM), interaction.*

1. INTRODUCTION

One of the most thriving sectors in the whole world—the construction industry is not only a metropolitan-based one involved with planning, design, construction, and maintenance of real estate properties and public infrastructures, but also a multidisciplinary-based one participated by varieties of stakeholders such as clients, project managers, architects, structural design teams, consultants, site engineers, and contractors. Therefore, the natural characteristic—fragmentation of the construction projects indispensably needs both onsite and offsite collaboration from those project participants who have potential to limit or boost the development of construction operation in terms of their actual position, specialism and experience in the project. Yet, not only constructing the built environment is becoming more and more complex, but also building owners and occupants are demanding more options, more technologies, and more sustainability; so concerted actions and implementation of consensus decisions are highly required to address the increasing complexity and demand of modern projects. Furthermore, poor collaboration on project requirement often loses track of construction processes and induces confusion, misinterpretation, and ignorance of information between project and project participants resulting in unprofitable projects (low performance). As a result, the construction industry has continued seeking new and innovative methods and systems for more effective collaboration. On the other hand, technology is advancing to keep pace, and virtual reality (VR) is one emerging example. VR has been commonly defined as a digital technology in term of visualization which is capable of totally immersing users in a computer-generated environment or virtual space via a VR headset.

Among all proposed approaches, a great deal of interest lies in the use of collaborative VR driven by building information modeling (BIM) for enhancing project collaboration between multidisciplinary stakeholders. VR can assist design and construction tasks with its unique collaborative experiences by allowing shared visualization of 3D models and data through its lifelike experience during immersion between the design teams and the construction teams; this benefits project discussion and revision. In addition, VR helps visualize rich information imported from BIM authoring tools (e.g., Revit) for reducing the complexity of the project and create real-time interaction for sharing a mutual and reliable understanding among major project participants during the conceptual design. At present, VR is showing a great potential to deal with a variety of training, design and construction problems due to its practical solutions in digital visualization that facilitates more value-added activities especially remote design collaboration.

Although VR applications are mature and well established in enhancing data communication, efforts are still required for project visualization in a remotely collaborative manner. The deficiency in advancements in BIM-VR interaction and collaborative VR has impeded the adoption of VR in the construction industry. BIM-VR interaction refers to a compatible data transfer from BIM authoring tools to the VR headset (e.g. HTC Vive). Most current construction VR applications focus on importing building geometry for visualization while ignoring some building information such as structural data. Besides, collaborative VR refers to a multiuser VR-based system that enables real-time human-building interaction among remote VR users. Academically, there is a limited number of VR studies in construction having been conducted, and the current studies have mostly focused on enhancing one player application. More work is required to realize and capitalize on the benefit of collaborative VR system driven by BIM within the construction industry. The proposed research will be carried out to investigate the applicability of VR-based remote collaboration system in the conceptual design. Additionally, it will be based on BIM, game engines and networking protocol to bring a shared building geometry and information in the lifelike immersion of virtual environment to project stakeholders located remotely by using the HTC Vive. The proposed research is expected to practically adopt and employ collaborative VR system in the conceptual design.

2. LITERATURE REVIEW

2.1 Overview of Current Approaches for Remote Collaboration in Construction Projects

Construction projects have frequently had conflicts and criticisms between the project participants due to ineffective collaboration and difficulty of the geographically distributed working environment. Apart from that, the complexity of construction tasks and data management of the project are increasing dramatically due to the development in the construction industry. Furthermore, some shareholders come from a foreign country that is far away from the current project, so it is difficult to deal with the problems that happen immediately or to have an emergency meeting regarding decision making on project revision. Therefore, remote collaboration is an indispensable element to tackle many issues in terms of miscommunication, misinterpretation, distant barrier, etc. The current approaches being used in a construction project are BIM and cloud computing technology, and they are powerful in facilitating the natural characteristic of construction industry pertaining to remoteness and collaboration issues. BIM is a professional and intelligent process containing 3D model-based design solution system that sophisticatedly produces and stores information of architecture, engineering, and construction due to its tools and multifunctionality (Volk et al., 2014); whereas the cloud computing technology is typically known as a commercial service providing any powerful hardware or system based on customers' demand as “pay as you go”, to use anywhere and anytime by just having an internet connection (Abedi et al., 2012). This research proposes an approach by taking benefit of these two technologies to generate the VR-based remote collaboration system using HTC Vive.

2.2 Virtual Reality in Construction, Engineering, Education and Training (CEET) Applications

With the advent of advanced VR technology, CEET is embracing this technology for taking its benefit to generate a better and innovative way of the working environment resulting in time-saving and cost reduction. Currently, VR is growing rapidly in no other industry is this more relevant than in the CEET world. As a result, the integration and collaboration of these two worlds are running together for their own sake of development. As CEET are growing toward rich data and digital information management due to the growth of complicated and giant projects, more innovative and effective visualization approaches are essential for the efficient control of such important data. In practice, the main problems in the CEET sector are lack of data communication and participation of project stakeholders and gaps between design and construction; thus, VR is potentially suitable for solving such obstacles leading to the growth of research on the adoption of VR in CEET. Recently, many researchers have been finding efficient approaches to leverage VR for the greatest impact in the CEET.

In term of research trends in the CEET, there appear to be various feasible use cases of VR to assist architects and engineers in the design and construction process (Milovanovic et al., 2017). For example, the integration of BIM with the VR headset can capture the whole operation of construction, not only in the design stage but also in the construction stage. Furthermore, project participants such as owner, architect and structural engineer are fully immersed to see building geometry and building information that looks close to realistic from beginning to completion of the project due to the implementation of VR system on the headset. Most of the VR applications are still in the developing phase in term of the CEET area. For instance, the development of an interactive computer system regarding construction education aimed to provide game-based training on safety through computer-aided design and modeling (Goedert and Rokooei, 2016). Apart from that, in several engineering and construction practices, visualization improved users' understanding and provided sophistication on the complexity of the construction tasks. At the construction site, VR plays an essential role in assisting many construction tasks through its ability to provide a representation of the necessary data based on the working context. Moreover, the application of traditional safety training approaches used for job site mostly depends on lectures or discussions pertaining previous information or experience received from existing accidents, and sometimes such conventional practices are not effective (Hinze et al., 2013). After having accidents, safety manager surely collects the information such as the root and the seriousness of the accidents in order to generate some useful data for safety improvement. Nonetheless, such data could not provide any proactive actions to prevent every individual from unpredictable upcoming accidents. More essentially, data produced on the actual job site in real-time is known as the most useful data if it is properly delivered to those sensitive workers because they will always well-prepared in that hazardous working environment, so the way of effectively communicating information is indispensable in the construction safety. Consequently, the most important VR application is applying hazards via the simulation of the real job sites for safety management in construction in order to let the workers immerse in the lifelike VR experience of the unpredictable dangerous cases that could happen frequently and seriously during working due to the lack of information regarding the safety; this will result in reduction of fatalities and injuries of the workers. (Li et al., 2018).

With the significant advancement and adoption of VR in CEET, there will be numerous chances for taking the advantages of this technology to enrich the traditional methods used in current construction projects since VR potentially facilitates the construction tasks, solves the problems, changes the way the construction participants understand phenomenon, and increases consciousness and recognition from preconstruction stage to completion of the projects.

2.3 Virtual Reality for Remote Collaboration Applications

With the recent technological development in terms of the internet, network and computational hardware, the multiuser feature becomes more convenient for the researchers to develop in a VR environment. Many researchers in other industries, especially in manufacturing, have integrated networking protocols in their applications or systems. They found out that a multiuser function in VR context is a powerful tool to improve working performance and solve some emergency cases in a collaborative manner. Recently, there have been many studies being conducted on applying VR for remote collaboration. For example, Madathil and Greenstein (2017) developed a collaborative VR-based laboratory of 3D remote moderated usability testing and conducted comparative effectiveness in a controlled environment with two existing methods such as the traditional laboratory approach and Cisco WebEx (an online video conferencing and screen sharing approach). The controlled subjects (both participants and facilitators) were assigned to complete a representative task on a web-based shopping simulation, and there are similar outputs on performance between the collaborative VR system and the other two approaches in terms of task completion time and the quantity of defect identification. However, the participants tended to enjoy the VR-based condition and complete the tasks productively showing that the VR-based method could be a potential alternative to the existing approaches for usability testing. Besides, during operations on the real site, it is sometimes difficult to foresee potential risks, and some operations worth a great deal of expense and cause disastrous tragedy if they are misconducted. Additionally, some operations require collaboration involving more than one operator. These natural characteristics induce difficulty in organizing training on those operations. However, Li et al. (2019) presented an approach that allowed multiple workers to operate shipbuilding and installation operation together through a simulation deployment in the virtual space. The approach was applied in a real case of a block turn-over simulation to show the applicability of the presented research, and the result showed a successful execution of the operation which multiple workers were involved in the virtual environment of the training.

Although growing evidence has shown the potential of VR for remote collaboration applications, most VR studies have been in the manufacturing sector and focused on the training. For example, workers need training regarding the important tasks or operations with other workers or remote experts before the real situation happens. Despite the great accomplishment in the other sectors on collaborative VR, there is still lack of research conducting on the applicability and benefits of VR for remote collaboration in AEC pertaining to collaborative conceptual design in the immersive environment. Apart from that, at the simplest level, current design review task is often done on a PC with the computer-aided design software (e.g. BIM authoring tools). However, collaborative design review on screens cannot always meet all the requirements with regard to complex construction projects. Furthermore, it is found out that collaborative VR, that could bring the remote project participants together and provide a shared immersive environment, benefits the building inspection collaboration contributing to the effective collaborative design review. Therefore, the multiuser VR system could provide a possible solution to the previously mentioned collaboration problems in the AEC workflow.

3. RESEARCH METHODOLOGY

This proposed research aims to fill the gaps of the existing VR applications in AEC industry, especially the lack of a BIM data-driven multiuser VR platform, the VR-based remote collaboration system that will be specifically designed for the AEC applications is proposed and being developed. The proposed system is a cloud-based multiuser VR headset system that might collect data from BIM authoring tools and convert it into a multiuser VR environment to facilitate the collaborative conceptual design. In order to be able to effectively conduct the study, defined development workflow and tools would be required as described in the following sections.

3.1 Research Setting

In this study, a selected part of a newly constructed laboratory of Sirindhorn International Institute of Technology (SIIT), Thammasat University will be used as a test subject for the development and deployment of the proposed system. Since there are only 2D CAD drawings for the mentioned building, a BIM model will be created from 2D drawings, and material testing laboratory located at the 4th floor of the building will be used as the experimental subject.

3.2 Research Tools

Technically, building a multiuser VR-based system with functionalities and user interface as the research requirement needs to be developed from scratch; thus, defined development tools such as open-source software and computational hardware would be required to develop and deploy the proposed system (as shown in Fig. 1).

Fig. 1: Software and hardware for the development of the proposed system.

3.3 Proposed Procedures

Task 1: Literature review

In this task, an extensive and critical review of literature is conducted to get an insight and find the gaps in research regarding:

- Potential benefits of integrating Information Communication Technology (ICT) with the AEC industry.
- The collaborative tasks of the construction project, their issues and currently used approaches.
- VR applications and developments within the AEC industry.
- VR applications for remote collaboration within various industries.

The main purpose of this task is to ensure not only originality and rationale of the proposed study but also the latest development and issues of the VR applications relevant to the proposed study.

Task 2: Proof of concept

The proof of concept is conducted to examine whether there is feasibility for the development of the VR-based remote collaboration system and how it could be employed in the geographically distributed design. Specific research activities conducted in this task are described below:

- A sample of multiplayer Windows application was created by using Unity networking (UNet) protocol for sharing visualization via a server on AWS.
- Certain prototypes to be tested will be developed on Unity and deployed into VR mode to measure the applicability and capability of the developed system.

The outcomes of this task will involve working prototypes of the system for collaborative design.

Task 3: Exploratory study

It is essential to better understand the existing states of practice and knowledge in the collaborative design carried out in the construction project. For this task, an exploratory study will be conducted with the graduate CET students who have working experience during the conceptual design stage because they will provide useful information as preliminary data relevant to the proposed research such as:

- Current practices and issues in the collaborative conceptual design.
- Current approaches used in the collaborative conceptual design in term of technological support.
- Preferable functionalities and user interface (UI) of the proposed system.

The outcomes of this task will establish a baseline understanding and fundamental concept guiding the authors to an appropriate start and effective development steps of their proposed study.

Task 4: System development

Following the above tasks, the proposed system will be developed for the predefined design task of a selected part of a newly constructed laboratory that could represent the typical collaborative design. To succeed this, the following activities will be conducted:

- A complete system will be designed and developed to generate collaborative design environment via the existing 2D CAD drawings from the school facility management division.
- This developed system will be deployed on Windows and displayed by HTC Vive for conducting the test regarding the usability of the proposed system.

This task will produce a complete system that might facilitate the remote collaboration of the conceptual design (as shown in Fig. 2).

Task 5: System testing and evaluation

The developed system will be tested pertaining to the conceptual design review to demonstrate the usability, so the SIIT students will be recruited to play the role as owner, architecture and structural engineer. Experimental procedures will be conducted as follows:

- Recruitment session: 30 graduate students will be recruited to be participants of the system evaluation, and they will be separated into 10 groups of 3 people in order to perform the above-mentioned roles for the conceptual design review.
- Training session: before the start of the actual experiment, all students must familiarize themselves with the task to be conducted, and they will be assigned enough time to practice how to use HTC Vive and the proposed system.
- Real experiment: a BIM model of the material testing laboratory will be presented to 10 groups via HTC Vive in the VR environment. The goal of the task is one student will play the role of the owner who is not satisfied with the design of building components, and the other two will act as the architect who is trying to revise according to the requirements of the owner as well as the structural engineer who is assisting the architect with the possibility of redesign pertaining to technical concern. The students will complete the task in a collaborative manner.

After finishing the task, all the students will be allowed to evaluate the usability of the proposed system through predefined questionnaires (Likert-scale method).

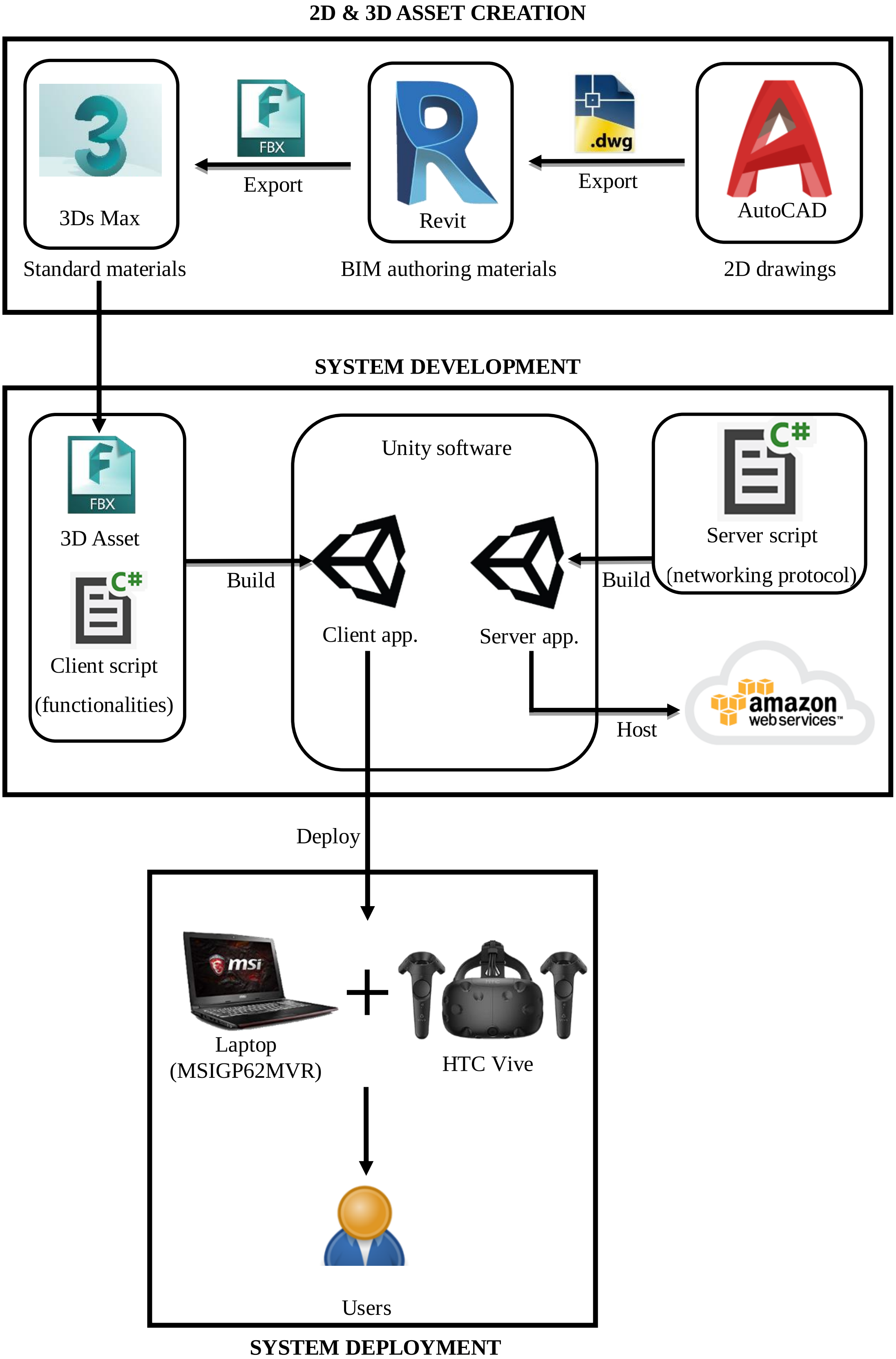

Fig. 2: Proposed system development workflow.

4. PRELIMINARY WORK

The system development of the VR-based remote collaboration system in conceptual design review is based on four main constructs: 1) 3D asset creation, 2) Windows application development (client application), 3) server application development (receiving request from client and sending back) and 4) the deployment of client application and server application (on AWS). According to the proposed system, the main technical part is the multiuser function which allows sharing visualization between users from a remote location. In order to find out the feasibility for the system development, a sample system using a multiuser function (UNet) and containing client and server application was built.

In this system, the only main purpose is to make the networking protocol works in the Unity by using UNet protocol in order to allow users to join the same scene with each other and share visualization and movement of the game object (spawning user of a cube). The system was separated into two applications, namely client and server, and both applications have to have the same networking architecture (as shown in Fig. 3). Technically, one of the most important steps is to generate the networking scripts (both server and client) using the Microsoft Visual Studio in order to let them be able to connect, listen and talk to each other. In the scripts, server IP address (Public IP address from AWS), room ID and types of channel for transferring the data such as the User Datagram Protocol (UDP) or Transmission Control Protocol (TCP) are the main parameters for the networking protocol that were constantly defined for providing connection and meeting map between the server and the clients, and the clients and clients. In term of the server application, it was built without UI but only the script attached to the empty game object in the scene for processing the code. Furthermore, receiving and sending request function have to define clearly to cover all the functionalities of the client application. For example, the server and the client both need to know the messages sent and received in order to execute the defined functionalities and update the scene of other clients to be in the same situation and environment and vice versa. By hosting the server on AWS, clients can connect to each other from anywhere and at any time. In term of the client application, users need to choose their role as the owner, the architect or the structural engineer on the buttons (as shown in Fig. 4) after connecting to the server. After clicking the role button, the application changed into another scene and spawned the cube which had the role tag on the top (as shown in Fig. 5). Therefore, they could see their own spawned cubes and perform their movement by using the computer keyboard. On the connection event, the visualization and the movement of any players were being shared and updated on every clients' application.

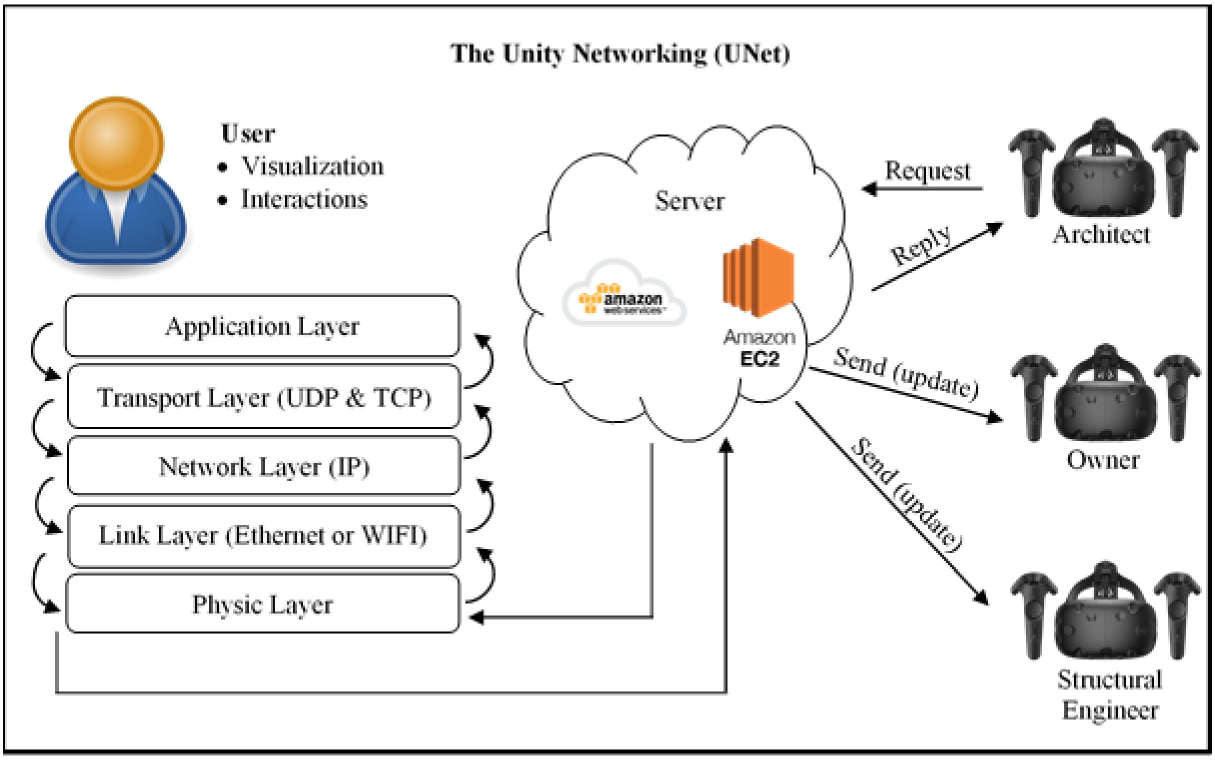

Fig. 3: System architecture of UNet for VR-based remote collaboration system.

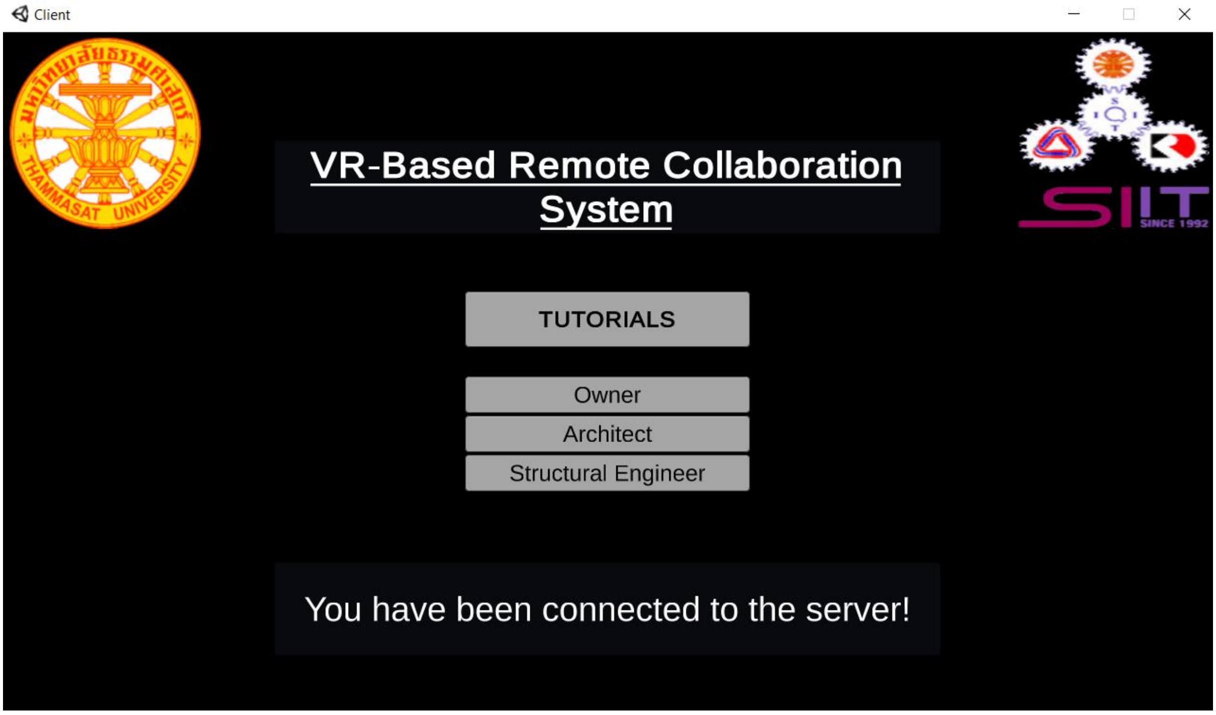

Fig. 4: Connection scene of the client application for the sample multiuser system.

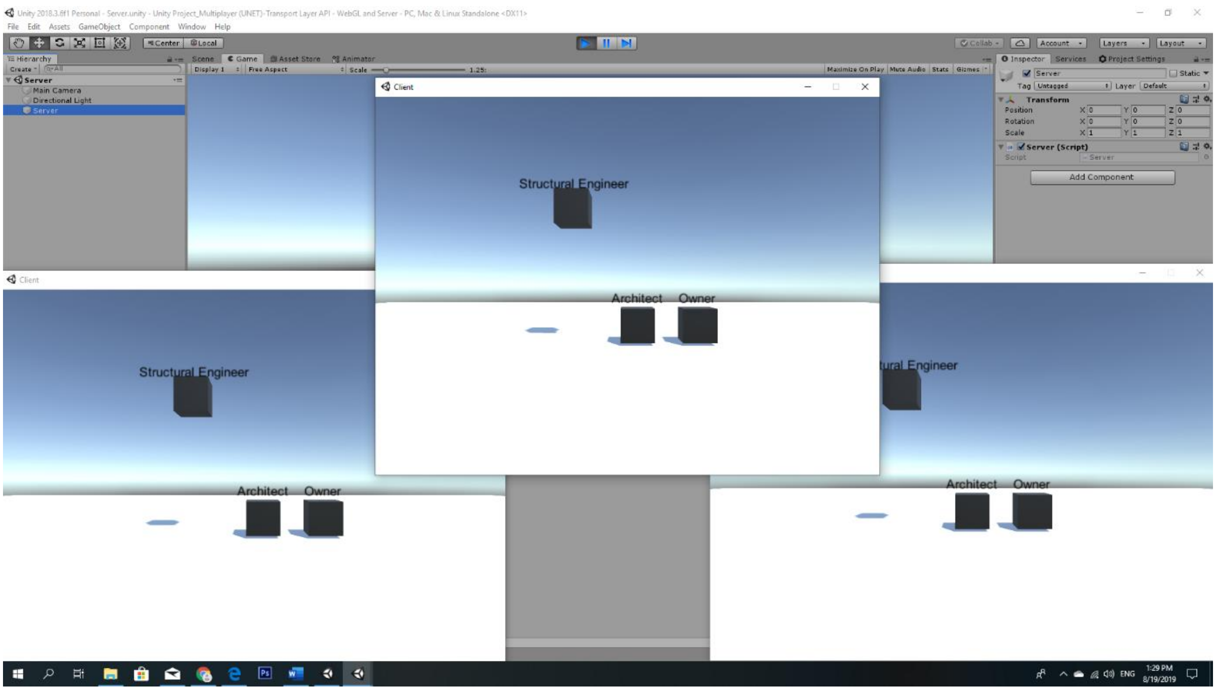

Fig. 5: Shared visualization and movement of three clients' application.

5. EXPECTED OUTCOME

The proposed study aims to integrate the VR-based system with the construction project by using the VR headset to assist current practices of remote collaboration in the conceptual design review. The main outcome of this research is a fully developed multiuser VR system that could be implemented in the collaborative design review resulting in facilitating the geographically distributed working environment and producing real-time collaboration among the construction project stakeholders. Expectedly, the proposed system might be practical and user-friendly in terms of functionalities and UI.

6. CONCLUSION, LIMITATION AND FUTURE WORK

6.1 Conclusion

The natural characteristics of the construction industry are the geographical dispersal and the multidiscipline contributing to the demand for digital collaboration. With the advent of the VR system and the existing BIM and cloud computing technology, the construction tasks are really leveraged with the integration of those technologies. In this proposed research, the authors proposed a new VR-based remote collaboration system that will provide the applicability of shared visualization and interactions for the conceptual design review between multidisciplinary participants in the construction project; and these could facilitate the collaborative design and solve the distant barrier. The proposed approach will allow remote connection from any users since the authors will host a server on AWS and use the networking protocol, so the users will be able to share their digital contents of the design model and perform the collaborative design review from anywhere and in real-time. By taking the potential benefit of VR system on the HTC Vive, the users can view the design in the virtual environment with any scales and any views of angle (360^0 rotation) by zooming or rotating controlled by both handheld controllers; this will provide an effective remote design review. As a result, the authors expect that the proposed study will show an improvement on the existing conventional collaboration approaches. Therefore, the authors will implement the system and conduct the test for usability through the questionnaires using the Likert scale method.

6.2 Limitation

The proposed study would not be solid, reliable and valid enough for the real application due to certain limitations that need to be taken into account. Time would be the first limitation for this study because developing a practical multiuser VR-based system takes considerable time, so it is really important to be well-planed and set priorities on the research tasks in order to ensure the completion of the proposed research. In terms of technical implementation, the functionalities of the proposed system are also considered as a limitation. For example, the authors use most of the commercial development tools with an education license from different companies, so they have surely limited the technical support from the outsources or needed advanced configurations from providers' experts; thus, this will limit the design capability of the system's functionalities. In relation to this, the authors will not implement any advanced security for the proposed system. Therefore, it will highly expose to cyber-attack from anonymous since the authors use cloud computing technology. Apart from that, there is a limitation regarding the experiment design that could influence data analysis results and the research findings. Since the authors conduct the data analysis on a small sample size with a student population, and the system is developed to address construction industry issues. Consequently, the output gets from the analysis could not deduce an effective assumption over the real situations.

6.3 Future work

In the current phase of this research, the preliminary work to prove the feasibility of technical implementation for the proposed system such as building a multiuser system—the server-client applications using the networking protocol with clickable button, input field texts, linked buttons, and scene management have been done. Furthermore, the exploratory study is being conducted through interviews with the experienced graduate students regarding their experiential critical issues in the collaborative conceptual design and solutions; this will provide support of the research gap findings. Meanwhile, the proposed system would start to develop according to the outputs of the exploratory study. Last but not least, the last task of the previously mentioned research tasks will be conducted after finishing the system development for the research findings and discussion.

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Assessing the cognitive load of a tower crane operator's workstation using Virtual reality and electroencephalography: A methodological Overview

Mehdi Hafsia & Yasmine Ouarti & Laure Ducoulombier
Bouygues Construction, Guyancourt, France
University of Versailles Saint-Quentin – Paris Saclay, Vélizy-Villacoublay, France

Eric Monacelli
LISV, UVSQ, Versailles University, Paris Saclay University, Vélizy-Villacoublay, France

Hugo Martin
C2S Groupe Bouygues, Guyancourt, France

ABSTRACT: *A construction site is a dynamic environment in which heavy equipment and humans interact and coexist. This makes the construction field one of the fields posing a significant risk on the safety of its workers. In this industry, equipment operators, and specially crane operators, play a major role in the successful progress of a project. Thus, a good mastership of the equipment can prevent delivery delays and avoid any accident that may occur in the event of handling errors. During crane operation, the operator may be distracted by multiple factors that can disrupt his concentration. Also, he has an important role in understanding the needs of ground-based workers, analyzing needs at time T of the site and taking the appropriate decision for a proper running of operations. These operations are therefore very demanding in terms of cognitive resources.*
Recently, Virtual Reality (VR), especially VR simulators, have started to be used as a training tool for equipment operators and showed its relevance in the improvement of the training process. However, it is not used to evaluate the cognitive ergonomics of the different equipment in the field of construction.
We developed a cognitive load assessment consisting of a reproduction of crane cabin in a virtual environment based on a construction site extracted from a BIM model and an electroencephalography headset to monitor the brain electrical activity, aiming to reproduce the daily work of a crane operator and to measure his attention in specific situations (Reactivity, behavior in case of accident-prone situation...).
This paper presents the functional specifications and describes the analysis system that combines VR and electroencephalography to assess attention and behavior of crane operator during his daily work.

KEYWORDS: *Virtual reality, electroencephalography, training, crane operator, cognitive load, prevention, security*

1. INTRODUCTION

The handling of heavy objects, working at heights and driving construction machinery make the construction sector one of the sectors presenting a significant risk to the health and safety of its workers (Jeong, 1998; Health and Safety Executive, 2017). These different activities and the different interactions that exist lead to a risk of accidents on the construction sites. These actions result from the co-activity that exists on a construction site between the workers themselves, the workers and the environment but above all the workers and heavy equipment.

Indeed, according to The Center for Construction Research and Training (CPWR), mobile heavy equipment is a major source of fatal accidents in the United States, with more than 7000 deaths between 1992 and 2010 (The center for construction research and training, 2013).

Workplace and worker safety has improved with advancements in regulations, consensus standards, and best work practices (Centers for Disease Control and Prevention, 1999). The construction sector has undertaken several actions to improve the health and safety of its employees.

As an example, Bouygues Construction has innovated and does set itself the objective of achieving "zero accidents on change. To this end, an information campaign has been set up to raise awareness among its workers in their workplace, thus going beyond the scope of training. This consists of the presence of awareness posters on construction sites, sessions to remind people of the basic safety rules and morning warm-up sessions. The company has also implemented more effective means to avoid accidents and long-term health problems such as robotic platforms to move or lift heavy loads.

One of the innovations adopted by the company is the use of virtual reality (VR) for worker training. This technology was initially used for architectural and technical validations and as an aid to the sale of construction projects since the democratization of building information modelling (BIM) (Azhar, 2011).

Workers are trained in virtual reality in several different ways, such as detecting risks on a virtual construction site, using a tool and applying its operating procedure in complete safety, or adopting the right reflexes before starting the work day (wearing personal protective equipment, etc.) (Hafsia *et al.*, 2018).

For several years, we have seen the appearance of simulators for driving construction machinery (Freund, Rossmann and Hilker, 2003). These simulators are inspired by those used by the aeronautical or automotive industry. In these industries, simulators are used for the prototyping and the development of certain equipment (Kallmann *et al.*, 2003), test driver and vehicle performances in controlled environments, to train pilots and to put them, safely, in “dangerous situations” and to study their behavior in certain position. (Allen *et al.*, 1975; Bella and Calvi, 2013).

However, these simulators are also used to study ergonomics (Kallmann *et al.*, 2003). Indeed, some of them are used to observe different cognitive states such as sleepiness, fatigue, stress or cognitive load (Chan *et al.*, 2010; Balandong *et al.*, 2018).

Bouygues Construction is working on the "Tower Crane of Tomorrow" and the future crane operator's substation to improve productivity and accelerate its construction processes. To help the company to design the most ergonomic tower crane operator station, we used a crane simulator combining virtual reality and electroencephalography-based cognitive load assessment (EEG). Part of this work allows the improvement of the crane operator's daily life by rethinking a better ergonomics of his workstation.

This article presents the risks associated with the use of the tower crane. We define the notion of cognitive load and the means of measuring it. Then, we present the method we used to evaluate the ergonomics of the tower crane operator workstation.

Finally, we conclude by discussing our approach and the future implications.

2. SAFETY: AN IMPORTANT ISSUE FOR THE CONSTRUCTION SECTOR

Construction is a dangerous field due to the machinery used, among other things. One of these devices that are at risk is the crane. Indeed, Neitzel reports that a U.S. Bureau of Labor data set dating from 1987 lists more than 1000 accidents involving cranes. In the same article, the author states that a British report indicates that 17% of fatal accidents in the United Kingdom involve cranes (Neitzel, Seixas and Ren, 2001). In Tam's study, we find that the main causes of accidents related to tower cranes are falls from height, collisions with or by a moving object, collisions with a falling object and entrapment between two objects (Tam and Fung, 2011). However, 87% crane-related deaths mainly affect workers on the site and not crane operators (Neitzel, Seixas and Ren, 2001).

However, these studies do not necessarily reflect accidents related to the crane malfunction itself and since Reason argued that the statement that the human contribution to accidents is about 80 to 90% in all major accidents is close to the truth (Reason, 1997), we decided to observe the crane operator's behavior and analyze the different cognitive phases and more precisely the cognitive load.

In construction, as in labor-intensive industries, working conditions play a central role in terms of performance but also in terms of safety. Shorter and shorter deadlines, working hours and the risks associated with the job, among others, represent a source of psychological stress (Chen *et al.*, 2017).

In the case of the crane operator, since the crane is an important element on a construction site (Shapira *et al.*, 2007, Shapira and Elbaz, 2014), the risks are even higher. The movement of heavy loads, the processing of information gathered by the various sensors present (anemometer, load indicator, etc.) and the monitoring of the organization of the construction site make the crane operator's position stressful and requiring a lot of energy and mental resources This stress influences the mental load and can have adverse consequences on the health of the crane operator and the safety of construction workers (Gaillard, 1993). Hence, we conducted tests to measure the cognitive load of the tower crane operator.

3. COGNITIVE LOAD

Cognitive load is a term used to describe the intensity of brain function when performing a task. This theory was developed by John Sweller and explains, during a learning phase or problem solving activity, the success or failure of an individual. It combines information storage capacity and the integration of new information (Sweller, 1988). It thus represents the interaction between what the task requires and the human processing capacities or resources (Welford, 1978).

Cognitive load can be measured by observing psycho-physiological changes (Ryu and Myung, 2005; Haapalainen *et al.*, 2010). In fact, the complexity of a task influences certain psycho-physiological factors such as pupillary responses, eye movements and blink interval (Beatty and Lucero-Wagoner, 2000; Ikehara and Crosby, 2005; Iqbal and Adamczyk, 2005), heart rate (HR) and heart rate variability (HRV) (Mulder, 1992; Fredericks *et al.*, 2005), electrocardiogram (ECG) (Ryu and Myung, 2005), galvanic skin response (GSR) (Shi *et al.*, 2007), respiration (Mulder, 1992) and electroencephalogram (EEG or brainwave) (Wilson, 2002; Antonenko *et al.*, 2010).

Recently, the introduction of portable EEG measuring devices has facilitated the acquisition of brain waves outside laboratories and opened the door to non-invasive field experiments. These devices have been used on construction sites to measure factors such as valence (Jebelli, Hwang and S. H. Lee, 2017) and stress (Jebelli, Hwang and Lee, 2018). Based on these studies, we focused on measuring and observing the different brainwave levels to evaluate the ergonomics of the crane operator's workstation during the performance of a task.

4. METHODS

We decided to observe the crane operator and evaluate the ergonomics of his workstation. Indeed, the crane is an important tool on a construction site (Shapira *et al.*, 2007). The proper use of the crane is essential to meet the tight deadlines imposed by the projects.

In order to conduct our study, we measure the electrical activity of the brain using an electroencephalogram headset, the B-Alert X10 from the Advanced Brain Monitoring company (ABM) (Johnson *et al.*, 2011) (Fig.1).

Fig. 1: B-Alert X10 EEG headset

To do this, we studied two different situations: 1) a real situation (on construction site) and 2) a virtual environment situation extracted from the BIM model of Bouygues Construction training center (Fig.2). In both situations, we asked the crane operator to perform a number of tasks while measuring his cerebral activity to assess his cognitive load.

For the real workshop, first of all, we took measurements in the cabin at the top of the tower crane. We started with a ten-minute test to get reference values. Then, we asked the crane operator to perform the traditional tasks he is used to performing during his working day.

For the virtual workshop, we reused the same reference values as those obtained during the first phase of the

Fig. 2: Bouygues Construction training center 3D model

exercise. We immerse the crane operator in a virtual tower crane cabin located in the virtual reproduction of the Bouygues Construction training center thanks to the HTC Vive virtual reality headset. We used the real crane cockpit he is used to and we used the controllers to perform the actions in the serious game for more realism (Fig.3).

Fig. 3: Virtual workshop including the crane

In the serious game, we proposed two different configurations of crane operator workstations: 1) top of a tower crane (Fig.4) and 2) bottom of the tower crane (Fig.5).

The crane operator had to move a load from a starting point and drop it off at the arrival point. Obstacles can be found between these two points and the crane operator must avoid them. Each exercise was used to record the execution time, the accuracy of the charge deposition and the electrical activity of the subject's brain. These exercises were set up in order to compare the different ergonomics of these configurations based on the evaluation of the cognitive load.

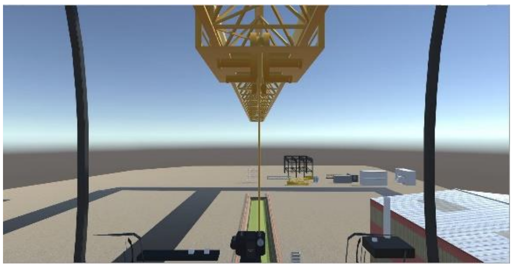

Fig. 4: View from the top of a tower crane

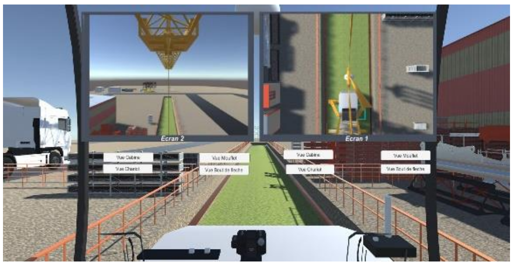

Fig. 5: View from the bottom of a tower crane

In the case of the substation at the bottom of the tower crane, since the crane operator's actual vision will be replaced by camera returns, we studied the different layouts of the display screens to optimize the design of the crane operator's workstation on the ground, based on the crane operator' feedback and the study of the variation of its brain waves.

Once the data has been collected, we used the software provided by ABM, B-Alert Live. This software allows to visualize the subject’s cognitive load, high engagement and distraction in real time, but also to visualize them offline. It also allows to visualize the surface and thermometric distribution of the different brain waves (alpha, beta, gamma and theta). The different results collected make it possible to evaluate the ergonomics of the different configurations tested in order to propose an optimal solution.

5. CONCLUSION & FUTURE WORKS

In this article, we have presented our approach to evaluating the ergonomics of a tower crane operator's workstation.

The simulator has been designed in order to test two different configurations 1) the comparison between the current crane operator's workstation and the crane operator's workstation at the bottom of the crane 2) the ground crane operator's workstation with different screen layouts that transmit the video stream from the cameras installed on the crane. These configurations are presented in a virtual environment.

The crane operator was immersed in a virtual crane cabin and had to perform a number of tasks based on the transport of a load on a route with obstacles using the actual controls of a crane chair that we have connected to the virtual interface. During these exercises, the electrical activity of the participant's brain was recorded using an EEG headset as well as the time and accuracy of the task execution and the crane operator's returns were logged and analyzed for the purpose of comparing the different situations proposed.

The next steps will be to include other psycho-physiological factors in our study such as heart rate, respiration or GSR.

We are also considering extending our approach to other workstations in order to improve the ergonomics of other workstations.

Finally, we will consider automating the processes for detecting cognitive load peaks in order to predict a state of fatigue or stress and thus avoid accidents on construction sites. The results of this studies will be published in other articles.

ACKNOWLEDGMENTS

We would like to thank Tech Ergo Appliquées (TEA Ergo) company for their help with the EEG headset. My thanks go to Houssem Zagheden for his proofreading. I thank him as well as Sylvain Chevallier and Benjamin Nguyen for their extraordinary support.

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BLOCKCHAIN TECHNOLOGY AND BIM: AUTOMATED CODE COMPLIANCE PROCESSES

Nawari. O Nawari, Ph.D., P.E., F.ASCE
School of Architecture, College of Design, Construction & Planning University of Florida; USA, e-mail: nnawari@ufl.edu

Shriraam Ravindran, M.Sc.
Ph.D. student, School of Architecture, College of Design, Construction & Planning University of Florida; e-mail: shr1raam@ufl.edu

Adel Alsaffar, Ph.D.
Assistant Professor, College of Architecture, Kuwait University, Kuwait, e-mail: dr.alsaffar@gmail.com

ABSTRACT: *Blockchain is a technology notion that devised from the first cryptocurrency known as Bitcoin and was soon distinguished to have a much more extensive range of applications beyond serving as the platform for digital cryptocurrency. A blockchain technology (BCT) is principally a decentralized and an immutable ledger that records every transaction made in the network. The implementation of a decentralized distributed technology in any industry would result in increased security, impose accountability, and can potentially accelerate a swing in workflow dynamics from the current centralized organization to a decentralized, cooperative chain of command by reassuring trust and collaboration. This paper investigates the potential integration of the BCT with the BIM process in advancing the automation of the compliance checking process. Furthermore, the research examines how employing distributed ledger technology (DLT) could be beneficial in the automating building code compliance verification by reinforcing cybersecurity, providing more reliable data storage and management of permissions, ensuring change tracking and data ownership. The study evaluates the Hyperledger Fabric (HLF) as a key BCT in advancing the BIM workflow and proposes an integrative HLF+BIM framework for enhancing the automation of the automated building code compliance process.*

KEYWORDS: *Blockchain, BIM, Hyperledger Fabric, Automated Code Compliance Checking*

1. INTRODUCTION

The blockchain is a digitized, decentralized ledger of data, assets, and all related transactions that have been executed and shared among participants in the network. While it is most associated with digital cryptocurrencies such as Bitcoin, blockchain is viewed as an emergent technology that could potentially revolutionize and transform the current digital operational landscapes and business practices of finance, computing, government services, and virtually every existent industry (Crosby et al., 2015; Crosby M, 2016). The chief hypothesis behind blockchain is the creation of a digital distributed consensus, ensuring that data is decentralized among several nodes that hold identical information and that no single actor holds the complete authority of the network.

A Decentralized Ledger Technology (DLT) is a peer-to-peer network generally incorporates a decentralized consensus mechanism, distributing the computational workload across multiple nodes present throughout the network, facilitating the nodes to create connections, and they ensure the links stay alive, while also providing every node in the network receives and transfers out data (Nakamoto 2008; Wang et al. 2018; Zheng et al. 2017). This mechanism excludes the likelihood of a system failure or a complete network blackout. DLT usually achieve this by integrating a decentralized consensus structure before the blockchain initiating transaction operation. The network participants agree in advance and decide on a consensus mechanism appropriate to their requirements. Every endorsing node in the network runs the same consensus algorithm; thus, the system does not need any third-party administrator to oversee the transaction operations (Brakeville and Perepa 2016).

Blockchain can address accessibility and visibility of the data in a secure and efficient manner since the ledger is distributed (Brakeville and Perepa, 2016; Clack *et al.*,2016a; Frantz and Seijas *et al.*, 2017). It facilitates setting different levels of privacy as every participant is essentially a stakeholder, and no single participant has full administrative privilege. Thus, formulating and enforcing consensus is crucial to the blockchain operation, with terms to data updates, error-checking, and collective decision-making (Nawari and Ravindran, 2019).

Smart Contracts (SC) are contracts programmed with the blockchain that automatically executes upon the fulfillment of certain business conditions, and removes the requirement of a third-party intermediary for overseeing the transaction in real-time (Dhawan, 2016; Bhargavan *et al.*, 2016; Clack *et al.*, 2016a, 2016b; Seijas et al., 2017).

HLF is a platform for generating distributed ledger blockchain systems, supported by a modular design, offering a flexible digital framework that delivers high levels of confidentiality, and scalability. It is designed to support pluggable implementations of different components and accommodate the complexity and details that exist across the economic ecosystem. The Hyperledger blockchain aims to be a general-purpose, enterprise-grade, open-source DLT that features permission management, pluggability, enhanced confidentiality, and consensus mechanism and is developed through a collaborative effort.

Building Information Modeling (BIM) is at the forefront of digital transformation in the AEC industry, encouraging collaboration and trust, and simplifying data exchange. BIM models present a comprehensive design and construction model of the building that can include all aspects of the facility, such as architectural components, structural elements, and MEP design areas. Further, several built-in plug-ins in BIM platforms like Autodesk Revit enable the simulation of external site conditions, geography, weather, as well as carry out energy analysis, building energy modeling, structural analysis, etc. In the future, BIM development will eventually aim to unify all design and analysis tools in one platform. However, the current BIM process has several limitations such as no archival of BIM model change and modification history, difficulties in assigning responsibilities and liabilities, insufficient cyber-resilience and cybersecurity, and lack of legal framework detailing model data ownership and legal contractual issues (Eastman et al. 2011; Ahn et al., 2015)

Employing BCT in the BIM process can address several issues that are currently phasing the BIM implementation in the AEC industry. For instance, these include cybersecurity, reliable data storage and management of permissions, change tracing, and data ownership. This paper proposes a framework that aims at integrating HLF and the automation of the design review process in a BIM workflow.

2. PURPOSE AND OBJECTIVES

The primary goal of this study is to examine the BCT and its integration with the BIM workflow to enhance the automation of the building code compliance checking process. The objectives of the research include a) review Hyperledger Fabric (HLF) and its potential applications in BIM workflow, b) propose a framework for integrating HLF and the automation of the building code compliance checking process to enhance the cyber-resilience and security, data storage and management of permissions, and data ownership.

3. METHODOLOGY

The study approach is based on an organized review and evaluation of the HLF, and the potential of its integration with BIM workflow to improve the security and efficiency of the design review process. This includes the retrieval of the relevant data from the literature sources assessing the quality of the content and synthesizing the data to develop a framework for integrating the HLF with the automation of the building code compliance checking process. The collected literature is evaluated and analyzed to correlate their findings with the goals and objectives of the research. Figure 1 depicts an overview of the research approach.

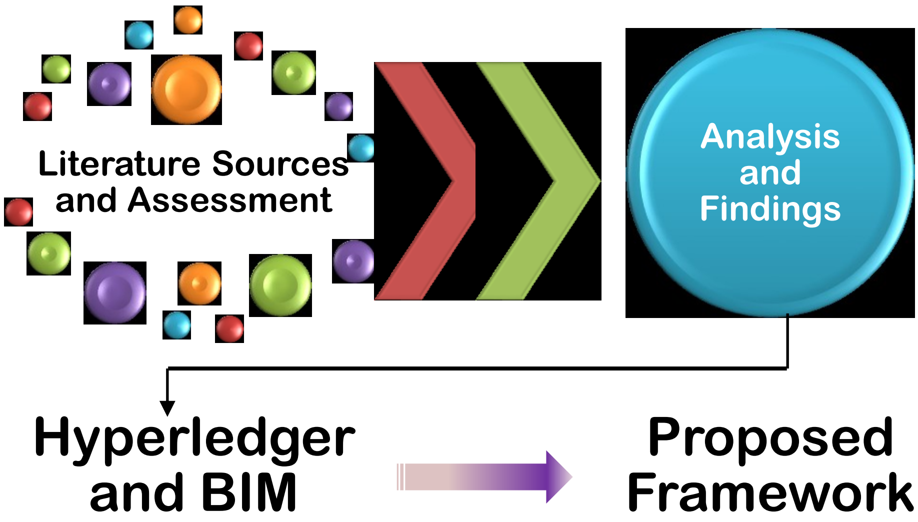

Fig.1. An overview of the research methodology.

4. HYPERLEDGER FABRIC (HLF)

Hyperledger is a collaborative effort founded by the Linux Foundation in 2016 to advance cross-industry BCT. It aims at the development of distributed applications written in standard general-purpose programming languages (Andreoulakis et al., 2018). It is a cross-industry open standard platform for blockchain that seeks to transform the technique business transactions are conducted universally.

HLF is one of the blockchain projects within Hyperledger. Like other BCT, it has a distributed ledger (DL), uses Smart Contracts (SC), and is a system by which participants manage their transactions. In HLF, SC is known as chaincode. It is executable code, deployed on the network, where it is invoked and validated by peers during the consensus process. The standard programming language used in developing chaincode is Go, Ruby, Java, and NodeJS (Hyperledger, 2018).

The fundamental differences between HLF and other blockchain systems are that it is private and requires permissions (Nawari and Ravindran 2019). In contrast to an open permission-less system that allows unknown identities to participate in the network, the nodes of an HLF network join through a trusted Membership Service Provider (MSP). Moreover, Hyperledger Fabric has the ability to create channels, allowing a subgroup of participants in the network to establish a separate ledger of transactions (Nawari and Ravindran 2019). This is an especially important option for BIM workflow where subcontractors can exchange data within the only subgroup of the network. For example, the structural engineer of record of the project can exchange information with steel connection subcontractors only while still being part of the HLF network and sharing those transactions with the rest of the nodes (Nawari and Ravindran 2019).

5. AUTOMATED BUILDING CODE COMPLIANCE CHECKING PROCESS

Regulations are normative text prescribed by governing entities to enforce constraints to design and engineering processes and manufacturing based on existing conditions, and function as the defining text for laws, codes, specifications, standards, etc. Automating design review and compliance processes in the AEC industry would benefit the industry, saving time, money, labor, and minimizes scope for risk and human errors. While much of the decision-making and consideration of the code is dependent on the experience of the reviewers, automation could at least enforce the upper and lower limits and report results instantaneously. Translation of various clauses and statements into computable language presents a significant challenge in achieving automation (Eastman et al. 2009; Nawari 2018). However, following an ideal framework to develop a tool that successfully accounts for all regulations through the accurate interpretation of formal language and model data exchange could be pivotal in increasing efficiency and upholding safety standards in any AEC projects. Automating design review and compliance processes in the AEC industry would greatly benefit the industry in terms of increasing productivity, minimizing resource consumption, and reducing the scope for human errors.

Nawari (2019) developed the Generalized Adaptive Framework (GAF) that aims at establishing a computable model with the clear syntax to accurately characterize building code requirements, to reduce model complexity and develop a unified format to exemplify building regulations and building information modeling to automate design review and compliance processes. However, the compliance checking process must be secure with reliable data storage and management of permissions, change tracking, and collaborative. Thus, this study proposes a framework that integrates the HLF and the GAF to advance the security and efficiency of the automatic building code checking process in a BIM environment.

6. PROPOSED FRAMEWORK

The proposed framework aims to use HLF to implement an automated Design Review Process based on the Generalized Adaptive Framework (GAF) (Nawari 2019). Figure 2 below delineates an overview of the integrated HLF and GAF framework to an automatic design review and compliance checking process. The four main elements of the framework are the GAF, Smart Contracts (Chaincode), membership services, and ordering services.

The HLF is based on a permissioned blockchain network that provides security to protect data exchanges between members of entities who share a mutual goal but have intellectual properties that they need to secure while exchanging information. The proposed framework has a modular architecture. The main modules are depicted in figure 2 and include:

(a) Membership services: A membership service provider (MSP) allocates cryptographic identities to peers participating in the network, and maintains the characters of all nodes in the system. This module serves to create a root of trust during the network formation.

(b) Ordering services: A service that broadcasts the state updates to peers in the network and establishes consensus based on the order of transactions via, the Ordering Service Nodes (OSN), or orders that establish the total order of all transactions in the Fabric. The ordering services in HLF represent the consensus system. The ordering service groups multiple transactions into blocks and outputs a hash-chained sequence of blocks containing transactions.

(c) Chaincode (Smart Contract) services: It is an application-level code stored on the ledger as a part of a transaction. The chaincode runs transactions that may modify the data on the ledger. A chaincode is installed on network members' machines, which require access to the asset states to perform read and write operations. The chaincode is then instantiated on particular channels for specific peers.

(d) GAF: The GAF represents the business logic that is written as a chaincode. The GAF has algorithms that can be expressed and executed in JAVA programming objects to extract, access, and link BIM and regulations data to report the results of the design review process.

Currently, AEC industry depends on the "security through obscurity" method to protected engineering design data, which stresses the privacy of the application and mechanisms of the cybersecurity system. Thus, a small leak of data can possibly risk the entire network (Kshetri et al. 2017). Also, BIM platforms provide various multifunctional workspaces which address asset management, performance monitoring, and change management through the life-cycle apart from supervising the planning, design, and construction phases of the project. To enable uninterrupted collaboration among all peers in a BIM workflow, BIM platforms service the Common Data Environment (CDE), which provides a single repository for project data that is utilized to assemble, manage, and allocate information for multidisciplinary teams. It requires auditing, monitoring, and tracking of data through the CDE, which will develop throughout the project life-cycle. Since automatic design review and compliance checking process in BIM environment encompasses complex data transactions involving collaborative actions and information exchange between actors, technology, and methods and inter-relationships, it is crucial to consider cyber-security implications, assess current levels of reliability, address present drawbacks, and reinforce security. These drawbacks are discussed in the proposed framework using the MSP and OSN of the Hyperledger Fabric.

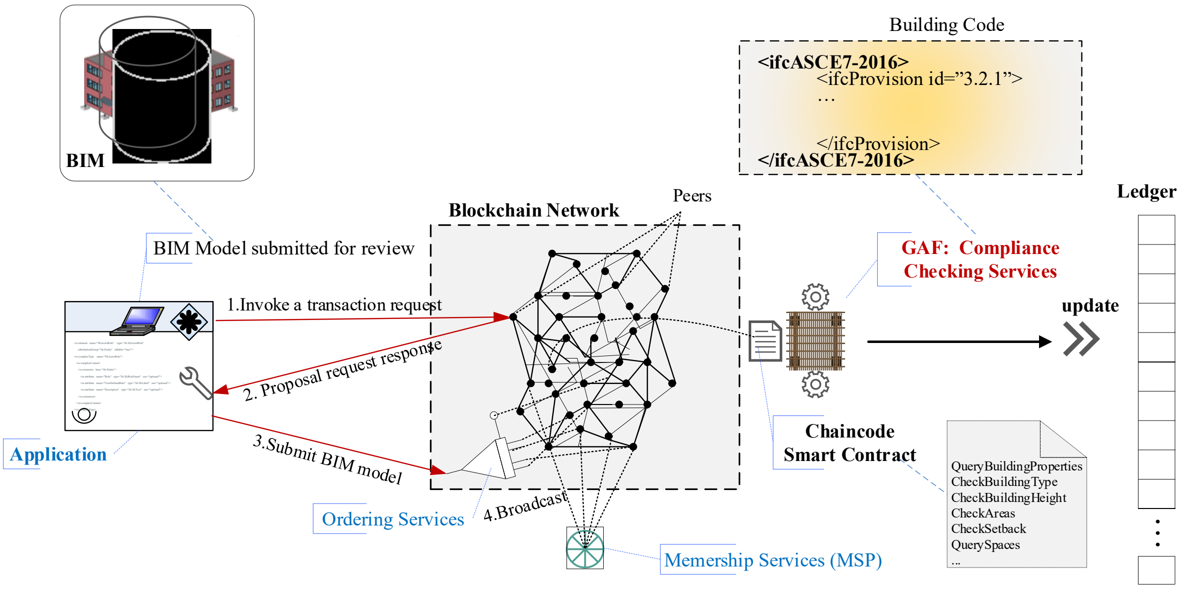

Fig. 2: Overview of the Integrative HLF + GAF Framework for automating code compliance checking process.

The blockchain network consists of a set of nodes (peers) (see Figure 1). Since the system is permissioned, all nodes that participate in the network have an identity, as provided by the membership service provider (MSP). Nodes in such a network can have one of the three roles:

(i) Clients submit transaction request for execution, assist in composing the execution phase, and, finally, broadcast transactions for ordering services.

(ii) Some specific peers execute transaction proposals and validate transactions. This step is also called endorsement, and the peers are called endorsing peers (or endorsers). All peers maintain the blockchain ledger, an append-only data structure recording all transactions in the form of an encrypted (hash) chain of data, as well as the state, concise representation of the latest ledger state. Note that not all peers execute all transaction.

(iii) Ordering Service Nodes (or orderers) are the nodes that as a group forms the ordering service. The ordering service creates the entire order of all transactions invoked in the system, where each transaction contains state updates and dependencies computed during the execution phase, along with cryptographic signatures of the endorsing peers. Orderers are exclusively unaware of the application state and do not participate in the execution nor the validation of transactions.

7. CONCLUSION

The blockchain system is an emerging information technology which is characterized by a distributed, full-lifecycle traceable data ledger of transactions for every network participant, and security and privacy of the network that is based on consensus algorithms. Due to these positive features, BCT has gained recently extensive traction in numerous domains.

HLF is a BCT that is predominantly suited for implementing the automation of building code conformance verification process in a BIM workflow, due to its ease of programming (using SDK), flexibility, user-defined smart contract (chaincode), robust security, identity features, and modular architecture with pluggable consensus protocols. The proposed integrative BCT+GAF framework aims to address the limitation of the current BIM process and provides secure, reliable automation process of the design review and compliance checking in BIM workflow. The chaincode technologies (also known as Smart Codes) available in HLFs are promising technologies for invoking the GAF in a more secure and efficient process in the AEC industry, particularly for the compliance checking process. Furthermore, the HLF can address other current concerns facing the BIM workflow, such as data confidentiality, the speed of transactions, model changes tracing and permission management that arise from using centralized BIM work processes. Future research will focus on expanding the integrative framework to include other related issues such as data ownership and legal issues.

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AS-BUILT DETECTION OF BRIDGE STRUCTURE USING DEEP LEARNING AND VOLUME DETECTION SYSTEM USING BIM MODEL

Ryu Izutsu, Nobuyoshi Yabuki, and Tomohiro Fukuda
Osaka University, Japan

ABSTRACT: *Construction process inspection of bridges is generally performed by taking pictures and comparing them with drawings. Since this work is time-consuming and error-prone, a more accurate and efficient method of capturing the progress is desired. The purpose of this research is to construct a system that can efficiently capture the progress of the construction by detecting each bridge structural component such as a column and a beam under construction from images taken by a camera. This system can efficiently capture the shape of civil engineering structures. The time required for bridge inspection can be reduced. First, we developed a Convolutional Neural Network (CNN) that could detect bridge components under construction from images by fine-tuning the existing Segmentation CNN. Next, we constructed a system that can capture each bridge member from an image by constructed CNN model. The result of detection shows the shape of the completed part of the bridge at the time of taking images. The actual bridge under construction is detected by utilizing the developed system. Subsequently, the accuracy of the attribute information in the image is confirmed by checking the result of the detection image. Finally, we constructed the system that reproduces the current construction site situation from the entire Building Information Modeling (BIM) models by utilizing the CNN detection results. The current construction status is reproduced from the completed BIM model by using the shape image. We conducted accuracy verification and evaluated the developed system by comparing the actual construction site with the reproduced BIM model. Cost management can be performed by adding the attribute information of the components price to the BIM model in advance by using this system.*

KEYWORDS: *Convolutional Neural Network, Deep Learning, As-built Detection, Segmentation, Bridge Structure*

1. INTRODUCTION

In recent years, visual capturing of the construction progress has become possible by using the photographs taken at the construction site, detailed drawings, and BIM model of the construction site. However, this work is not only time-consuming but also prone to human error. Therefore, an automatic system is desired to capture construction progress more accurately and efficiently.

Recently, the technology of object detection using deep learning has been developed. The recognition accuracy of objects using deep learning has been developed with the advent of Caltech 101 (Fei-Fei et al., 2007) which is a data set of digital images and ImageNet (Deng et al., 2009) which is an image database. In ImageNet Large Scale Visual Recognition Challenge (ILSVRC) which is a large-scale object recognition competition that has been held since 2010, the object detection accuracy using deep learning has been higher than human detection accuracy since 2015. Researchers have been developing advanced detection systems using the detection results. However, these published trained models detect objects such as people, cats, and horses, and cannot detect objects that do not exist in the image database.

In this research, we developed a CNN that can detect each structural member such as a beam, column, cross beam, floor slab, and joint under construction by fine-tuning on the existing segmentation CNN. Then, we developed a system that can perform segmentation for bridge structures by CNN model. The system can detect the bridge structures in the photo by confirming the image. First, various bridge photographs are taken to prepare an image data set for deep learning. Next, to detect bridge structural members using deep learning, we changed the training weights of existing deep learning models such as U-Net (Ronneberger et al., 2015) by fine-tuning using various bridge photos. Then, we develop a system that can detect specified target structures from images by the constructed CNN model. This system confirms the shape of the bridge from the detection result image. Finally, we constructed the system that reproduces the current status of the construction site from the entire BIM model by using the detection results and the BIM model. Then, we conducted accuracy verification and evaluated the field situation reproduction system developed by comparing the actual construction site with the reproduced BIM model.

2. LITERATURE REVIEW

2.1 Object detection using deep learning

Currently, many object detection algorithms using networks similar to Region-CNN (R-CNN) (Gidaris and Komodakis, 2015) have been proposed. First, R-CNN is one of the state-of-the-art CNN-based deep learning object detection approaches. This network resized the input image to CNN and calculated the number of features by extracting about 2000 candidates of the region in which the object appears in the input image. Next, Faster R-CNN (Ren et al., 2015) with faster inference speed and learning speed than R-CNN was announced. The speedup was achieved by incorporating the Region Proposal, which had been time-consuming in previous neural networks, into CNN. Besides, Faster R-CNN uses a learning technology called Multi-task loss and has an end-to-end structure that allows the entire model to learn. As a representative deep learning neural network constructed using the same idea as the R-CNN algorithm for object detection, U-Net was developed. U-Net supplements the details of the information in the image by directly connecting the feature map output from each layer of Encoder to the feature map of the corresponding layer of the Decoder. U-Net can perform more accurate image analysis.

2.2 Related research in detecting existing structures

Much research has been done to automate progress and production management in construction. For construction sites, a system has been proposed to recognize the completion part of the construction by using object recognition from the captured image data and automatically recognizes three-dimensional objects (Fathi et al., 2015). However, this system can only confirm the installation situation on the image, and the recognition accuracy is not high performance.

Management systems using three-dimensional models have been proposed. A method has been proposed for detecting structural members such as slabs and girders in existing bridges from point cloud data by segmenting and constructing a three-dimensional model from the detection results (Lu et al., 2019). This method makes it possible to construct a three-dimensional model efficiently from the point cloud. However, it is not possible to detect concrete bridges or truss bridges with complicated geometrical shapes. Furthermore, it is shown that the detection performance of structural members is affected when the point cloud data is distributed at narrow intervals and unevenly. Also, to create a detailed BIM of an existing facility, a method has been proposed in which three-dimensional measurement values are obtained as point cloud using a laser scanner, and BIM model of a building is made from the obtained point cloud (Tang et al., 2010). This method can be considered as an efficient BIM creation algorithm since it can construct BIM models of existing structures. However, in this method, verification is performed on only simple planes. Therefore, there are problems to be solved, such as occlusion and modeling of complex structures.

Furthermore, a 3D modeling system that reproduces the construction situation was proposed. Recognize and monitor the structure using color and 3D data to monitor the progress of construction work, and create a 3D model using the information of the recognized 3D structural members (Son and Kim, 2010). This method enables the efficient construction of a 3D model of the construction status from image data taken at the construction site, so it can be used effectively as a method for managing the progress status. However, since this 3D model information is constructed from 3D data based on color information, if an object of the same color exists in the captured image, it will be erroneously detected and the reproduction rate of the progress status will be Since it is about 90%, the problem with this system is that the progress can be grasped only to some extent.

In recent years, with the development of computer vision technology, it has become possible to automate human work. A system was developed to automatically detect structural members in a room by utilizing two-dimensional image data (Hamledari et al., 2017). However, the tasks that can be performed by computer vision technology are limited, and there is a need for a system that can perform various detections with high accuracy.

3. PROPOSED METHOD

Figure 1 shows how the proposed system works. The proposed system can detect each structural member of the viaduct by preparing an image data set for deep learning using the images of the bridge and fine-tuning on CNN. Figure 2 shows the system that selects the BIM model of the corresponding member from the detection result image. Figure 2 (a) shows the method of the proposed system which confirms each structural bridge member, such as a beam, column, cross beam, floor slab, and joint, from the image. The image of the actual viaduct structure is input, and detection is performed for each structural viaduct component. Figure 2 (b) shows the procedure for obtaining element numbers from the BIM model. We show the procedure of the system that can reproduce the current construction status by using the BIM model and the detection shape. This system uses the detection result image as a mask image on Unity which is game engine software. Rays are emitted from the camera set on Unity toward the mask image. The camera position will be adjusted with the AR system. If the color of the mask image with which Ray collided is white, the element number of the BIM model existing on the extension line is written in Excel. Otherwise, Ray is erased and BIM models outside the detection result are not selected.

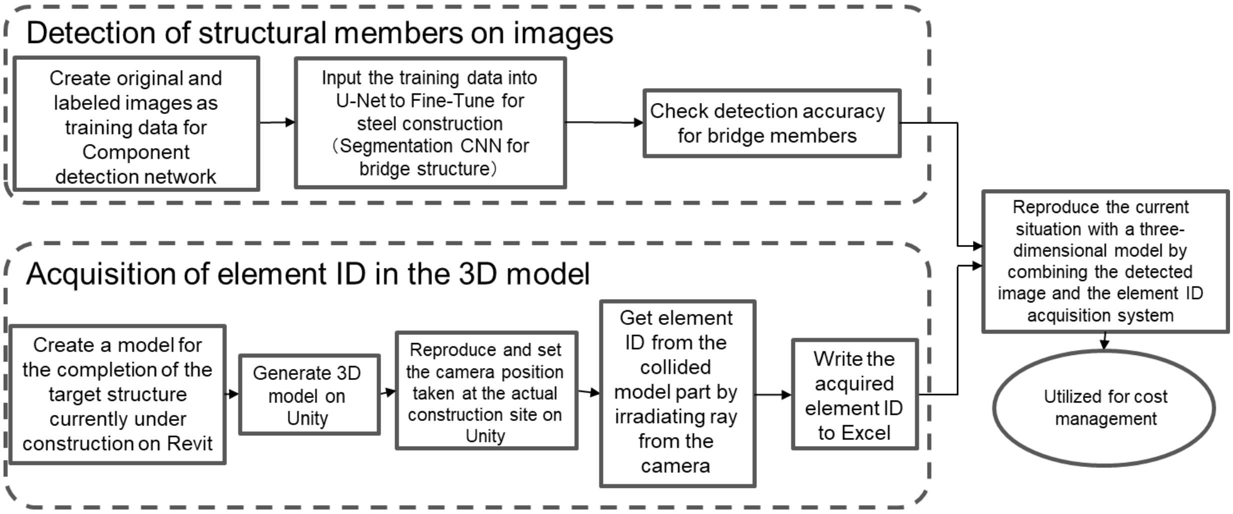


Fig. 1: Development procedure of the proposed system.

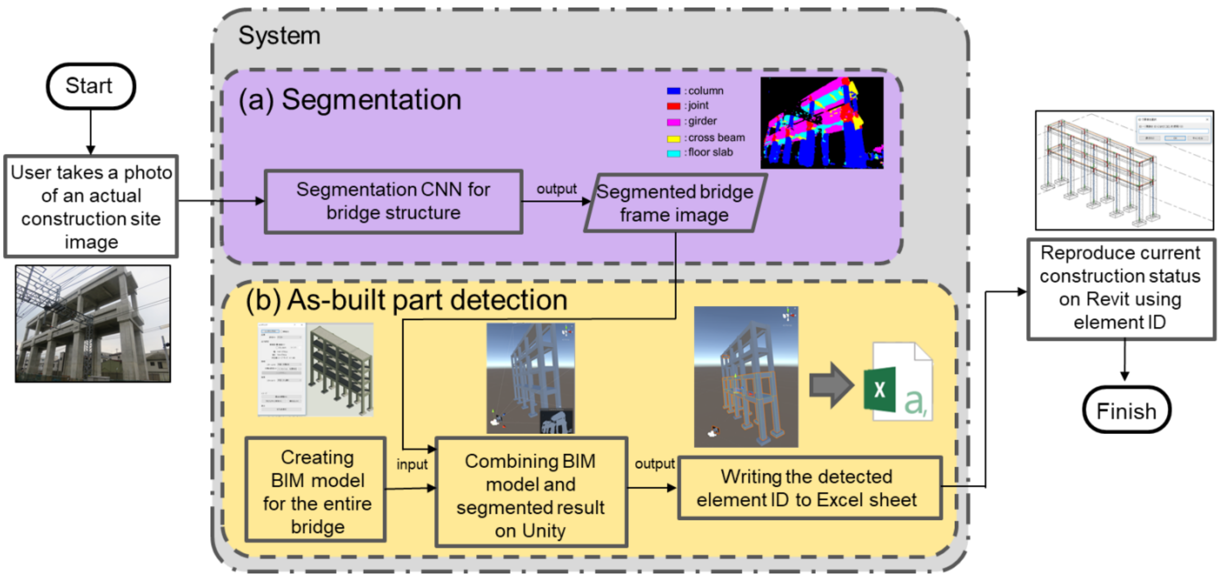


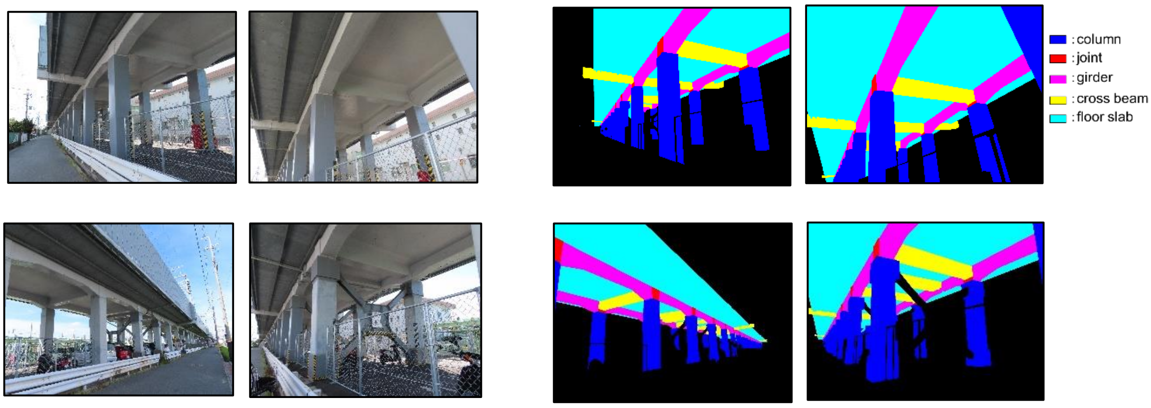
Fig. 2: Detection procedure for current construction model.

3.1 The training dataset for the viaduct structure

Since no trained model for the viaduct structure has been published, it is necessary to prepare the training data set for the viaduct structure. Therefore, we took pictures of various shapes bridge including the Tokaido Shinkansen in Japan. Annotation data is generated by creating corresponding mask images and used as the training data set. 1200 images of the bridge were prepared as training image data sets and 100 of them were selected at random as test images.

3.2 Segmentation by CNN for the viaduct structure

The data set for training was made to perform segmentation detection of the viaduct structure. The mask image is created by changing the beam, column, cross beam, floor slab, and joint of the detection target color to each color and the background color to black. The created mask image is then used as a training data set (fig.3). The image size is adjusted to 512 × 512 pixels since each training data set does not work well if the image size is too large during the input phase. By learning at this size, capturing the desired features inside the target image is easier.



Training photos Training mask

Fig. 3: An example of created annotation data.

3.3 Creation of target BIM model at the actual construction site

Currently, the viaduct for Hankyu Kyoto and Senri Line around Awaji Station in Hyogo Prefecture is under construction. A four-story station will be built around Awaji Station. We verified the system created in this study with the bridge in this viaduct. Figure 4 shows the construction site photograph as of August 2019 and the BIM model for the same section created in Revit.

Fig. 4: The construction site photograph and the BIM model for the same section.

4. SYSTEM DEVELOPMENT

The training data set made in 3.2 was changed to an appropriate format. Then, using the training data set made in 3.2, fine-tuning was performed to change the learning weight of U-Net. Based on U-Net, we constructed a CNN capable of performing segmentation detection on targeted members (Figure 5). It was originally proposed for segmentation of medical images. To accurately represent the boundary of the detected objects, measurement has been made to detect, adjustments to the image can then be made, such as increasing the loss at the boundary between the object to be detected and the background. On the other hand, SegNet (Badrinarayanan et al., 2017), which is one of a popular model for Semantic Segmentation, is a deep learning model that performs segmentation of landscape images faster and using less memory. Since the Encoder-Decoder structure is adopted, processing can be performed at higher speeds. However, in the proposed system, it is necessary to accurately detect only the construction parts/ elements that are completed by using the photograph of the detection object. Therefore, we chose to use U-Net in the proposed system as it does not emphasize real-time processing performance at high speeds.

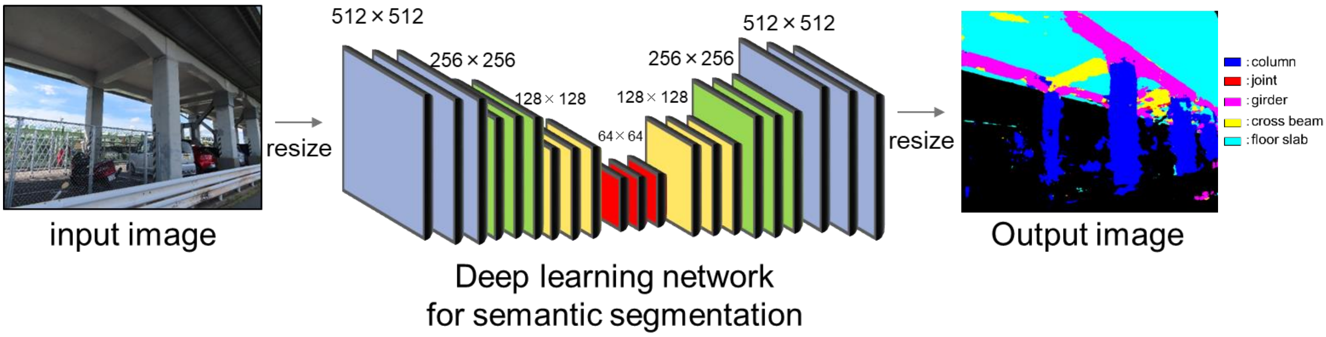


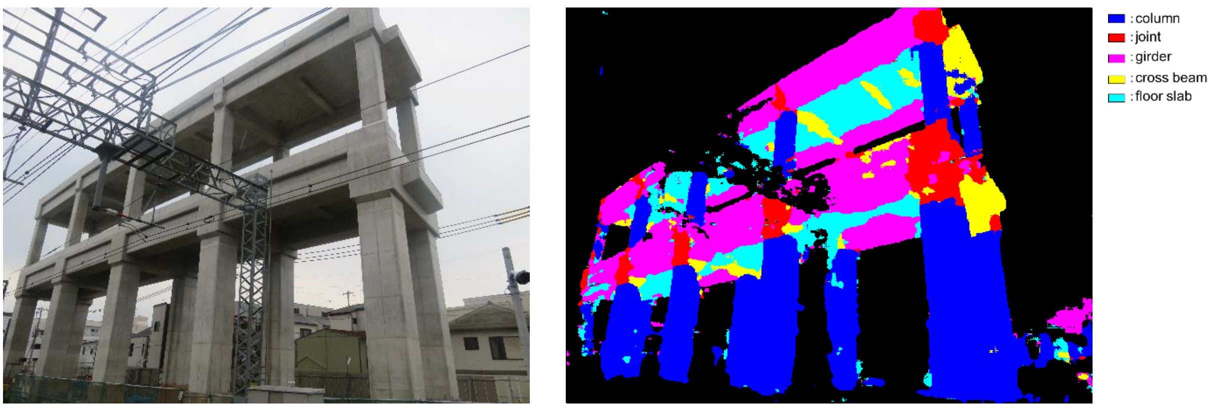
Fig. 5: Structure and contents of learning of CNN based on U-Net.

5. RESULT

5.1 Segmentation result using actual construction site images

We verified whether it is possible to detect a bridge member from a picture of the actual construction site using U-Net which can detect columns, joints, girders, crossbeams, and floor slabs of various viaduct photos by fine-tuning. As a verification experiment to detection accuracy, we prepared an image with different shapes of the detection target and compared it to the CNN training data set and performed detection (Figure 6). As shown in Figure 6 (a), the target structure is concealed by the wire pole. This image is not included in the training data set.

Although the result detected from the image at the actual construction site is highly accurate in determining the shape of the entire target structure, it is possible to confirm the false detection of the detailed shape of the target member. (Figure 6 (b)). The cause is considered to be a problem that occurred because it was difficult even for experts to detect beams and cross beams. Furthermore, it is considered that the problem was caused by the low brightness around the slab. This problem can be improved by increasing the brightness of the photo, or by adding image data from the construction site in the case of various weather conditions to the training data set.



(a) Construction site image (b) Detection result for the image of (a)

Fig. 6: Detection result of proposed segmentation system.

5.2 Verification experiment of construction status reproduction system

We constructed the system on Unity that can obtain the element ID of the construction completion part from the 3D model created in Revit by using the detection results in Figure 6. The detection result image converted into a black and white image is used as a mask image to reproduce the current situation from the predicted BIM model. Specifically, the model created by Revit is displayed on Unity, and the position of the camera shot in the actual construction site is adjusted by AR system to reproduce the camera location in 3D space. Then, the converted detection image is placed in front of the located camera. Rays are emitted from the located camera by pressing the execute button on the Unity screen. Since the irradiated ray has a collision determination, if the color of the colliding mask image is white, it is possible to obtain the element ID of the BIM model existing on the extension line by continuing to irradiate the ray. The obtained element ID is automatically written on the Excel sheet. Otherwise, Ray is erased and BIM models outside the detection result are not selected. Figure 7 shows the image before the system is executed and the image where the element ID selected after execution is highlighted.

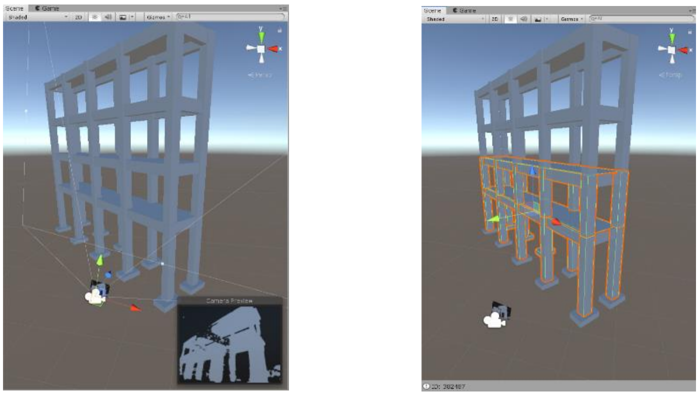


Fig. 7: Diagram showing the entire system on Unity and the selected model after running the system.

It is possible to confirm that the part of the component that reproduces the current construction status is selected from the completed BIM model by confirming the detection results of the system. However, it can also be confirmed that the cross beam part on the 4th floor is erroneously detected. The cause is that a false detection occurred at the detection result stage using deep learning, and it can be determined that the problem can be solved by improving the accuracy of CNN. Figure 8 shows an Excel sheet that stores the obtained element ID and a model reproduced on Revit from the element ID. A system that can display the selected model on Revit by entering the element ID in the part enclosed in red in the right figure of Figure 8. By adding unit price information to each member of the reproduced model, the cost for the current construction status can be calculated. The cost for the current construction status can be calculated by adding unit price information to each member of the reproduced model.

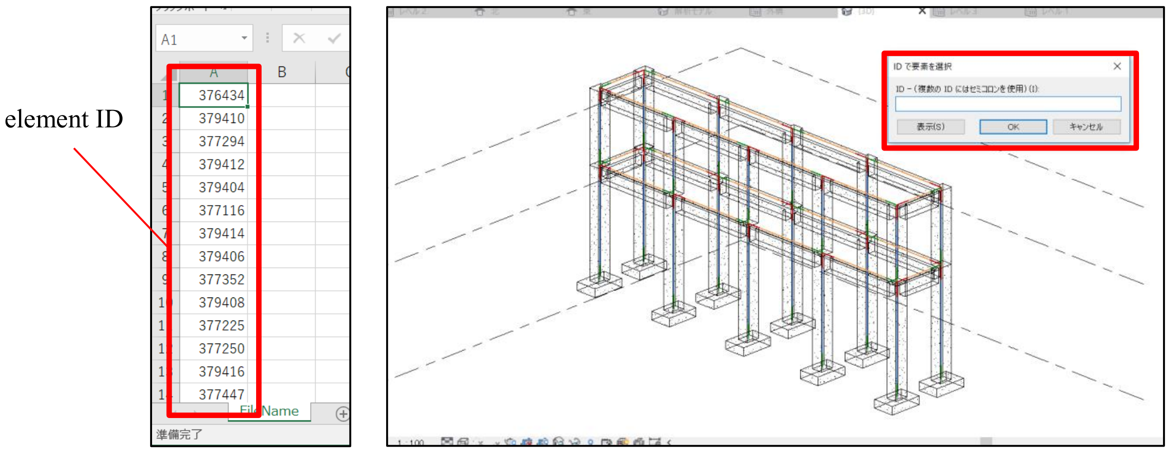


Fig. 8: Display the current model on Revit from the element ID.

6. CONCLUSION

Currently, the technology of object detection using deep learning has been developed by researchers all over the world. However, only using existing training data sets, the objects that can be detected are limited. Therefore, when trying to detect a new object using deep learning, it takes much time for the tasks to be completed, such as collecting image data of various objects and adding the images.

In the proposed study, we verified whether it was possible to detect civil engineering structures such as viaduct at actual construction sites. By fine-tuning to the CNN which constructed the image of the training data set created by taking a photo of the viaduct of the Tokaido Shinkansen, it is possible to detect the shape of each structural member from the actual construction site photograph. Besides, we constructed a system that can check the current construction status by using the BIM model and the image that was detected from the images taken by using deep learning CNN. For future development, a training data set for the structural member is created to improve accuracy and increase the types of objects to be detected by adding image data of various types of objects to be detected. Besides, we will improve the system so that the manual camera alignment can be automated by using technologies such as AR.

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A BIM-BASED USER-SPECIFIC FIRE EVACUATION GUIDANCE SYSTEM USING CUSTOMIZED EARPHONES

Kayla Manuel, Nobuyoshi Yabuki, and Tomohiro Fukuda
Osaka University, Japan

ABSTRACT: *In the event of a fire emergency, egress-seekers are often disoriented amidst the chaos, making it hard evacuate. Egress-seekers may not be aware of alternative routes or means of escape in the building, such as service exits, which could alleviate congestion at prominent exits preventing unnecessary deaths. In the proposed system, Building Information Model (BIM) implementation ensures that these alternative exits are known to egress-seekers and therefore trapped egress-seekers are better informed of alternative routes. Traditional two-dimensional evacuation signs in a building indicate a single path of escape and are insufficient as they are static and can easily be occluded by crowds or smoke. The proposed system provides instruction in the user's preferred language, resolving any language barrier issues. Evacuation instruction is then sent to customized earphones able to detect user face orientation. A user's face orientation is important in the proposed system when considering the worst case scenario; in which smoke density is at its highest and visibility at its lowest; equivocal to that of being blind or in a dark room the system can still adequately guide users. Evacuation instruction is user-specific and distinguishing characteristics include body traits, disabilities and health-related information which are then taken into consideration as these could impede an egress-seekers ability to evacuate. Once these are considered, the shortest and safest route is calculated for each egress member. The proposed system is made up of three main components; the game engine, the situation monitor and the user interface. The Situation Monitor plays an integral role in providing an overview of the current fire situation and the status of all occupants seeking egress. Aside from providing users with evacuation instruction, the Situation Monitor acts as a central database to be used by emergency personnel to inform rescue protocol.*

KEYWORDS: *Fire evacuation guidance, BIM, indoor localization, BLE beacons, RSSI, emergency operations.*

1. INTRODUCTION

Although buildings are growing taller and more complex in nature, in the event of a fire buildings with simplistic plans and fewer floors are as prone to the loss of lives, as that of complex buildings. On the 18^{th} of July, 2019 an animation studio in Kyoto, Japan, saw the loss of 35 lives during a fire disaster. The three-story rectangular structure, which at the time was occupied by 71 people, indicating nearly half of the occupants were unable to escape in time. Apart from the arsenic nature of the fire and questionable fire regulations implemented, other causal factors hindering escape, in cases such as these, could have been blockage of exit doors and escape paths as well as confusion amongst the occupants. All of the occupants were employees, so they could not have been unfamiliar with the buildings' layout, however, in emergency situations egress-seekers become disoriented amidst the chaos and their visibility and mobility is lowered as a result of the worsening smoke conditions.

Therefore, the proposed system is aimed not only for large-scale multi-story buildings, but also for use in buildings of various typologies to assist in evacuation. The proposed fire evacuation guidance system uses Building Information Models (BIM) in conjunction with Internet of things (IoT) sensor data to provide customized navigation instruction to each occupant in their preferred language, based on their respective locations, mobility and respiratory traits. The term 'exit' described hereinafter, includes windows at ground level, should exit doors become unavailable. Analysis conducted by Spearpoint (2012) about an infamous fire disaster at a station nightclub in Chicago, it was discovered that many occupants survived because they used windows on the ground floor level when exit doors were blocked by bottlenecks or structural failure. It was reported around 101 of the 355 survivors escaped through the windows of the building, meaning nearly 28.5% survival rate. The combined use of BIM and IoT sensor data will be used to continuously monitor the state of the fire, the building, and its occupants. Modified earphones provide egress-seekers with customized navigation to their nearest, safest exit.

The ambiguity of dynamic fire events can result in occupants wasting precious time during building egress. Therefore, a fire evacuation system should be prompt and dynamic in its navigation instruction by providing users with alternative escape paths should the need arise. The originality of the proposed work is in the unconventional evacuation instruction; for example instructing users to access the roof space for refuge and rescue personal are privy to this information in order to modify their rescue efforts accordingly, such as helicopters with a situation appropriate amount of aid (blankets, first-aid kits etc.). This rationale of tracking people trapped on a roof could then be applied to other disaster management areas, such as flooding. Another evacuation instruction is the use of connecting buildings as alternative means of escape. Current evacuation methods, order all egress-seekers to exit at ground level, which is usually limited to two main exits resulting in bottlenecks. Inclusion of an adjacent building means additional exits and evacuees are given reprieve from smoke inhalation which could improve the survival rate.

Egress-seekers are often reported to be disoriented during emergency situations. If the proposed system is implemented during evacuation drills, users can become reliant on the system thereby gaining confidence in the system's ability to assist in building egress. This could in turn, lessen their panic and confusion, setting users at ease if they believe using the system increases their probability of survival.

A consequence of fire disasters is smoke and crowd occluding user visibility is low and user mobility is slow due to smoke inhalation and physical obstructions. Therefore in the proposed system user-specific instruction is relayed to modified earphones, users are free to open doors and windows or move obstructing objects. In many cases, users may wish to assist those around them in escape and hands-free operation will support this natural human instinct.

Distinguishing characteristics of egress-seekers include but are not limited to; age, gender, dependents, body size, respiratory capacity and mobility. Physical disabilities hindering a user's evacuation ability include occupants who are visually-impaired or wheelchair-bound. Health-related issues hindering evacuation include respiratory capacity which can lower an occupant's chance of survival, if they suffer from asthma or emphysema (Atila et al., 2018).

Kobes *et al.* (2008) stated that when creating a fire response system, the following 3 factors should be considered; the fire, the building and the people. The structure of the works presented in this paper will follow the same structure relative to these three core aspects. Fire related aspects include smoke and temperature changes, building considerations involve boundary conditions primarily consisting of walls and exits as well as the evacuation paths which are created by considering the boundary conditions. Finally, considerations for people involve each user location and their respective characteristic traits.

2. LITERATURE REVIEW

Previous research in evacuation guidance systems, focus solely on the visual aspect which attempt to impose trending technologies such as Artificial Reality (AR) and Virtual Reality (VR) within the disaster management field (Zadeh, 2010). While these technologies are useful in other areas such as standard navigation and marketing applications (Lee and Han, 2017) they should not be relied upon as effective evacuation guidance, apart from its use in simulating emergency situations for evacuation drills. In the evacuation guidance system developed by Ahn and Han (2011), image-based recognition in conjunction with phone accelerometer data was used to detect user locations in indoor environments. To utilize their system, first a user is required to take a picture of a feature element in their immediate surroundings such as a room number in order for their relevant evacuation path to be shown. Apart from this being a tedious task to complete, users are required to do so under pressure amidst the chaos, and smoke density and crowds can occlude room distinguishing features, making the application unusable.

Our proposed system does not paralyze users with information but simply provides them with navigation instruction in a voice command format. Previous studies have considered effects of crowd behavior in their fire evacuation systems, however, in the proposed system the primary concern is that of the individual egress member (Chu *et. al*., 2015). The only time crowd consideration is taken into account is when dividing the total number of users by the available exits (Lujak et al., 2017).

Previous studies integrating BIM in order to improve evacuation methods are limited in their use of BIM semantic data. The BIM models being used mainly as geometric boundaries for path creation (Zadeh, 2010; Wang et al., 2014; Cheng, 2017). However, research conducted by Atila *et al.* (2018) proposed a user-centric evacuation system with three main functionalities; dynamic routing, indoor positioning and a user-interactive mobile application. The application used an Artificial Neural Network (ANN) for path suggestion based on data received from occupants and IoT sensors. To track user locations, a spatial model was created consisting of nodes and links. The nodes were created using Radio Frequency Identification (RFID) tags placed at intervals in the building and links were created by connecting these nodes. Sensors continuously monitor the areas around the nodes for changes in temperature, Carbon Monoxide levels, and human density. Navigation parameters in the ANN network were based on the changing indoor environment conditions as well as the physical features of each person. For instance; if a user with asthma approaches an area with high Carbon Monoxide readings, the proposed system re-navigates this individual around high risk areas in order to increase the chance of survival.

The downfall of the study conducted by Atila *et al.* (2018) is in their use of the spatial model. Although using RFID tags for indoor location tracking, the building properties were not considered. In the proposed system, however, implementing a semantically rich BIM model is highly advantageous. One such benefit, is the fact that material properties of building elements and their respective fire-resistant properties are found in semantic data. BIM model file size can become quite taxing on the systems computational speed, however because the BIM model is cloud based, only relevant voice commands are sent to users. Connection failure is another concern however, because users transmit and receive data via local area network (LAN) connection, the last submitted route is still available to users.

In the proposed system, occupant locations are detected using Bluetooth Low Energy (BLE) beacons. Indoor location tracking has been extensively researched (Zafari et al., 2019; Depari, 2018). Although further development in indoor location accuracy is needed, by installing multiple beacons and incorporating triangulation, tracking accuracy can be further improved (Javaid et al., 2015). Apart from tracking user locations, BLE beacons also detect area-specific environmental changes such as humidity and temperature, to be used as constraints when computing the navigation paths.

3. SYSTEM ARCHITECTURE

The proposed system architecture shown in Figure 1, provides user-specific navigation instruction in a voice command prompt to modified earphones. In the following sub-sections, the proposed system is divided into the three main components; the game engine on a PC monitor, the Situation Monitor (SM) on a tablet device acting as a server and the user interface for client/s. Specifications for the software and hardware used in the prototype system are shown in Table 1.

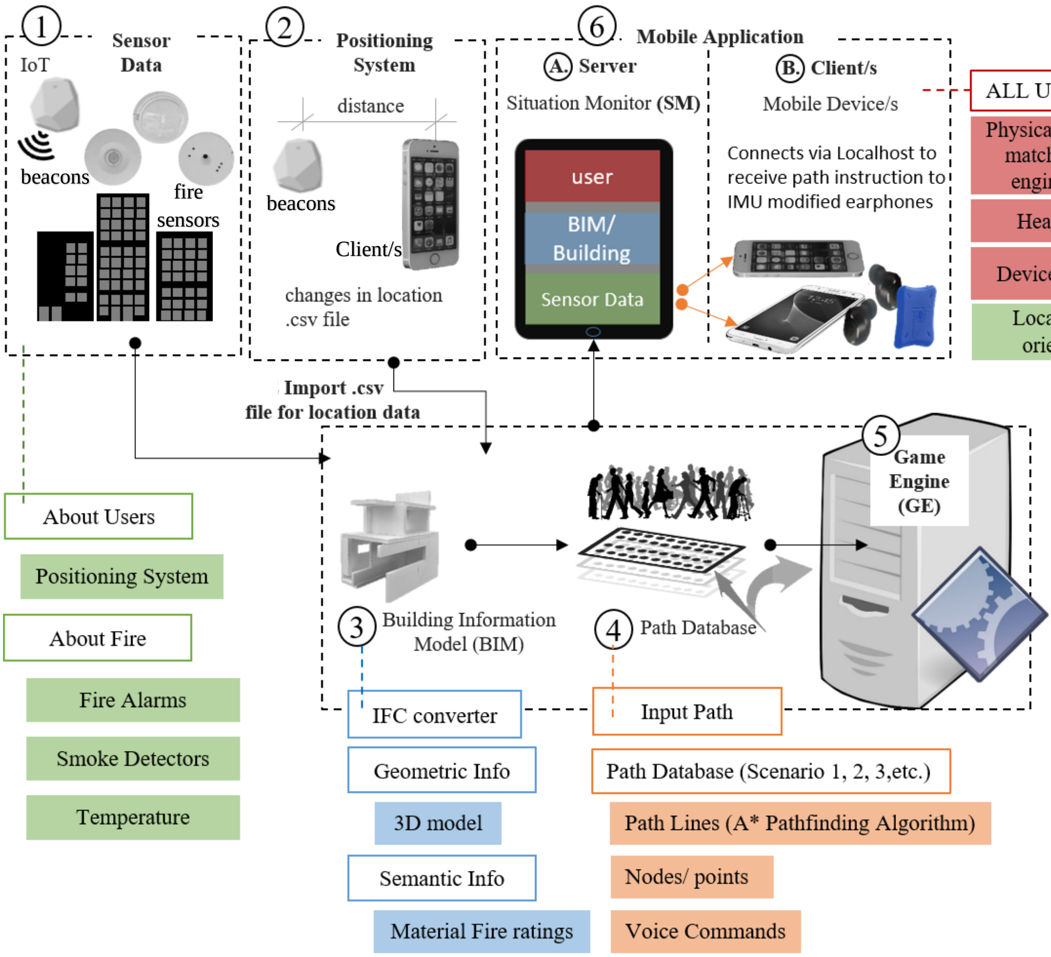

Fig. 1: Diagram showing the proposed system architecture.

Table 1: Specifications of the software and hardware to be used in the proposed system.

#	Components	Specifications
1	Sensor Data	Beacons used to monitor initial temperature readings from beacons and changing user locations.
3	BIM model	Autodesk Revit 2019

3	IFC converter	*BIM Importer:* converts BIM model to IFC format
4	Path Database	A* pathfinding project plugin used in the game engine.
5	Game Engine	Unity (ver. 2018.3.5f1)
1	Beacons	*Estimote* Proximity Beacons with Bluetooth® SoC, ARM® Cortex®-M4 32-bit processor with FPU, 64 MHz Core speed, 512 kB Flash memory, 64 kB RAM memory
5	Desktop Computer	Windows 10 Education (64 bit)
6	Earphones	Akiki TWS- P10 True Wireless earphones
6	IMU	LP Research Motion Sensor Bluetooth version 2 (LPMS-B2) with 9-Axis Inertial Measurement Unit (IMU) / AHRS with Bluetooth Classic and BLE Connectivity
6	Mobile device	iPhone (IOS 12.0) and Android devices (min. API level 24)
6	Tablet (SM)	Samsung Galaxy Tablet S3. (Android Oreo: API level 28)

3.1 Game Engine

The game engine is comprised of sensor data, user locations, Building Information Model (BIM) and the path database. BLE beacons track changes in sensor data and user locations, the BIM model includes semantic properties and the path database contains user-specific navigation instructions.

To obtain sensor data, initial temperature readings are taken from various areas as measured by the beacons and are imported into the game engine in csv. file format, thereafter a simulated fire event is created in the game engine to show changes in temperature, as the fire progresses.

In the proposed system accurate user locations are not needed. Raw localization is used instead, as this is sufficient enough to instantiate navigation instruction, based on which room or corridor section the user in. BLE beacons are sparsely placed, as shown in Figure 2. If higher accuracy is required a denser deployment of beacons can be adopted. In the proposed system, user proximity to a beacon ID with the strongest received signal strength indication (RSSI) value is indicative of which beacon the user is closest to and which area the user is in.

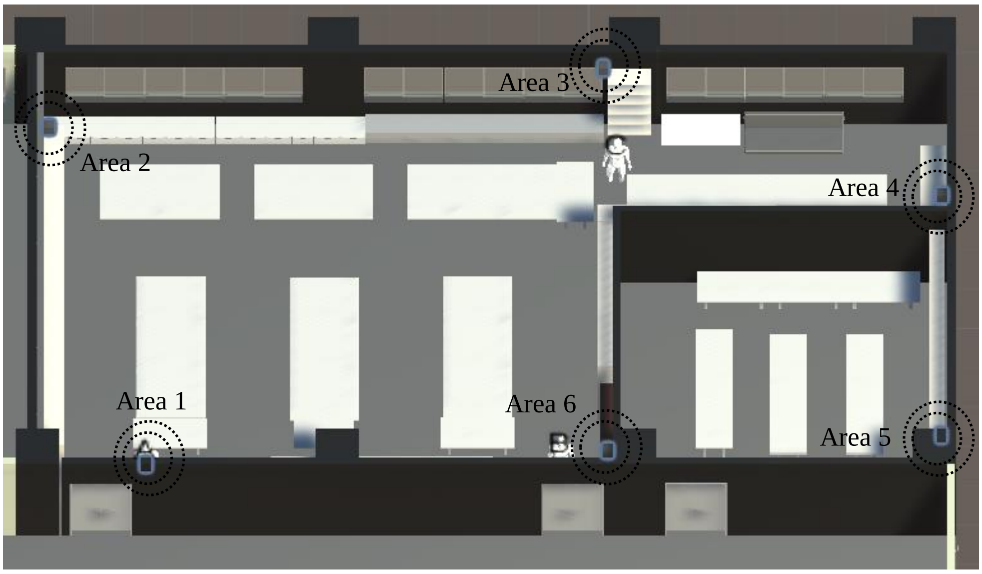

Fig. 2: Room 411, M3 Building in Osaka University Suita Campus showing user avatars in relation to beacons

In the initial setup, the BIM model is imported into the game engine as an Industry Foundation Classes (IFC) format to ensure semantic properties are intact. Alarms, smoke detectors, beacons and BIM model elements are created in the game engine as Game Objects (GO) and colliders are attached to each GO. A collider is an invisible shape used to handle object collisions (Figure 3). Box colliders are used in the proposed system to detect collisions between user avatars and the aforementioned Game Objects. If a user exits one points of interest (POI) and enters into another, this change is tracked and which exit a user should take in the event of an emergency is shown. Colliders are also attached to furniture to navigate users around these obstacles as well.

After importing the BIM model into the game engine a path database is created. The path database is made up of several path maps which are cached to an external server, to be localized within later by the egress-seekers. Each path line is created by connecting an initial starting point to a destination target. Target destinations are Game Objects that are interchangeable from the inspectors panel in the game engine. In our case, these will be doors and windows from the imported BIM model. The A* pathfinding algorithm was used to compute paths by linking nearest nodes and is a widely accepted method for pathfinding and grid traversal. This is because the A* algorithm covers less area thus computational time is reduced and is faster than that of other methods, such as the Dijkstra's algorithm (Wang et al., 2014). In the game engine, for each node in the evacuation path a waypoint GO prefab is spawned with a sound file attached. When collision is detected between the user avatar and spawned waypoints the relevant sound file will play. Path instructions are made dynamic through user properties and environmental factors. When user locations in the real world overlap with virtual waypoints their relevant instruction is given (Figure 4).

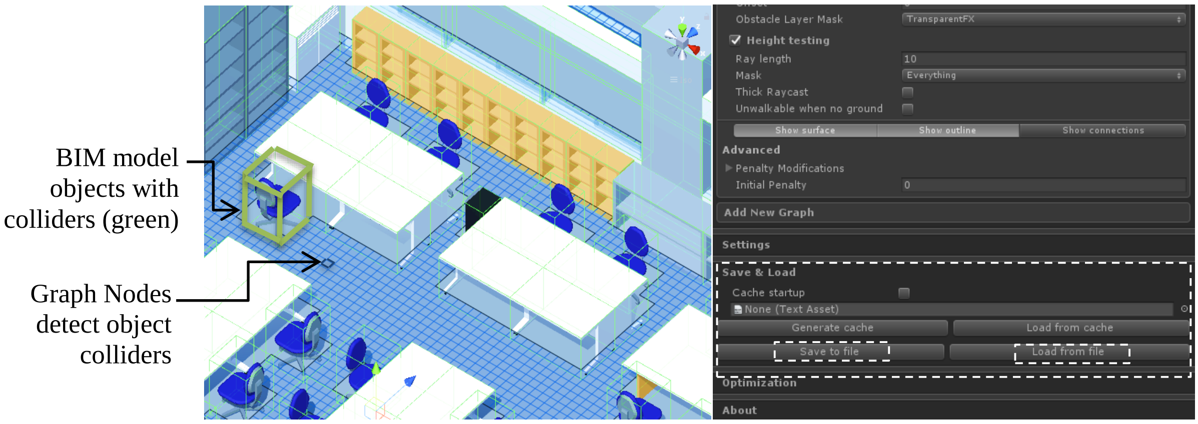

Fig. 3: A screenshot in the game engine of the graph nodes and graph cache system for path database creation.

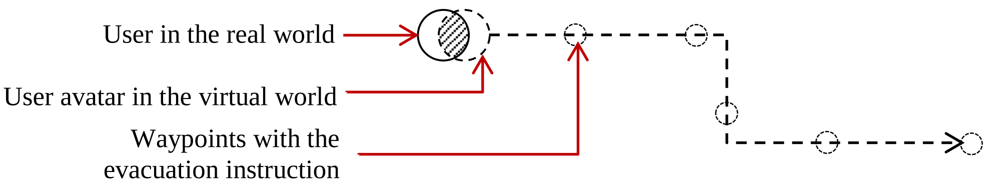

Fig. 4: Diagram showing object persistence between the real and virtual worlds.

3.2 Situation Monitor

During a fire emergency, the Situation Monitor (SM) displays all the necessary information about smoke detectors, beacon temperatures, points of interest (POI) such as rooms, exits, stairs and corridors as well as other information such as user path instructions and current status of users (deemed safe, need help, at risk). The accumulated data serves as an overview of the current fire situation, used to support decision makers in their rescue efforts and provide egress-seekers with navigation instruction. Figure 5 below, shows the Situation Monitor, where users are tracked and their position in relation to the nearest exit is continuously being monitored.

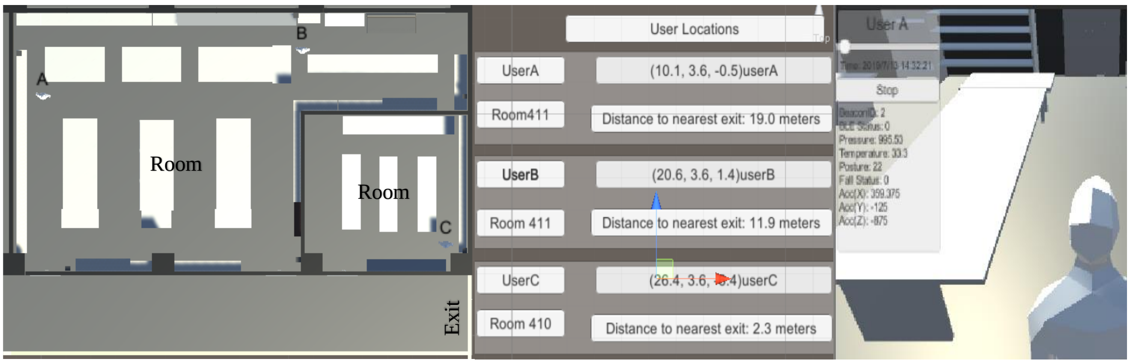

Fig. 5: A screenshot of the Situation Monitor within the game engine.

3.3 User Interface

Mobile devices connect to the Situation Monitor (SM) using the same localhost address and navigation instruction is then broadcast to those seeking egress. Considering low-visibility caused by smoke and crowd occlusion, users receive evacuation instruction by voice command, unless hearing impaired, through modified wireless earphones to ensure hands-free operation. The wireless earphones are customized by attaching an inertial measurement unit (IMU) to one of the earphones in order to gauge the user's head orientation. The modified earphones hereafter, the *Face Orientation Detector* (FOD), tracks users' head movement while their phones, irrespective of orientation, are being tracked by the BLE beacons. The FOD device transmits the monitored data via Bluetooth packets to the *Situation Monitor* (SM). For example, if an evacuation instruction says 'go straight', based solely on the users x, y and z coordinates, if the user is not facing in the direction of the path, the evacuation instruction sends them in the wrong direction. When face orientation is known the system can accurately guide users in building egress. Should a user turn their heads to look behind them, they are still essentially facing forward, therefore the IMU device is only attached to one earphone (Figure 6).

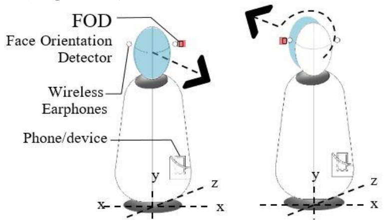

Fig. 6: Diagram showing modified earphones for customized evacuation instruction.

Figure 7 shows how waypoints are configured for instantiation upon collision. The user avatar has a capsule collider attached to it and when it collides with any of the waypoints an audio source file prompts a "*head straight"* command prompt. This process of attaching sound files to a waypoint is applied to all spawned waypoint prefabs based on their respective tags; "straight ahead", "RUN!", "the exit is *x* meters away", and so forth.

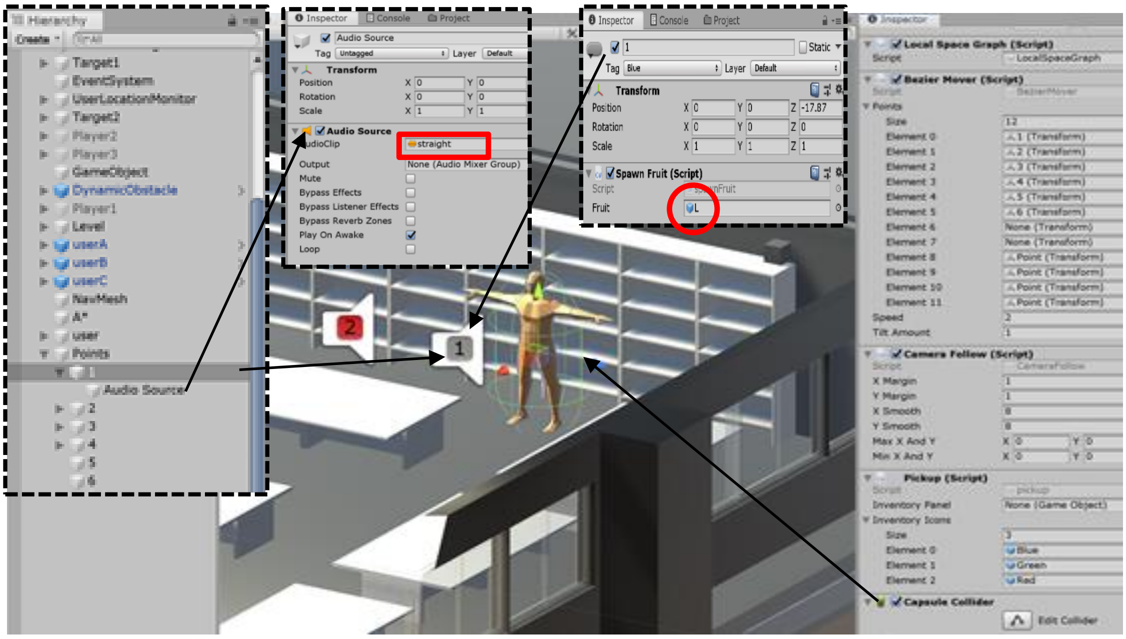

Fig. 7: A screenshot of the waypoints configuration when user avatars collide with the waypoint prefabs.

4. CONCLUSION

Current evacuation guidance systems are not intuitive enough to successfully provide evacuation navigation to egress-seekers in the event of an emergency. Buildings with simplistic floor plans are as difficult to escape from, as buildings with complex geometry due to the unpredictable nature of fires. Previous studies, propose implementing visual applications such as AR and VR wayfinding methods to assist egress-seekers in evacuation. The drawbacks of these methods is heavy reliance on visuals when visibility is low, caused by smoke and crowd occlusion. The proposed system provides users with navigation instruction to egress-seekers by sending voice commands to modified earphones. The earphones are modified by adding an inertial measurement unit (IMU) in order to detect the direction in which an egress-seeker is facing. The proposed system can also facilitate rescue operations by providing an overview of the current fire situation and relaying the necessary information to fire fighters and rescue teams. The Situation Monitor provides rescue operation managers with an overview of the fire, users and exit conditions and the location of these in relation to one another. Moreover, in the aftermath of a fire disaster the recorded data can then be analyzed at a later stage in order to improve on future fire rescue operations.

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DATA FORMATING AND VISUALIZATION OF BIM AND SENSOR DATA IN BUILDING MANAGEMENT SYSTEMS

Ivaylo Ignatov Ignatov
Student of Architectural Technology and Construction Management, University College of Northern Denmark UCN, Aalborg, Denmark

Peter Nørkjær Gade
Department of Architectural Technology and Construction Management, University College of Northern Denmark UCN, Aalborg, Denmark

ABSTRACT: *Building sensor data is getting increasingly more significant for our goal to find effective ways of operating and maintaining buildings. Development in the Internet of Things (IoT) brings us numerous and more connected methods of data acquisition. There has been an interest in using Building Information Modelling's (BIM) advantages in enhancing the management, analysis and visualization of operational building data in contemporary Building Management Systems (BMS). With the emergence of Smart Building technologies, which provides us with larger and more complex data about building systems' performance, there is a need to understand and address the challenges, BIM and BMS face in the successful handling and analysis of large and dynamic sensor data. In this paper, we investigate how universal data formatting can contribute to the faster, easier and more practical management of BIM and sensor data. Since BIM is designed to act as an organized database for design and construction information, our investigation aims to use the built-in BIM ontology to organize the sensor data. We propose a data handling framework, involving data conversion and mapping algorithms, to format and link the different datasets into simple and easy-to-read data objects. We have then developed a prototype, demonstrating the BIM and sensor database management and linkage, and subjected the newly formatted data to a simulated BMS environment, that analyses and visualizes the BIM-enhanced and highly dynamic sensor record data.*

KEYWORDS: *Building Management System (BMS), Building Information Modelling (BIM), sensor data, data analytics, visual programming, data formatting*

1. INTRODUCTION

With the boom of the data industry in the last couple years, and the emergence of a wide variety of data acquisition tools, many large industries are implementing powerful data analysis software, in order to streamline their processes and monitor product usage and performance (Rathore et al., 2016). One such, is the AECO industry, specifically Building Operations. As the largest percent of the life-cycle cost of a building, and by far the biggest generator and handler of building data, building management stands as one of the best candidates for improving operational efficiency (Fan and Xiao, 2017). Recent development in the Internet of Things (IoT), Big Data and Building Management Systems (BMS) has enabled the acquisition and analysis of large amount and wide variety of operational data from smart sensors (Bilal et al. 2016). This data is identified as crucial for providing many value-added services in the Facility Management (FM) sector, such as reduction of waste energy, ensuring the comfort, health, and safety of the occupants, remote monitoring and control of building systems, and even prediction and prevention of system failures. However, successful utilization of building data analytics is stalled by undeveloped data management systems (Qolomany et al., 2019).

Utilizing Building Information modelling (BIM) for providing meaningful data, such as spatial information, material properties, orientation, etc., can leverage BMS to bring a more accurate and understandable analysis of the sensor data (Gerrish et al, 2017). However, current operational data analysis systems work with enormous amounts of highly dynamic data and rely on well-organized structure with software-specific ontology. The use of BIM is widely regarded as a successful strategy to store, organize and manage the heavy static metadata of design and construction but lacks the flexibility and capability to handle the data storage requirements and constant changes of dynamic data (Chen et al., 2014). Proper data formatting and link of the BIM-BMS data can help solve the time- and computational power-intensive analytical process. Data-interchange formats, such as JavaScript Object Notation (JSON), are not only easy to generate and parse, but also easy to read by both humans and machines. The possibility to convert large and dynamic datasets to a language independent text format can be used in both complex mathematical algorithms and pattern visualization, understandable by FM professionals, occupants and owners (Tang et al., 2019). However, research describing the advantages and practical uses of data formats like JSON in parsing both BIM data and building operational data together in a BMS environment, is limited.

This paper will establish the practical application of simple data formatting and direct data linkage within the BIM-BMS data framework. The following section will review the data management techniques in the construction and operation industries. In Section 3, we introduce the general challenges and opportunities for data formatting in BMS. In Section 4, the paper will establish a data-interchange framework, and in Section 5 develop a tool for simple link and visualization of BIM and sensor data. Section 6 discusses the results and Section 7 concludes this paper.

2. APPROACHES TO OPERATIONAL BUILDING DATA MANAGEMENT

The exponentially growing data record about everything around us and its analysis can be an extremely useful tool in improving productivity, connectivity, safety, and overall living standards, and will inevitable change the way businesses operate (Rathore et al., 2016). In the construction industry, this will affect the whole lifecycle of a building project – from the conceptual stages, through construction and operation, to recommissioning (Rathore et al., 2016). The emerging hyperconnectivity of IoT will increase the promise of Smart Building environments and automated operation processes using smart sensors and machine learning algorithms (Qolomany et al., 2019). However, this process will also make the storage and management of the data more complicated, as both the amount and diversity of data formats increases drastically. Growing networks of monitoring and operation devices need to be able to understand each other and communicate in the fastest and smartest way possible.

2.1 BMS operational data structure

The usage of building operation data for big data analysis and proactive facility management in contemporary BMS is a growing trend in the automation technologies. Smart building operation relies on constant data monitoring and data acquisition from smart sensors. Contemporary BMS deploys increasingly more sophisticated sensors. Many building products are moving to the state of location- and time-awareness, being able to identify environments and other devices, and even predict maintenance and repair needs (Tsai et al, 2014). That also means that the communication capabilities of devices and BMS have to adapt to the growing complexity of the data exchange within those networks and systems. Bali et al. (2018) describes this evolution of automation as "higher level management". The ability of a BMS system to syphon and analyze useful data into any needed form is illustrated via the framework in Fig. 1.

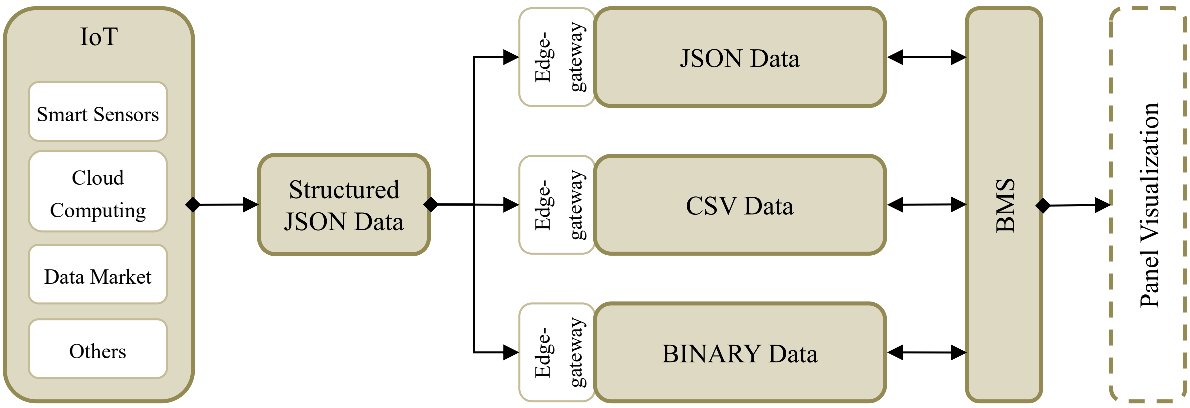


Fig. 1: Sensor data handling framework.

Qolomany et al. (2019) identifies several challenges with contemporary acquisition and analysis of sensor data:

- Data reliability – product connectivity and quality can greatly influence the reliability of data generated from the sensor. Also, environmental awareness is a notable validator of sensor data, however, not many sensors adapt this system.
- Data integrity – influenced by the quality of the sensor network and generally the IoT in a building or complex.
- Data interoperability – varying product manufacturer can have varying standards of data objectification and so require edge processing before the BMS.

The computational power of some smart sensors allows for structuring and restructuring of sensed data directly through the device. The aforementioned edge processing is used to determine in what format is the data to be exchanged (Fan et al., 2015), depending on the needs of the BMS. However, data can quickly turn to unstructured an accumulate to very large size, requiring more complicated queries and data mining algorithms in the Big Database (Motawa, 2017; Fan and Xiao, 2017).

2.2 BIM as a database and data exchange platforms

BIM-enabled processes have proven its advantages in design and construction stages (Bali et al, 2018), and is steadily making its way into the Building operations and Facility management industries. The same also outlines the advantageous capabilities of BIM ontology in storing, organizing and managing big amounts of important building data. In other words, BIM has the ability to act as a stable database for the metadata of the objects in the model. However, concerns over standardization and the data requirements for FM from BIM databases are present after a procurement of a project (Matarneh et al, 2019). The accuracy and level of detail of models can also play a big role in the validity of the data extracted for operational analysis (Chen et al, 2014). Therefore, many services are being developed to ensure the openness and consistency in the input, validation, and exchange of different BIM data formats throughout the project life cycle, illustrated in Fig. 2. Wang et al. (2013) puts forth web-based services, such as Building Feature Service (BFS), BIMServer, and Onuma Planning System (OPS), as a successful method of data storage, manipulation, access, and exchange between platforms.

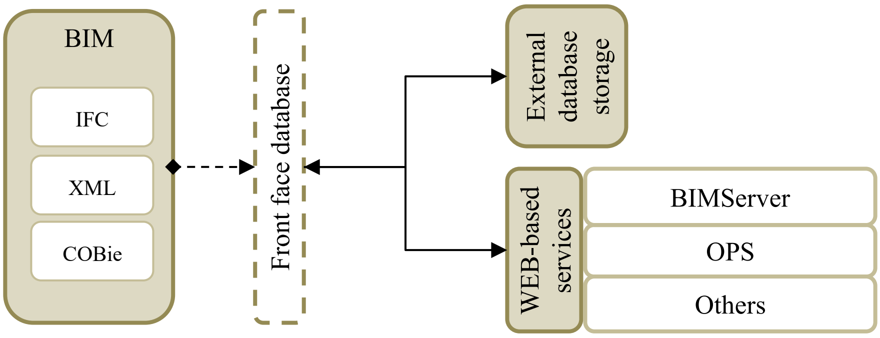


Fig. 2: BIM data storage framework

Many platforms nowadays are able to read and parse data in multiple different formats. Industry Foundation Classes (IFC) facilitate the interoperability requirements in the AEC industry well, and operate with universal data formats, such as text, so storing and reading data is simplified. However, this data format lacks the flexibility needed for computing highly dynamic datasets. In the building operation stages, IFC works best as a "front face database" where object data is only read and mapped to dynamic sensor data (Zhang et al., 2015). Other formats, such as Construction Operations Building Information Exchange (COBie), aim at facilitating the structuring of operational and building data in post-construction stages. However, COBie struggles to provide details on BMS data requirements for the FM practices, where specific data retrieval, change management and historic data tracking is critical (Dave et al., 2018). Also, a lack of data requirements from FM practitioners exists, that may infringe the practical information exchange process between parties (Dixit et al. 2019).

The powerful visualization capabilities of BIM are also acknowledged in their insightful and understandable delivery of analytical results. Both Bali et al, (2018) and Oti et al, (2016) claim that BMS induced BIM data can influence value-bringing decisions during the design the building. Oti et al. (2016) also claims that meaningful visualization of data patterns, such as energy consumption, supported by BIM space data can aid the quick understanding of non-experts including occupants about influence of people over building systems, and so may influence their behavior and reactions.

2.3 Data interchange formatting and database queries

Device generated data has proven cutting-edge in streamlining performance and bringing value, connectivity, safety and security to cities and communities (Rathore et al., 2016). However, since the booming rise of IoT, researchers attempt to standardize the format in which this data is exchanged (Mezei et al., 2018). This is especially true for BMS, where wide variety of data is being analyzed. Simple data formats like JSON, illustrated in Fig.3 are often preferred for exchanging highly dynamic data (Afsari et al, 2017), such as sensor data, as it is easy to read and parse, and queries to enormous operational databases prove faster. JSON's simplicity is also preferred when describing complex objects with simple values (Gerrish et al, 2017). However, proper string validation standards, such as RFC 4627 or RFC7159 are recommended before the data is used.

```
"Supply System":
      {
        "ID": "id",
        "Phase": "DD",
        "Air Flow": 600,
        "Mechanical": {
               "eff.": 18,
               "wpd": 24 565,
               "water flow": 0.76,
                      },
        "IDs": [116, 943, 234, 3893]
      {
```

```
[
 {
  "element": "element_1",
  "location": [37.54, 190.20, 4.05],
  "id": 356729
 },
 {
  "element": "element_2",
  "location": [37.37, 191.45, 4.05],
  "id": 283848
   }
]
```

Fig.3: Example JSON object description. A JSON object (left) and an array of JSON objects (right)

Mezei et al. (2018) proposes a specific dynamic data description, with a custom conversion language, specific for sensors. This conversion algorithm can be performed via edge processing, or during database queries. However, specific sensor languages lack the semantic interpretation needed when parsing externally enhanced sensor data. Concerning BIM databases, Afsari et al. (2017)'s results showcase the advantages of JSON data format in the description of IFC or COBie data. The same also propose a successful JSON serialization schema for web-based BIM databases. However, the issue of data ownership, standardization and responsibility remains, as the web-based database requires upkeep (Matarneh et al. 2019).

3. CHALLENGES AND OPPORTUNITIES IN THE LINK BETWEEN SENSOR DATA AND BIM DATA

The technological advances in building data acquisition and data management systems are well acknowledged (Fan and Xiao, 2017; Fan et al., 2015 and Tsai et al., 2014). However, there have been challenges in parsing this data in a simple and fast manner in a BIM-enabled environment. More often than not, data collected from smart sensors comes in deviating formats, quickly grows very large in size, and is too unstructured to be used in a meaningful way straight away. The technological advances of BIM offer opportunities to overcome some of those issues through its naturally built-in ontology framework (Matarneh et al, 2019). BMS data analysis often proves more accurate and coherent when paired with the rich metadata of the BI model (Oti et al, 2016). However, BIM data suffers from the same data formatting complications, and struggles to render highly dynamic data and address changes to its structure in an understandable way.

One objective of standardizing the different data exchange formats is utilizing a conversion method into a common data-interchange format. This leverages a wider and faster use of operational data, that is also easy to link to the BIM assets (Gerrish et al. 2017).o Afsari et al. (2017) proposes JSON as a suitable link between datasets, as it is both a light and an easy to read format, with little to no storage requirements. However, it is recommended to use validation sequences before parsing any of the data. This is important because smart sensors can be used for monitoring information from as simple as occupancy, to complex as security protocol execution (Qolomany et al. 2019). Such data, while convertible, can prove difficult to handle and modify. Similarly, BIM databases, while incredibly structured, can also prove hard to modify. Instead, Gerrish et al. (2017) proposes that the BI model is stored as a meta database, that information inquiries can be sent to. That database can be both web- or cloud-based (BIMServer), and industry professionals being responsible for updating any new static data in the model.

Another notable challenge in the BIM-BMS data link is parametrizing the data, in order to map specific sensor information to a specific asset in the BI model, such as sensor value ID or network IP (Zhang et al., 2015). While IFC formats give a well-connected sensor export data, there is a merit to not model actual geometry as the carrier of the identification parameter, due to possible model complications. Instead, a simple parameter linked directly to the monitored geometry, such as rooms, spaces, mechanical installations, etc. can contribute to a faster mapping algorithm.

There are many opportunities in the formatting of sensor data, concatenated with the structured BIM data (Tang et al., 2019 and Matarneh et al., 2019). A primary target of a BIM-BMS link is the fast and easy data analysis capabilities and the powerful visualization of the data, such as energy usage, comfort and safety, in real-time. However, practical examples of BIM data conversion and linkage to JSON are limited and a worthwhile opportunity for the enhancement of sensor data analytics and BMS.

4. A PROPOSED FRAMEWORK FOR UTILIZING DATA FORMATTING FOR ANALISYS AND VISUALIZATION

We propose a schematic framework of the BIM-BMS data conversion method to open JSON database to improve the handling and storage of the building data. As illustrated in the figure, current BMS relies on restructuring and processing of the raw sensor data, especially when paired with external datasets, such as location-specific environmental datasets or BIM datasets. We propose creating an open big database with simple JSON string objectification, which can be stored, sorted, and accessed easily. Inquiries to this database can then be sent by multiple BMS and specialized analytical software, depending on their needs. Sensor data can then be read and translated fast and independently to any needed format. Such data flexibility has the potential to bring a wider spectrum of outputs, such as graphical data representation and time-specific visualization. BIM data is also treated as an autonomous database and the actual geometry and parametrization is not modified. Instead, inquiries to the set can be sent directly from the BMS in request to the specific building information needed for and after the specific building data analysis. Regardless of the BIM data format, IFC, XML, or COBie, we propose a simple data conversion algorithm to JSON during the request. Also highlighted in Fig. 4, is the lack of a midware, which removes the storage requirements of the converted BIM data. This achieves the objective of stable, light, and read-only databases for both BIM and sensor data. Such light open system should allow appreciable degree of flexibility in the code format of the data requests. Lastly, a proposed mapping algorithm should leverage the discoverability and linkage of specific sensor data to specific BIM data. That is achieved by using the natural parametrization of ontology matching in BIM formats.

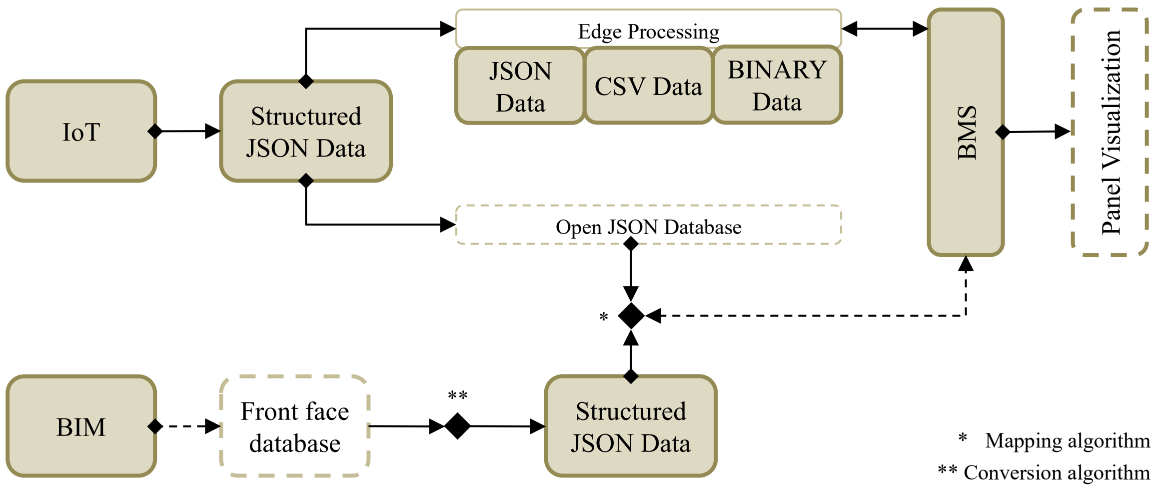


Fig. 4: Proposed framework for BIM-BMS link via JSON formatting and mapping algorithms.

5. CASE ILLUSTRATION OF FRAMEWORK IMPLEMENTATION

The proposed framework is implemented using a prototype as a demonstration of proof concept. The technicality of the prototype is explained in this section and a scenario of using the prototype in a simulated environment is described. The purpose of the protype is to illustrate the advantages of simple reformatting and link between sensor data and BIM data to a common dataset, that can be used by both FM professionals, design teams and automation technologists in fast and issueless analysis and troubleshooting.

5.1 Description of prototype for data formatting, linkage and visualization of sensor and BIM data

The approach adopted in developing the prototype is the BIM-BMS link via JSON formatting and mapping algorithms. The sensor data is supplied as a sample data from smart sensors measuring dust accumulation and median particle sizes in confined spaces. The sample is built on the base of Indoor Air Quality and Ventilation Duct System Health monitoring, including generated data type, sensor IDs formats and value types. Analytical data, or sample threshold values are taken from the World Health Organization’s assessment of healthy indoor air quality. The BIM platform used is Revit 2020, and the direct programming tool for data requests from the BIM database is carried out in Python using Dynamo 2.4.0. Dynamo is also used to read and map the identification parameters of the sensor values to the appropriate geometry, and to successfully format concatenated data to JSON, validated via the RFC 4627 Standard. A BMS environment is then simulated using Grasshopper visual programming tool for Rhino3D. Using Python code, linked data is requested from the sensor network database, parsed via predetermined BMS algorithms and visualized in a simple and understandable way. Opportunities are identified and prospects for future development put forth.

5.2 Sensor data acquisition

As previously mentioned, the sensor data used for this prototype is based on an air quality monitoring system, measuring dust accumulation and median particle sizes. As illustrated in Fig. 5, the sample data received is syphoned through the network gateways as a simple JSON string with own ontology. The value contents include identification data about the sensor, as well as id information about its monitoring records. Values can be both strings, numbers, boolean values and arrays. The sample sensor data comes from one sensor monitoring the air quality in one room in the building, with a record taken once a day for a week. Such time-aware smart sensors provide a more complex but more valuable data, enabling the opportunity for historical record analysis.


```
"sensor_id": "5d92458262adcb1fc5574af6"
"sensordata": [
      {
        "id": 0,
        "mps": 26,
        "da": 1.22,
        "dt": "2019-09-22 9:00:00"
      },
      {
        "id": 1,
        "mps": 23,
        "da": 1.34,
        "dt": "2019-09-23 9:00:00"
      },...
```

```
{"sensor_id":"5d92458262adcb1fc5574af6","sensordata":[
{"id":0,"mps":26,"da":1.22,"dt":"2019-09-22
9:00:00"},{"id":1,"mps":23,"da":1.34,"dt":"2019-09-23
9:00:00"},{"id":2,"mps":17,"da":1.85,"dt":"2019-09-24
9:00:00"},...
{"sensor_id":"5d924582bc06a7ab740702b2","sensordata":[
{"id":0,"mps":1,"da":2.42,"dt":"2019-09-22
9:00:00"},{"id":1,"mps":12,"da":0.57,"dt":"2019-09-23
9:00:00"},{"id":2,"mps":30,"da":1.59,"dt":"2019-09-24
9:00:00"},...
{"sensor_id":"5d92458266188ceb79eb6a52","sensordata":[
{"id":0,"mps":21,"da":1.75,"dt":"2019-09-22
9:00:00"},{"id":1,"mps":18,"da":1.55,"dt":"2019-09-23
9:00:00"},...
```


Fig. 5: A sample of JSON string data representing air quality monitoring sensor records. Single sensor (left) and simulated lineated database (right).

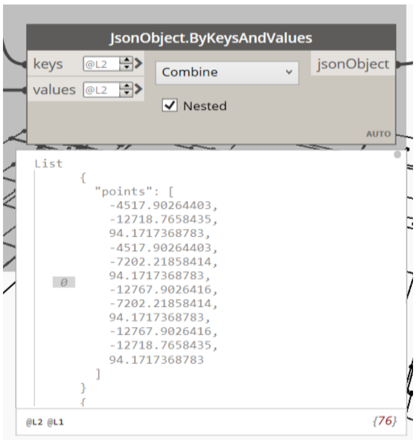
To showcase the capabilities of the prototype, additional sensor data has been generated on the base of the sample sensor, and the sensor identification codes simulated. A simple validation check using the RFC 4627 JSON Standard, with both web-based and Python/C/JS-based validators available, proves enough to ensure the usability and stability of the database.

5.3 Constructing BIM data formatting and mapping algorithms

Regarding the BIM database, we are using a sample Revit project, with the added functionality of a constructed sensor network within the model. That can be done as early as the design stages of the project, and as late as retrofitting and refurbishment. The parametrizing process of objects in the model can be fully automated, as a database can be built by the sensor identification numbers and manufacturer information, from which the BIM database can be updated. As earlier described, the responsibility for keeping the model updated can fall in either the FM company’s hands, or any owner-assigned mediator, depending on the ownership agreement.

5.3.1 BIM data conversion to JSON strings

In the case of our prototype, the sensed data is reliant on room spaces, and influences ventilation duct systems. Therefore, the objective of our database query is extracting relevant geometrical room boundaries and IDs, such as name, location, area, and which sensor is responsible for monitoring the said space. As shown in Fig. 6, a simple Dynamo script is defined, that accesses the BIM database and extracts any data required by the BMS. This data is then processed and converted to JSON strings. It is important to note that multiple parameter values from multiple elements in the BIM database can be extracted and converted at once but deviating value formats (e.g. formatting multiple arrays and string values) require list processing functions in the query script. Even so, JSON data still proves easy to convert to, organize, combine and parse.




```
"sensor_id": "5d92458262adcb1fc5574af6",
"location": [
      -8411.16498384,
      -9761.20203163,
      94.1717368783
    ],
"spacename": "CH/PH Stock",
"points": [
      -4517.90264403, -12718.7658435, 94.1717368783,
      -4517.90264403, -7202.21858414, 94.1717368783,
      -12767.9026416, -7202.21858414, 94.1717368783,
      -12767.9026416, -12718.7658435, 94.1717368783
    ],
```


Fig. 6: Sample Dynamo script for inquiring and converting BIM data to JSON strings. Individual conversion node (left) and combined string of required model data (right).

Any parameter value can be called out of the database as long as it exists in the model. Validation of the converted data is performed via the previously describe validation method. The data has the possibility to be stored in an external or cloud server. However, complications with updating the database afterwards may arise due to data size and complexity, and is therefore, not recommended if the data in its current state is to be used only once or strict storage requirements are in place.

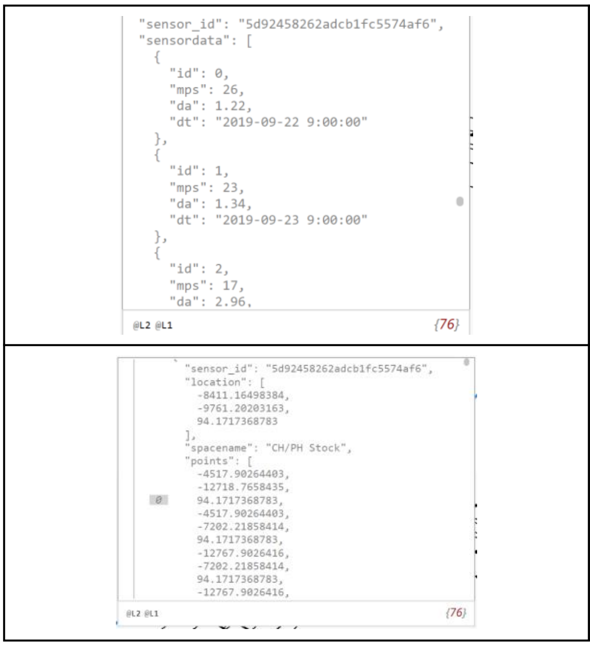
5.3.2 Mapping sensor data to BIM object data

To successfully map the appropriate sensor data to its corresponding object data, two objectives are required to be completed:

- A parameter in the model geometry, correspondent to the identification parameter of the sensor from the sensor network.
- A consistent JSON data structure, validated by the same standard.

The objective of the data formatting algorithms is providing datasets in an interchangeable format. As such, the data has the possibility to be organized, mapped and combined by one algorithm, which can ensure the consistency of the resulting data and no additional validation check is required. The identification parameter can be a simple string value, attached to one or more objects in the model, if several different objects' information is required.

As a programming tool, that has a direct access to the BIM database, Dynamo is also useful for developing the simple mapping script. However, regardless of the coding environment, an additional inquiry has to be made to the previously established sensor database. Fig. 7 illustrates the coded query requesting the information for specified air quality monitoring sensors from the sensor database, and the mapping algorithm, whose objective is to find the similarly ID'ed objects' data from the converted database and combine the data in a structured way. Note the consistency of the two JSON strings.




```
"sensor_id": "5d92458262adcb1fc5574af6",
"location":
   [-8411.16498384, -9761.20203163, 94.1717368783],
"spacename": "CH/PH Stock",
"points": [
-4517.90264403, -12718.7658435, 94.1717368783,
-4517.90264403, -7202.21858414, 94.1717368783,
-12767.9026416, -7202.21858414, 94.1717368783,
-12767.9026416, -12718.7658435, 94.1717368783
          ],
"sensordata": [
      {
        "id": 0,
        "mps": 26,
        "da": 1.22,
        "dt": "2019-09-22 9:00:00"
      },
      {
        "id": 1,
        "mps": 23,
        "da": 1.34,
        "dt": "2019-09-23 9:00:00"
      },...
```


Fig. 7: Simple script for reading sensor data and specified BIM data, mapping and combining in a JSON string. JSON objects of sensor and BIM data (left) and combined string JSON data (right).

5.4 Simulated BMS environment and JSON data visualization

Concatenated JSON data of sensor records and BIM data is light, simple and well-structured, which allows BMS for more than just reading and parsing. A simulated BMS environment, analyzing the daily dust accumulation in rooms in a building, has the opportunity to graph, isolate and even animate sensor data, layered onto the BIM boundary data. The scripting of the queries is written in Python, using the visual programming platform Grasshopper for Rhino3D, and the same platform to visualize the data layers. An advantage of such process is the facilitating of understanding of the building system's behavior in the context of its environment and users. As shown in Fig. 8 simple queries by the simulated BMS to the JSON database, can very quickly extract useful data about the records of the space, analyze, and in Fig. 9 visualize them, in order for the systems to take appropriate actions.

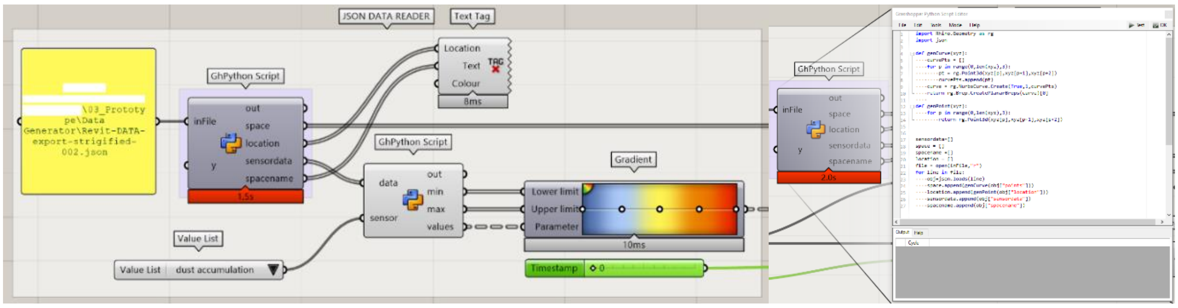


Fig. 8: GH script for queries to the linked JSON database and an algorithm analyzing dust accumulation in rooms.

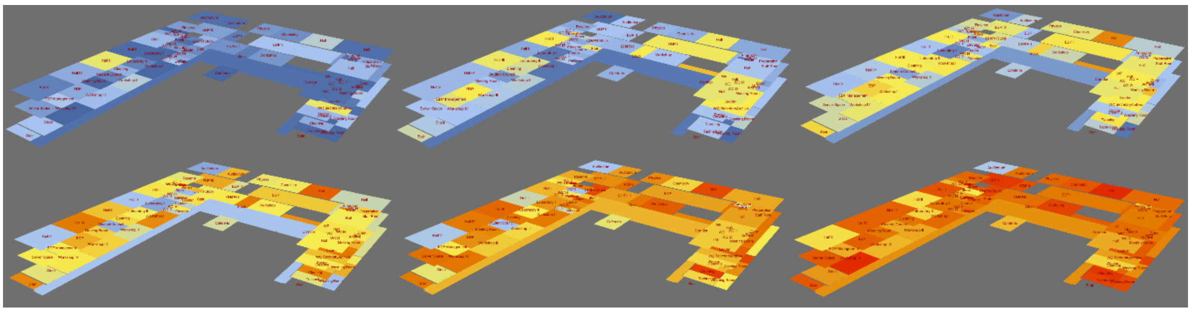


Fig. 9: Visualization of the sensor data from six days of dust accumulation records.

Predetermined threshold values are monitored, and value deviations coded to lead to an automatic database query that extracts more useful BIM data about e.g. the cleaning facilities, manufacturer of the ducts, replacement requirements, access, etc. Historic visualization can prove useful in finding causes and influences of system malfunctions, or usage and trigger patterns.

6. DISCUSSION

Our findings suggest that data format conversion proves a useful process for the simplification of operational building data manipulation and a satisfactory facilitator of linking and analyzing sensor and BIM data. Simple data interchange formats, such as JSON, provided an advantage in the speed of the data extraction and analysis in contemporary BMS, especially when handling large amounts of dynamic datasets. The use of BIM data demonstrated a leverage in the accuracy and understandability of the analysis and a strong support for the visualization of building operations data patterns and historic records. This supports the idea that data formatting is a practical approach for the AECO and FM industries in keeping up with the ever-increasing demands for dynamic data analysis in automated building operations. Similar results were observed by Mezei et al. (2018) in their sensor data format standardization attempts, yet limited attention has been put to semantic interpretation of the diverse data. Our results point to simple JSON data interchange format as successful in describing and storing the large data flow from the growing IoT in Smart Buildings. As observed by Afsari et al. (2019), JSON data formatting can play a key role in the efficient standardization of web-based BIM information exchange as well. Our findings contribute to this idea by demonstrating successful link and exchange of useful BIM data, such as facilities information, and dynamic sensor data between platforms, using JSON, while still retaining the ontology of the building information models. This allowed for a more useful database through semantic queries. Results also strengthen the idea of the use of BIM data as a validator of the BMS analysis and a useful tool for the visualization of systems performance data by providing the environmental context, system descriptions and information structure. Garrish et al. (2017) also puts forth practical methods and insights of linking BIM and building energy performance data. Our research, however, also attempts to successfully exploit large sets of sensor data from e.g. data mining or big databases.

While this paper displays the advantages of data formatting of operational building information and the BIM-BMS link, the proposed practical framework explores a limited number of BIM data exchange methods. The authors acknowledge the current trends in facilitating BIM interoperability via web-based services but choose to construct a simulated information exchange platform for a simplified access to BIM and sensor data. As such, further research into the different methods of web-based BIM data transfer and storage can be beneficial to future developments in the area.

7. CONCLUSION

The understanding of the challenges and opportunities for BIM-BMS link is fundamental for the development of a successful method for achieving this. In this paper, we explore the advantages of simple data formatting, such as JSON, in the link between BIM and sensor data in a BMS environment. Practical application concluded that data format conversion can prove a useful process in streamlining the integration of big dynamic sensor data from IoT and BIM data in modern BMS. It supports the idea that a common data format simplifies the handling and storage of such diverse datasets. It showcases significant increase in the speed and accuracy of the analysis and brings notable values for the automation of the FM industry, such as visualization of historic data patterns and automating maintenance procedures, by its enhanced contextual awareness, and simple data structure. While previous findings also demonstrate a leverage in BIM data standardization, our study was successful in maintaining the semantic ontology of the database when linked to other highly varying datasets. It is possible that other BIM and FM data exchange methods may prove more useful for the access and extraction of operational building data. Future researchers should consider investigating more diverse methods of building data and exchange, such as web-based services and linked data platforms in the analysis of sensor and BIM data. As we showcased, the access to and diversity of the data contemporary BMS operates with is hindered by increasing storage demands and complexity. These future prospects may prove advantageous for FM professionals in more easily accessing and storing information from IoT devices and may uncover more practical solutions for BIM-BMS interoperability.

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DEVELOPING A DATABASE TO CAPTURE, STORE AND SHARE FALL-RELATED SAFETY KNOWLEDGE TO ENHANCE FALL PREVENTION IN CONSTRUCTION INDUSTRY

Vigneshkumar C[a*], Rita Yi Man Li[b], Roode Liias[c], Urmi Ravindra Salve[a]

[a]Department of Design, Indian Institute of Technology Guwahati, Guwahati, India
[b]*HKSYU Real Estate and Economics Research Lab, Hong Kong Shue Yan University, Hong Kong*
[c]*Department of Civil Engineering and Architecture, Tallinn University of Technology, Tallinn, Estonia*
[*]*vigneshkumarchellappa@gmail.com*

ABSTRACT: *In many countries, fall from height is a leading cause of fatalities and injuries in the construction industry. Many of these happen due to the dynamic nature of work, workplace uncertainty, as well as risky activities. Hence, effectively acquire, store and share the knowledge of fall safety to address these construction hazards is needed to reduce the likelihood of accident. This paper developed a framework based on safety knowledge which could facilitate the knowledge of safety officers/experts during risk management process at pre-construction stage. This proposed framework aims at acquiring, storing, reusing and transferring knowledge of safety among practitioners about fall-related hazards and required measures to enhance safety awareness via Cloud SQL. The database for fall-related safety facilitates the understanding among practitioners in the construction industry for better safety planning and fall prevention program.*

KEYWORDS: *Knowledge management, construction industry, fall-related safety, practitioners, BIM.*

1. INTRODUCTION

Falling from height is the leading cause of deaths and injuries to workers in the construction industry (CI) of many countries. Regions including the US (Bobick, 2004; Li *et al*., 2019), UK (HSE, 2018) and Hong Kong (Wong *et al.*, 2016) has recorded high accident rates due to fall. Rules and regulations are often set by the government to prevent workers from falling at workplaces. However, these regulations could not encompass all possible hazards on construction site (Hadikusumo and Rowlinson, 2004). Hence, companies are developing their system for risk management during the pre-construction stage of a project to prevent workers from falling during construction.

Risk management in a construction project is a knowledge-intensive process (Ding *et al.*, 2016), consists of hazard recognition, quantification of risk and setting control measures at an acceptable level (Chantawit *et al*., 2005). Traditionally, the processes of hazard identification and risk assessments are carried out by safety officers based on their individual experiences and information such as regulations, national or international guidelines, accident reports, records and 2D drawings (Hadikusumo and Rowlinson, 2004). The control measures are put in place once the possible risks are identified and evaluated. In this case, safety knowledge, experiences, and perceptions of the safety officers are of greater importance. However, due to construction uniqueness, complexity, and dynamism, a considerable number of hazardous conditions are hidden (Guo *et al*., 2015). Knowledge of safety supervisors alone could not be sufficient to prevent hazards at workplaces. And the fact that workers are exposed to these conditions that contain heavy machines, work-at-height and other serious safety risks (Hallowell, 2012). Hence, to address these challenges, construction companies have to adapt to changes by effectively acquire, store and disseminating new system approaches that prevent falls at workplaces. This can be accomplished by an effective knowledge management process.

Knowledge plays an essential role in decision making regarding construction means and methods and implementation of practical solutions to issues (Ferrada and Serpell, 2014). Effective knowledge management improves the performance of construction projects by enhancing learning ability (Kivrak *et al.*, 2008), productivity (Carrillo and Chinowsky, 2006), reduce project time and cost (Shelbourn *et al.*, 2006). It also helps stakeholders to work faster, smarter and innovative (Ruikar *et al*., 2007). Although some studies related to knowledge management and its significance in safety management, such as (Hadikusumo and Rowlinson, 2004; Ding *et al.*, 2016; Goh and Guo, 2018), no studies attempted to capture the knowledge of fall-related safety. For example, identification of hazards, through risk assessment of fall hazards and providing adequate control measures, where the poor fall planning system is one of the major contributing factors to fall from height (Hsiao and Simeonov, 2001; Kines, 2002; Huang and Hinze, 2003; Bobick, 2005; Chi *et al*., 2005; Chan *et al.*, 2008; Adam *et al*., 2009; Wong *et al.*, 2009; Lombardi *et al.*, 2011; Peng *et al.*, 2014; Schoenfisch *et al.*, 2014; Cakan *et al*., 2014; Moore and Wagner, 2014). This could be achieved by capturing the knowledge of experienced practitioners (EPs) such as project managers, site engineers, site managers, and other experts in the CI. This is because they are one who is involved in the dynamic working environment and have the potential to make decisions in many cases/scenarios related to safety including work-at-height at construction workplaces.

Therefore, this study developed a framework to enhance safety knowledge of practitioners from CI for enhancing fall prevention. This paper, first, provides an overview of KM and safety knowledge management (SKM) in construction and challenges with capturing the fall-related safety knowledge for practitioners. Next, the paper describes the conceptual framework and gives a review. The paper concludes by stating this paper's contribution and future scope. This framework could act as a decision support tool in the future during the pre-construction stage of construction projects for better fall safety planning. Such a study is needed world-wide because of a lack of safety knowledge in CI across all countries.

2. OVERVIEW OF KNOWLEDGE MANAGEMENT AND SAFETY KNOLWEDGE MANAGEMENT IN CONSTRUCTION

2.1 Knowledge management in construction

CI is a knowledge-based industry, and knowledge management is vital to enhance the performance of an organization (Kivrak *et al.*, 2008). KM in the CI promotes a combined approach to create, access and utilize the experts' domain knowledge on processes, services, and products (Lin *et al*., 2006). There have been several definitions for KM; Webb (cited in Hallowell 2012) noted "to enhance efficiency and create value, knowledgeable assets must be formalized and optimized." Beckman (mentioned in Hadikusumo and Rowlinson 2004) defines KM as "experience, knowledge, and expertise must be identified, shared, and used to transform the intellectual asset into a valuable business asset." Therefore a lot of models have been proposed by many researchers for the KM process in construction project management (CPM). For example, Kamara *et al*. (2002) developed a tool CLEVER (cross-sector learning in the virtual enterprise) to provide a KM issue definition and strategy formation for the CI; Tserng and Lin (2004) proposed a model which helps the users to access documents related to construction projects in different formats. Recent studies such as (Ho *et al.,* 2013; Deshpande *et al.,* 2014; Baley *et al.,* 2016; Grover and Froese, 2016) adopted ICTs for capturing and reusing the knowledge to facilitate KM in CI.

Knowledge can be categorized as explicit and tacit (Smith, 2001). According to Sherehiy and Karwowski (2006), explicit knowledge is formally articulated and transmitted between individuals in coded databases such as best practices, procedures, and regulations. Tacit knowledge is developed unconsciously by an individual through experiences and very difficult to communicate (Alter, 2002). Tacit knowledge is related to practical aspects and is typically transferred through a meeting, face-to-face personal communications, and even through electronic tools such as intranets, email and other online chats (Hallowell, 2012). To develop an effective KM system, both explicit and tacit knowledge is equally essential (Hallowell, 2012). Sherehiy and Karwowski (2006) found that when both tacit and explicit knowledge interact, continuous improvement of organizations occurs. This interaction continues the collaboration of individuals who apply both kinds of knowledge to address project-based challenges.

2.2 Safety knowledge management in construction

Safety knowledge management is an emerging topic in the CI. The main objective of the processes of knowledge management is to create, store, transfer and reuse the knowledge (Alavi and Leidner, 2009). Although there have been a lot of studies on knowledge management, only limited studies addressed the role of knowledge acquisition, storage and transfer in construction safety management (CSM). For example, Hadikusumo and Rowlinson (2004) developed a Design-for-Safety-Process (DFSP) tool to capture the knowledge of safety engineers to enhance the organization's training and safety program. Cooke *et al.* (2008) developed a decision support tool (ToolSHeD^{TM}) to help construction designers by integrating health and safety in the design phase of the construction projects. A study by Teo *et al*. (2005) found that workers' safety-related knowledge has a strong impact on workplace safety. It confirms that safety knowledge is one of the success factors for workplace safety. This study recommended that an organization should not only capture and store safety knowledge but also transfer and retain by the workers. Hallowell (2012) aimed to identify the safety KM strategies employed in American CI to prevent accidents/injuries. This study found that organizations are much more efficient in acquiring, storing and transferring explicit knowledge than tacit knowledge. Recent studies adopted information and communication technologies (ICTs) such as building information modeling (BIM) and ontology to facilitate KM in construction safety. For example, Ding *et al.*, (2016) formalized construction safety knowledge and linked it with BIM for hazard analysis and safety task scheduling; Guo and Goh (2017) developed an ontology for the design of the active fall protection system (AFPS) which attempts to facilitate sharing and reusing of knowledge among professional engineers. Goh and Guo (2018) developed a knowledge-based *FPS*Wizard system to facilitate knowledge sharing among users to support the design of AFPS. However, Obaide and Alshawi (2005), stated that there are no such globally accepted studies for all knowledge types and organization types.

3. APPROACH TO CAPTURE FALL-RELATED SAFETY KNOWLEDGE

Knowledge capturing is the first and the most challenging step in KM processes. Obtaining knowledge means acquiring the responses of 'know-how' queries to solve similar issues in the future (Hari *et al.*, 2005). This process further transfers specific knowledge to an organization knowledge for improving the performance of the projects (Wang and Meng, 2019). Knowledge is captured from external and internal sources of organizations. Tacit knowledge (i.e., thoughts and experiences of practitioners) is trying to obtain than explicit knowledge such as written documents, regulations, books, and so on (Alavi and Leidner, 2009). In terms of construction safety, explicit knowledge can be acquired from current theoretical statements written in safety guidelines, rule book, safety regulations, accident reports and organization records. Tacit knowledge exists in the form of an unstructured manner in an individual's (i.e., project manager, site manager, site engineer, safety manager, safety officer, quantity engineer, safety engineer, and other experts) mind.

The simplest way to capture the knowledge of practitioners in CI is through discussions. However, there are lots of challenges and limitations that exist to carry out this way. For example, several tools are required during discussions for representing cases such as method statements and drawings, which serve as texts and two-dimensional (2D) drawings. It may be challenging to understand the instances (Collier, 1995), as the 2D drawings do not represent the processes of construction instead it only represents construction components such as beams, columns, and walls (Young, 1996). By comparison, BIM provides an information-rich environment for construction hazard recognition and risk quantification in the domain of CSM, (Smith and Tardif, 2009). More proactive and construction risk management can be accomplished in the BIM environment (Ku and Mills, 2008). Studies have proven the capability of BIM on enhancing the performance of safety by hazard identification and risk mitigation in CI (Zhang *et al.*, 2013, 2015; Ding *et al.*, 2016). Hence, this study adopted BIM to simulate the construction processes for capturing fall-related safety knowledge from the practitioners.

4. CONCEPTUAL FRAMEWORK OF FALL-RELAED SAFETY KNOWLEDGE SYSTEM (F-SKS)

The framework of F-SKS consists of three components such as knowledge acquisition; knowledge storage; and knowledge sharing (see Fig. 1) and is discussed below.

4.1 Knowledge acquisition

The first step of this system is to capture the fall-related safety knowledge of EPs from CI. The practitioners may include project managers, assistant project managers, site engineers, site supervisors, quantity engineers, quantity surveyors, site managers, site division head, safety officers, safety managers, junior safety engineers, executives, and other experts. In this step, BIM technology will be used to capture their knowledge which provides the virtual model and construction simulation in the virtual environment (VE). BIM technology can design a 3D model of building elements and also simulate the processes of construction (Li *et al.*, 2008). Hazards and risk factors could be easily identified by the practitioners based on the 3D models and construction simulation (Guo *et al.*, 2013).

Using BIM technology, 2D drawings will be transferred to 3D models. The pictures may include architectural, structural and mechanical services of building, site layouts, workers, construction equipment and temporary agents such as ladder and scaffold. Then these 3D models could be combined with plans such as activities, sequences, and project schedule to simulate the construction processes visually. The process of creating such a construction simulation is shown in Fig. 1. Then by using the resource models in VE, these models will be operated. This is similar to the actual practice and thus, information-rich about the construction environment could be achieved.

The construction VE will provide a better platform for practitioners to identify fall-related safety issues, including hazards and risk levels. By walking through the virtual site, practitioners can easily recall their experience and recognize the fall risks. The virtual site provides accurate information about the construction process, and thus, practitioners can effectively identify the fall safety issues in advance. An active control measure for controlling or mitigating these issues will also be captured from the practitioners.

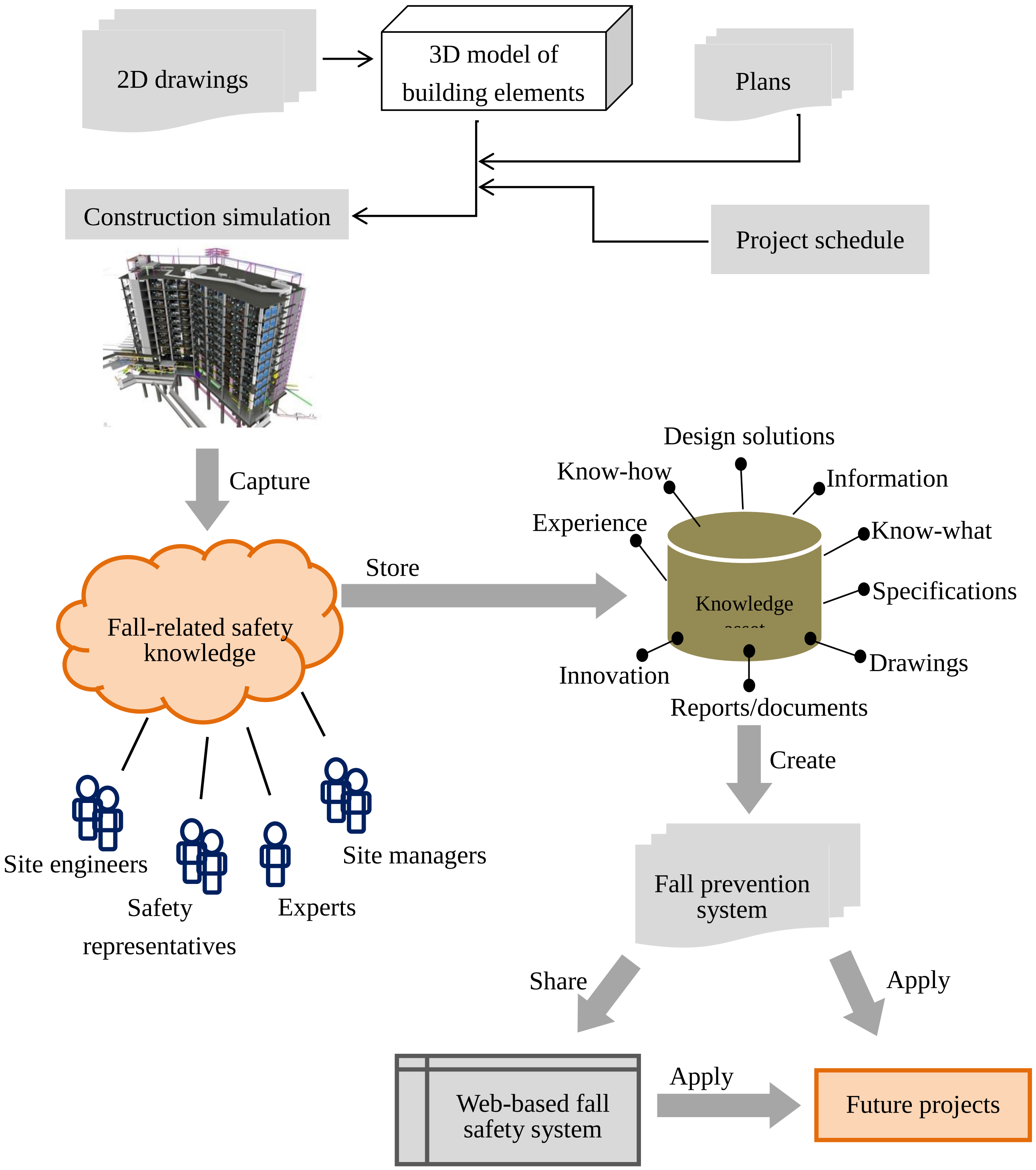

Fig. 1: Conceptual framework of F-SKS

4.2 Knowledge storage

When the submitted fall-related safety knowledge is validated, it will be stored in a system called a knowledge bank. During the construction stage, safety-related issues, know-how, solutions, and know-what is in the minds of practitioners. In any project, decision-making, problem-solving, and innovations are created in the construction phase. Knowledge of practitioners will be stored as explicit knowledge that could be packaged as data. It will be documented in any of the forms such as drawings, pictures, manuals, articles, written statements, specifications, and other forms. This will be later included in organizational documents such as a fall prevention system that can include mission statements, process maps, and others. As explicit knowledge is available in document form, it can be easily managed during the entire life cycle of the construction project.

4.3 Knowledge sharing and reuse

The final step in this system is knowledge sharing which actively presenting knowledge in particular web-based system. The safety officer/expert (user) can easily access this system to facilitate the KM process. The experience can be reused, once the explicit knowledge is saved in the system. Users can gain knowledge from the fall-related safety issues and can access this system for use in other similar construction projects. The organizations which are using information technology (IT) tools can use web-based systems.

5. A PROTOTYPE SYSTEM BASED ON THE MODEL

Based on the proposed framework, a prototype will be designed and stored in Cloud SQL. The prototype (fall-prevention system) will be created which may include the details of activities, hazards list, risk level, photos with construction hazards and risky fall from height activities, and so on. A scoring system will be used to rank various risks in order of importance. The scoring system contains the categories of probability of occurrences and severity of consequences as shown in Table 1 (Zhou *et al.,* 2011). The normalized score for the probability and severity of each hazard will be reflected in the prototype. The risk level of hazards will be calculated by multiplying the probability and severity of each risk (i.e. risk level = probability of occurrences x severity of consequences). Fig. 2 demonstrates that risk will increase if either probability or severity rise, or both rise concurrently, and the majority of the safety measures will allocated to the dark-shaded cells in the upper right; high probability, high severity. A schematic view of the prototype is shown in Table 2. Further information which may be needed for users for fall prevention will be modified and updated in the prototype.

Table 1: Scoring system for probability of occurrence and severity of consequences (Zhou *et al.,* 2011)

Probability of occurrence	Severity of consequences	Score
Never	Insignificant	1
Unlikely	Minor	2
Possible	Moderate	3
Likely	Major	4
Always	Catastrophic	5

Probability of occurrences x Severity of consequences =

Fig. 2: Risk level of hazards

Table 2: Schematic view of the prototype

SI No	Activity	Sub-activity	Hazards	Possible outcome	Existing control measures	Probability	Severity	Risk Level	Additional control measures	Photos
1	1	1.1…								
2	1	1.2…								
3	2	2.1…								

Validation and verification tests will be conducted to evaluate the performance of this system. Validation aims the effectiveness of this scheme, while verification determines whether the system functions properly. This will be performed by allowing the users to use this system, and then asking them to provide comment by responding questionnaires. The prototype will be validated and verified against the criteria set out in the technology acceptance model (TAM) proposed by Venkatesh and Davis (2000).

6. CONCLUSION

To enhance fall prevention in CI, this study developed a framework of F-SKS as a vital platform to facilitate safety knowledge among participants. BIM has been adopted in F-SKS, as it illustrates visual experience with problem descriptions and solutions in the VE. The BIM approach could identify valuable fall-related safety knowledge relevant to activities hazards and risks. Based on this framework, a prototype will be developed later and validated to evaluate the performance. The significance of this present study could facilitate the safety knowledge of safety officers/experts in fall risk identification and mitigation processes.

The framework developed in this paper has the following limitations. Firstly, it is focused only on fall-related safety risk management processes. In any construction project, risk management is an essential process for fall prevention (Ding *et al.,* 2016). Nevertheless, many working-at-height scenarios still need a proper prevention system. Secondly, this prototype proposed in this paper targeted only the large-scale residential building projects because of its complexity and vulnerability to construction workers (Guo *et al.*, 2013). The last limitation of this paper is that this study targeted the safety officers/experts as users who prepare a fall prevention plan during the pre-construction phase of the construction projects. This is because the traditional processes followed in many countries for preparing a fall prevention plan is ineffective (Guo *et al.,* 2013).

7. ACKNOWLEDGEMENT

This article is supported by the Department of Design, IIT Guwahati, Research Grant Council, (grant number UGC/FDS15/E01/18), European Regional Development Fund, and Archimedes Foundation, Tallinn, Estonia.

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EVALUATION OF MICROSOFT HOLOLENS AUGMENTED REALITY TECHNOLOGY AS A CONSTRUCTION CHECKING TOOL

Loporcaro G., Bellamy L., McKenzie, P. & Riley, H.
University of Canterbury, Christchurch, New Zealand

Ralston, S.
Trimble Inc., Christchurch, New Zealand

ABSTRACT: *Increasing productivity is one of the most important objectives of the construction industry. Building Information Modelling (BIM) was introduced to facilitate collaboration and coordination in the life-cycle of buildings and infrastructures. More often, BIM models are preferred to traditional 2-dimensional drawings to communicate the design to the project stakeholders such as design team, contractors, and the client. Conversely, it is common to use traditional 2-D drawings on-site in the construction phase. Construction mistakes are often the results from errors in the construction drawings or from their misinterpretations. Over the last years, augmented and virtual reality has been introduced in the architecture, engineering and construction industry (AEC) as visualization and collaboration tools. This paper aims to evaluate Augmented Reality (AR), in particular, Microsoft HoloLens, as a construction checking tool. The paper compares different construction checking tools such as the traditional tape and measure, Trimble SX10 laser scanner and the Microsoft HoloLens using Trimble Connect as BIM software, to the Trimble SX10 Total Station, a current industry leader in surveying technology. Comparisons were based on accuracy, speed of testing, ease of use and efficiency. Testing was undertaken by comparing benchmark virtual models of the testing rooms, obtained from an initial survey, and the actual physical rooms. Results indicated that, overall, the HoloLens was the most efficient construction checking tool within a 15 mm to 50 mm accuracy range. It was not as accurate as a laser scanner or tape measure, which indicates further improvements are required before this technology can be recommended as a general construction checking tool.*

KEYWORDS: Augmented reality, Construction checking tools, Digital technologies, HoloLens

1. Introduction

In Augmented Reality (AR), 3-dimensional virtual objects are overlaid upon the physical world (Azuma, 1997). Although AR was initially developed in the 1990s (Milgram, Takemura, Utsumi, & Kishino, 1995), this technology has seen rapid market growth over the last decade, particularly through the popularisation of AR technology with handheld devices and smartphone usage. As this technology becomes increasingly common in many industries (medicine, education, marketing, gaming, etc) (Billinghurst, Clark, & Lee, 2014), its functionality could be extended to be used as a construction checking tool within the Architecture, Engineering and Construction (AEC) industry. The technology's potential could allow an accelerated construction checking process, enabling the user to recognize discrepancies within the built design, faster and more efficiently than current construction checking methods.

Microsoft HoloLens, shown in Figure 1, is a visual headwear device that uses a beta version of Trimble Connect software, a collaboration platform developed for the construction industry. HoloLens is equipped with a holographic display and Trimble Connect software which imports virtual models (e.g. SketchUp format) from cloud storage and overlays the model through the HoloLens headset onto the physical world. The result immerses the wearer into a blend of realities. The user can interact with the virtual model with intuitive hand gestures. Such technology is currently used for visualization purposes within the architectural industry, but more technical applications of this technology within the Civil Engineering discipline would see its commercial value rise (Blanco, Mullin, Pandya, & Sridhar, 2017).

Figure 1 The Microsoft HoloLens device

1.1 A brief summary of AR as construction checking tools

Augmented Reality as construction monitoring tool has been investigated by a number of researchers over the recent years (Kwon, Park, & Lim, 2014; Meža, Turk, & Dolenc, 2015; Park, Lee, Kwon, & Wang, 2013; Yabuki & Li, 2007; Yeh, Tsai, & Kang, 2012). Yabuki and Li (2007) developed a prototype AR technology for checking steel reinforcing bars in bridge piers. Checking reinforcement layout based on 2D drawings is impractical, therefore such a system could reduce inspection time and costs. Park et al. (2013) created a framework to detect, classify and communicate defects on construction, while (Kwon et al., 2014) developed a management system to detect defects in reinforced concrete structures using BIM, image-matching and augmented reality. Meža et al. (2015) identified that the challenges associated with the use of AR in construction include: the virtual model not aligning well with the surrounding area; the small size and resolution of the hardware; and difficulties arising from obstructions within the field of view, such as a high constructions or fences, and healthy and safety risks associated with the use of the device within a environments . Another concern, made by Meža et al. (2015), was the potential safety implications of using AR as a wearable mobile device on a live construction site and how this may distract the user from hazards in the surrounding environment. Meža et al. (2015) concluded that AR can facilitate the understanding of project documentation, especially in the visualisation of 3D models within the field. However, AR remains technologically constrained by barriers such as indoor GPS, visual occlusion, frame-rates of virtual elements and general responsiveness. Previous research employed prototype AR technologies often no commercially available. On the other hand, little research has been conducted to check the feasibility of commercially available AR devices such as Microsoft HoloLens.

1.2 Research aim

The aim of this research is to investigate the feasibility of Microsoft HoloLens as a construction checking tool. In particular, Microsoft HoloLens is compared as a length measuring tool to the traditional tape and measure tool and Trimble SX Laser Scanner. Comparisons are made on the following performance indicators: accuracy, reliability, speed of testing, ease of use, and efficiency.

2. Methodology

2.1 Performance indicator

2.1.1 Accuracy

In order to compare the accuracy of each measuring tool (Taper and measure, HoloLens and the Trimble SX10 Laser scanner), wall lengths and heights within a room are measured with each tool and compared to the corresponding lengths and heights of a benchmark model of the room. The benchmark model, considered the most accurate model of the room, was created from measurements obtained using a Trimble SX10 Total Station (https://geospatial.trimble.com/products-and-solutions/trimble-sx10). Any discrepancies between measurements with each construction checking tool and benchmark measurements will yield an error. Thus the accuracy of each tool can be quantified based upon the size of these errors.

Additionally, spatial errors are evaluated via a coordinate system. Coordinate deviations between the benchmark corner positions and virtual model corners yield an error. Through these comparisons of accuracy, the reliability of these results was also ascertained.

2.1.2 Speed of testing

The speed of construction checking was timed for each different method, with times being averaged to give an average checking time for each method. This average measure mitigates the associated 'learning curve'; an inherent part of any familiarisation process.

2.1.3 Ease of use

The complexity of a construction checking tool can be a barrier to its use in the construction industry. A subjective ranking of the complexity of the four construction checking techniques was given with a brief explanation as to its position.

2.1.4 Efficiency

Often quick construction checks are needed with results accurate to a desired level of accuracy. The efficiency of each tool was evaluated within target accuracy ranges (< 5 mm, 5 – 15 mm, 15 – 50 mm) based on the average time of testing.

2.2 Test procedure

2.2.1 Benchmark survey

Benchmark surveys were undertaken of five rooms selected on the University of Canterbury campus. These surveys were undertaken with the Trimble SX10 Total Station using its Direct Reflex (DR) capabilities. The survey was conducted by an experienced operator to ensure the reliability of the dataset. The Total Station was placed at the centre of each room in order to capture the coordinates of all the room corners and edges. Rooms with large architectural/structural features, such as curved and angled walls or large columns were discarded, as this would have increased the testing difficulty and might have affected the error analysis. Plain rectangular rooms were the ideal candidates.

During the benchmark survey, the Total Station (Figure 2) was set at a height where all, or most, of the vertices of the room were easily captured. A backsight was arbitrarily set and thus the x-axis and y-axis were arbitrarily set within the room. The z-axis was aligned to be perpendicular to the floor plane. The Total Station's position was 'zeroed', giving its position within the room as (0,0,0) in x, y and z coordinates. Systematically, the corners of each room were mapped using DR. Each point mapped was noted with a number on an accompanying sketch for reference, as results would be issued in a CSV file. The CSV file was exported to SketchUp as a series of points in space, enabling a virtual 3D model to be created. Figure 3 shows a model created from the Total Station DR points.

Figure 2 Benchmark survey using the Trimble SX10

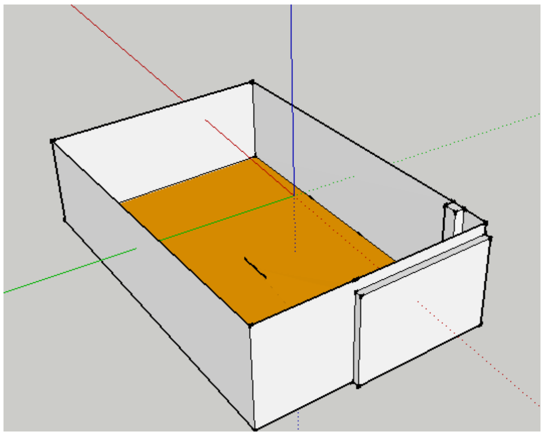

Figure 3 Benchmark virtual model in SketchUp

Within the virtual benchmark model, lines from diagonal corners were drawn, creating a large “X” across the floorplan of the model. At the intersection of these lines, a one-metre line was drawn back towards the mid-span of one of the walls. This line served as a reference line. The same line was recreated in the physical room whereupon virtual models from the HoloLens tests would be anchored. The purpose of the benchmark models was to enable a comparison for lengths within the model to the corresponding lengths found from the construction checking tools methods.

2.2.2 Microsoft HoloLens testing

A blind-testing method was developed. Three virtual models of each room were created in SketchUp by reducing the dimensions of the benchmark models. One person created the reduced models, while the other engaged in the HoloLens testing.

The benchmark CSV points were taken and reduced by the same arbitrary value in the x and y direction and a different arbitrary value in the z-direction. These points now represented a reduced version of the benchmark model. Three different sizes reduced models of the same room were created, with reductions in the x and y directions being anywhere between 0.1 metres to 1.5 metres. Height (z) reductions were typically no greater than 0.5 metres. Figure 4 shows the original benchmark model in white and a reduced model in yellow. The virtual model was uploaded on the cloud and the retrieved on HoloLens using the Trimble Connect HoloLens (TCH) application. Initially, the room had to be scanned by the HoloLens. The TCH application formed a mesh lining of the room (Figure 5). This process took between five and ten minutes, depending on the size of the room being scanned.

After the mesh had been fully formed, one of the three reduced models for that particular room was loaded by the TCH application and appropriately scaled to a 1:1 size. The reduced model was orientated and anchored so that the reference line on the model was aligned upon the physical reference line in the room.

The test was conducted by taking measurements at each corner perpendicular from the physical room to the reduced model as viewed by the HoloLens user. Measurements were taken using a physical tape measure, with the user standing directly above the tape to minimise parallax error and with the built-in, real-to-virtual measurement tool on the TCH application. Both sets of measurements were recorded. These measurement methods can be seen in

Figure 6 and Figure 7, respectively.

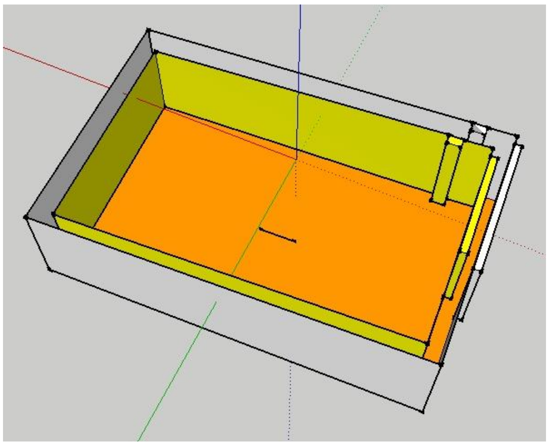

Figure 4 Reduced models fit inside the benchmark model

Figure 5 Trimble Connect HoloLens creates a mesh of the room

Figure 6 Physical HoloLens measurements

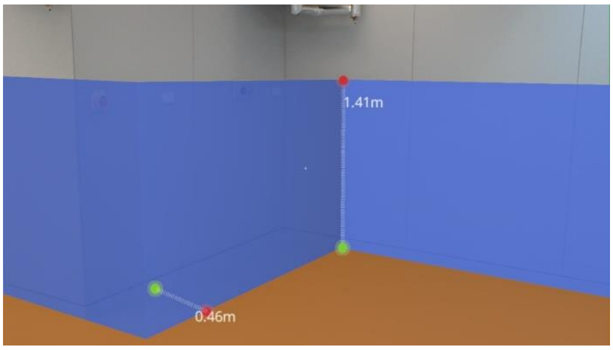

Figure 7 Real-to-virtual HoloLens measurements

Heights from the physical room floor to the top of the reduced model's walls were taken with both the physical and the virtual tape. Several heights were taken across the room, the number of which varied with the number of different roof/wall heights present.

Unlike the other testing methods, the lengths from the HoloLens testing had to be "assembled". Only the four external lengths and heights within each test could be used for comparison. An example of how one of these lengths was assembled is seen in Figure 8. Note that the lengths 'a_1' and 'a_2' are the perpendicular length measured from the physical wall to the virtual model.

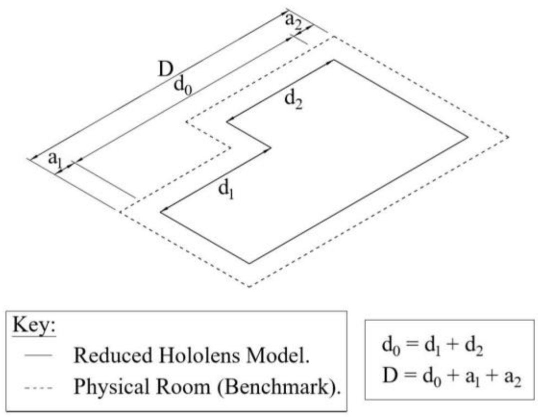

Figure 8 Assembly of HoloLens measured lengths

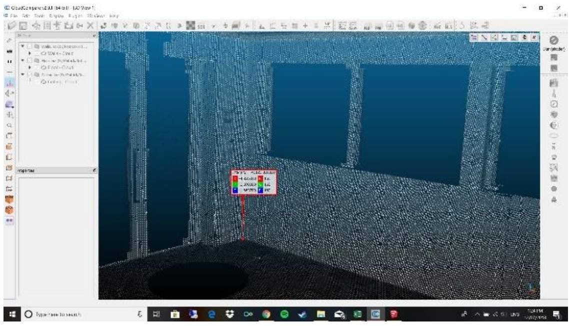

Figure 9 CloudCompare vertices selection

2.2.3 Trimble SX10 Laser Scan testing

A laser scan using Trimble SX10 (the same device used for the benchmark test) was undertaken. The laser scanner was set up to capture a 360° view of the room in a high-density 3D scan. The laser scanner captures thousands of measurement points within a room as a point cloud. The laser scan data files were opened using CloudCompare, with vertices being manually selected and recorded into a CSV file. Figure 9 shows how data points were selected from CloudCompare. Similarly to the benchmark models, the CSV file was exported to SketchUp and a virtual model of the 3-D scan was created. Each length within the model was given a number which corresponded to the same number and thus, the same length in the benchmark model.

2.2.4 Tape and measure

Floorplan lengths within a room were measured with a 30-metre steel tape by two people. All measurements were taken to the nearest five millimetres. Two vertical heights were taken, generally, on diagonally opposite corners of the room. All floorplan lengths and taken heights were modelled on SketchUp with the assumption that all vertices were exactly perpendicular (i.e. each wall was 90o to the adjacent wall).

2.3 Results and discussion

2.3.1 Accuracy: length measurements

The benchmark lengths were subtracted from the corresponding lengths found from each construction checking tool methodology to give error values. Errors that were positive showed that the particular construction checking tool used underestimated the benchmark lengths, while negative errors indicated an overestimation of measured lengths. Figure 10 shows this phenomenon. All the errors found across all five rooms for all construction checking techniques were used to create a distribution through statistical bootstrapping of errors (Figure 11). The normalised frequency plotted in Figure 11 accounts for different sizes of datasets for each construction checking tool. Table 1 shows the average errors and standard deviations. Outliers were removed from the datasets before the bootstrapping occurred.

The HoloLens with the physical tape gave the least accurate results with an average error of -87.7 mm. This indicated that the measured lengths were smaller than the benchmark measurements. Using the HoloLens accompanied with the virtual tape gave an average error of 22.1 mm smaller than the benchmark measurements. The error averages for both HoloLens data sets fall at the peak value (the median) of their distributions and shows that the HoloLens tended to overestimate spatial dimensions. However, the error averages for the laser scanner and tape & measure fall to the left of their largest peaks and result in a negative average error. The peak values for the laser scanner and the tape & measure are 3.9 mm and 10.1 mm respectively. It can be said that both the tape & measure and the laser scanner have a tendency to underestimate spatial dimensions.

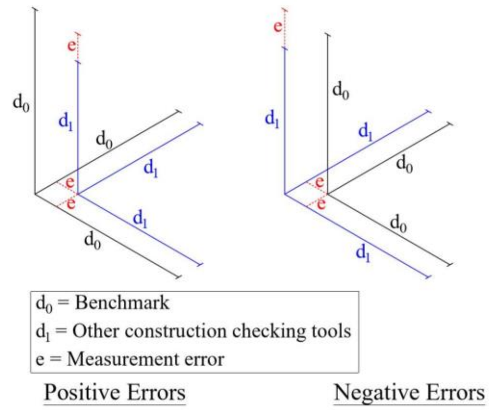

Figure 10 Errors detection using length-based comparisons

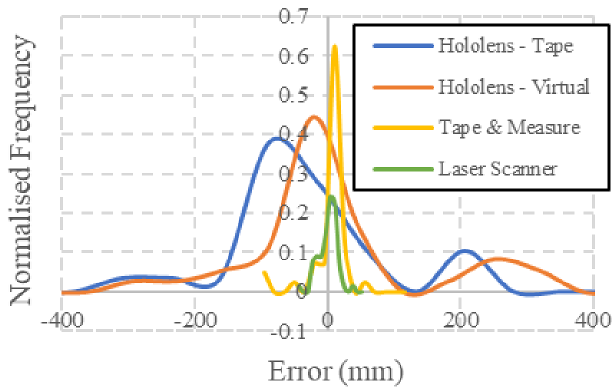

Figure 11 Distribution of errors associated with the lengths of each measurement

Table 1 Average errors and standard deviation

Method	Average error (mm)	Standard deviation (mm)
HoloLens (Tape)	-87.7	146.8
HoloLens (Built-in virtual tape)	-22.1	136.0
Tape & Measure	-5.0	30.2
Laser Scanner	-2.9	13.5

Theoretically, both sets of HoloLens results should show the same average error and display the same standard deviation. However, this is not true as the differences between these results can be attributed to a number of different factors. One of the main factors is the positioning of the mesh with regards to the wall. Here, the mesh was often not aligned upon the wall face exactly, being up to 50 mm either side of it. Real-to-virtual measurements are more accurately, mesh-to-virtual measurements as the HoloLens picks up the walls through the placement of the mesh and tries adopt them into the virtual space. As the mesh does not correctly line the wall, a systematic error was introduced into each virtual measurement taken. This error is one of the causes for the difference between the HoloLens two methods of measurements. The physical measurements taken with the HoloLens were taken from the physical wall to the virtual model. Errors could occur as a result of incorrect viewing of the tape (i.e. parallax error). Additionally, the HoloLens has a minimal scaling error associated with it. This is due to both HoloLens error results being significantly negative. This scaling error is more prominent in the HoloLens tape results than the HoloLens virtual measurements. While both sets of measurements are similar, the HoloLens tape measurements harboured a scaling error based on the perception of the HoloLens user. Predictably, the Laser Scanner and Tape & Measure results showed the greatest levels of accuracy. Ultimately, all results proved reliable as the distinctive peaks of the error distributions in Figure 11 would indicate.

2.3.2 Spatial comparisons

While lengths are typically the first form of measurement in construction practice, the HoloLens introduced some unique situations where the reduced virtual model had been properly anchored but showed a ‘skewing’ of the model. This set of data analysis focused on the positioning of the model within the physical space.

To examine the spatial accuracy of the HoloLens, the same testing data was used as the length comparisons. However, the data was used in its 3-dimensional form via a coordinate system to compare discrepancies between the virtual model and what is displayed through the HoloLens. The virtual models are not the same as what is viewed through the HoloLens and these discrepancies are ultimately the spatial error of the HoloLens. Using

Pythagoras' Theorem the spatial error can be calculated as shown in Figure 12.

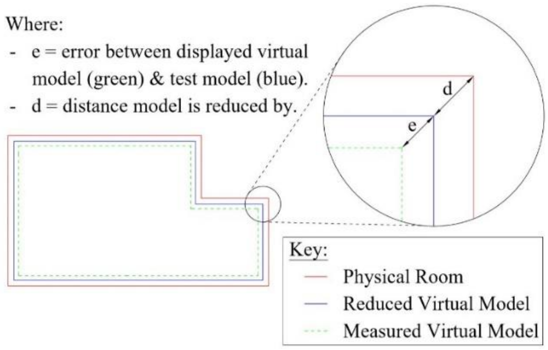

Figure 12 Errors detection using spatial-based comparisons

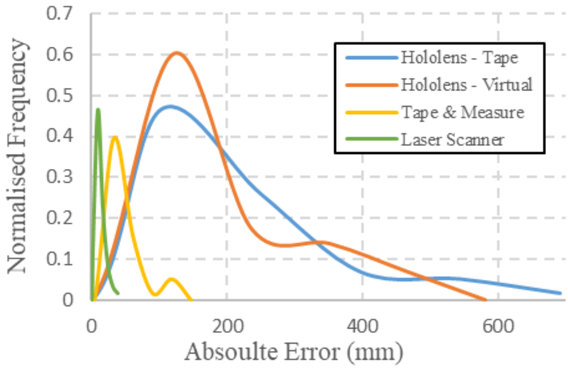

Figure 13 Distribution of errors associated with the spatial coordinate comparison

Note that Figure 12 depicts a perfect scenario whereby each model lines up perfectly within the next. However actual practice showed a skewing and slight rotation error between the physical room and reduced model. With no set coordinate system, or axis aligned, perpendicular or parallel to any of the physical walls, an absolute error using Pythagoras' Theorem seemed the most appropriate way to measure these errors. Laser scan and tape & measure errors were simply the same absolute distance between the benchmark and their respective scan and tape & measure models. Figure 13 shows all errors found across all five rooms for all construction checking techniques. Error distributions were created for each construction checking tool through a statistical bootstrapping protocol.

The average error and the standard deviations for these distributions are shown in Table 2. Results show that the most accurate construction checking tool was the laser scanner, while HoloLens, using the virtual measurement tool, gave the most inaccurate result with an average error of 121.4 mm. These large errors could be attributed to different factors such as scaling of the virtual model, inaccurate anchoring or measurements, or skewing of the model. As these errors are taken as absolute errors, the individual contribution of each of these factors cannot be ascertained. Instead, the HoloLens system's error is just evaluated as a whole.

Through further data analysis of these errors, it was found that the percentage error; the quotient of the error, e, over the distance the model was reduced by, d (see Figure 12), decreased rapidly with increasing distance. Figure 14 illustrates this phenomenon. This shows that smaller distances that were measured had larger percentage errors compared to the larger distances that were measured. This implies that as the measurements became larger, the size of the error that occurs is relatively consistent.

Table 2 Average errors and standard deviation

Method	**Average error (mm)**	**Standard deviation (mm)**
HoloLens (Tape)	102.7	147.2
HoloLens (Built-in virtual tape)	121.4	114.8
Tape & Measure	32.3	28.6
Laser Scanner	9.4	7.4

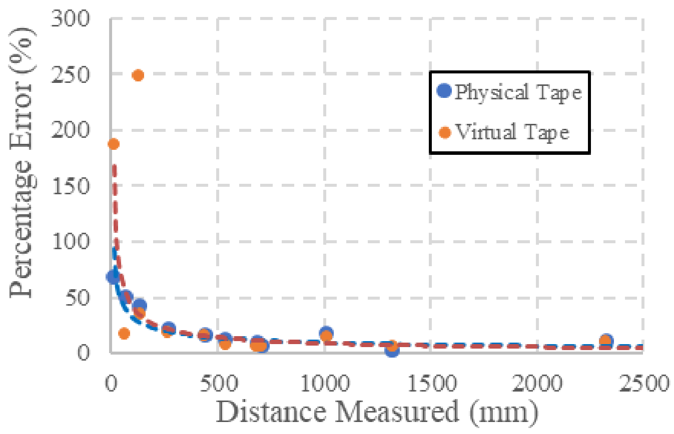

Figure 14 Percentage error with increasing distance

2.3.3 Speed of testing

Each test for every construction checking method was taken from the beginning of the test until the end of testing, including any initial setup time. Testing times progressively became faster as familiarisation with the technology increased. Increasingly faster times emphasises the inherent 'learning curve' associated with dealing with new technology. However, the average time for testing was deemed more appropriate to comment upon as these times have more value for field-testing. Table 3 shows the average time for each test across the five rooms surveyed.

Table 3 Average testing time across all rooms

Method	Average time (min' sec")
Tape & Measure	7'35"
Laser Scanner	12'52"
HoloLens (Tape)	5'54"
HoloLens (Built-in virtual tape)	9'13"
Total station (benchmark)	15'09"

2.3.4 Ease of use

These rankings are based on the subjective opinions of the authors of the tests. Table 4 ranks the ease of use of each construction checking tool. Measuring with a tape and measure device is an intuitive process since it is common practise, therefore it was deemed the easiest. Laser Scanner operation was of moderate difficulty, in part, due to the use of unfamiliar technology. However, once the Trimble SX10 Laser Scanner had been set up and levelled properly, the digital interface for the scan was intuitive and ultimately as simple as selecting a "start scan" button.

HoloLens operation was slow to begin with but became increasingly easier to use once the initial familiarisation with the technology had occurred. The HoloLens's intuitive hand gestures and vocal commands contributed greatly to its ease of use. Physical measurements taken were significantly harder than virtual measurements taken with the TCH application. This was due to the difficulty of seeing the physical tape over the HoloLens virtual display.

Table 4 Ranking of construction checking tolls from easiest to hardest

Method	Rank
Tape & Measure	1 (Easiest)

Laser Scanner	2
HoloLens (Built-in virtual tape)	3
HoloLens (Tape)	4 (Hardest)

2.3.5 Efficiency

The relative efficiency of each construction checking tool can be found by comparing the average time of testing to the average accuracy. Length based measurement errors have been used to evaluate the accuracy of each construction checking tool. Table 5 shows the most efficient construction checking tool for each accuracy range. Note that the times for testing across all five rooms were usually no less than 5.5 minutes and no greater than 16 minutes. This means that given a very large room (i.e. greater than 50 square metres) it would be outside the range of room sizes tested for this project and thus the most efficient construction checking tool for each accuracy range may change. Additionally, the efficiency ranking in Table 5 does not account for other technological capabilities, but for using the tools for surveying alone.

Table 5 Ranking of construction checking tolls from easiest to hardest

Desired accuracy range	Most efficient method
< 5 mm	Laser scanning
5 – 15 mm	Tape & Measure
15 – 50 mm	HoloLens (Built-in virtual tape)

3. Recommendations

This section focuses on addressing issues encountered during HoloLens testing and if possible providing recommendations. As the TCH software used by the HoloLens was still in its Beta version, issues/inconsistencies were always a probability. The following subsections categorise these issues.

One of the test rooms selected had two sections of wall that were matte black. Both, the HoloLens and the SX10 Laser Scanner could not mesh or pick up this surface and thus only partial data was used from this particular room. One major issue that was found during the testing was an apparent "parallax error". This was noticed when testing the HoloLens with the physical tape. With little or no head movements, the virtual model was perceived to have moved relative to the room. This was also apparent whenever the model was being anchored and whenever the anchoring of the reference line was being double-checked from any point that was not directly above the reference line. It was as if the HoloLens adjusted itself to its correct location the closer you moved towards the said location and in part explains the aforementioned scaling issue.

It would be significantly faster and more accurate if the model was able to directly "snap to the ground" or to the mesh upon the ground. Instead, the transformation tool was used as a "fine adjustment" to get the model floor plane lined up with the physical floor. This was hard to do accurately and became relatively time-consuming. This was a potential source of error for all z-axis measurements, as the judgement was used to subjectively place the virtual model on the ground whereas it may have been several millimetres above or below the actual ground level.

During two tests, the entire model misaligned along the horizontal plane and skewed itself upwards on an angle of 30° approximately. This may be attributed to the sloped ceiling of the room, which appeared to be of a similar angle. Collected results for these tests were aborted and testing restarted.

4. Conclusions

Through a series of tests, the accuracy of the HoloLens using the TCH application has been compared to other construction checking tools. The first test was a length based comparison where the HoloLens (Tape) was found to have the highest average error of 87.7mm. The laser scanner was the most accurate construction checking tool with an average error of 2.9mm. These results were reinforced through spatial comparisons where the HoloLens, had the highest average error of 121.4 mm. The laser scanner was the most accurate with an average error of 9.4 mm.

When considering the time that the different tools took to test, the HoloLens was the most time-efficient construction checking tools. However, even with its desirable time efficiency, the HoloLens is not accurate enough to be a viable construction checking tool at its current level of accuracy.

Further developments of HoloLens software and hardware will propel this tool towards becoming a viable construction checking tool.

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COUPLING VIRTUAL REALITY AND PHYSIOLOGICAL MARKERS TO IMPROVE PUBLIC SPEAKING PERFORMANCE

Md Nazmus Sakib, Megha Yadav, Theodora Chaspari & Amir H. Behzadan
Texas A&M University, College Station, TX, USA

ABSTRACT: *Public speaking skills are key to effective exchange of ideas. At the same time, talking clearly and concisely while projecting confidence and knowledge can play a major role in one's academic and professional success. Despite this, public speaking anxiety (PSA) remains a top social phobia across many population groups. In this research, virtual reality treatment (VRT) coupled with physiological markers is used to alleviate PSA. Subjects of this study are recruited from diverse group of students, and completed three treatments, namely PRE, TEST, and POST. In PRE treatment, participants spoke in front of a live audience. The TEST treatment consisted of 8 successive public speaking sessions in immersive VR with various environmental settings and audience characteristics. Finally, in POST treatment, participants spoke again in front of a live audience, to test the effect of VRT in mitigating stress. This paper presents results and analysis with respect to how self-assessments, audience evaluation, and physiological markers correlate with the effectiveness of the VR stimuli. Statistical analysis shows significant reduction of values between PRE and POST treatments for several self-assessment measures, audience evaluation scores of stress, and physiological features, pointing to an improved public speaking performance in POST treatment as a results of exposure to VRT sessions. Findings of this study lay the foundation for future work in creating personalized, technology-mediated public speaking intervention system.*

KEYWORDS: *Virtual reality; physiological signals; public speaking; machine learning; anxiety.*

1. FEAR OF PUBLIC SPEAKING

Fear of public speaking (FOPS) is a common type of social phobia (Mannuzza et al., 1995) which can negatively affect one's performance in personal and professional settings, especially in situations where a person has to give a talk or present in front of a large and/or unfamiliar audience (Heuett et al., 1999). The resulting stress, if not handled properly, can lead to public speaking anxiety (PSA) in the long-term. According to the National Institute of Mental Health (NIMH), 73% of people are affected by PSA (NSAC, 2016). A study found that sustained FOPS was also associated with lower income, school dropout, and unemployment (Stein, M et al., 1996). Preliminary studies have explored several ways to elicit PSA, including showing pictures of social stimuli (e.g., faces) (Dimberg et al., 1986), instructing speech delivery to an imaginary audience (Schwerdtfeger, 2004; Erdmann and Baumann, 1996), or presenting in front of a small-size audience (Kirschbaum et al., 1995; Zuardi et al., 1999). With the advent of virtual interfaces and interactive computing tools, recent studies have explored the feasibility of virtual reality (VR) applications for studying and quantifying public speaking skills, performance, and anxiety (North et al., 2002; Pertaub et al., 2002; Anderson et al., 2005; Heuett and Heuett, 2011; Diemer et al., 2014). Research has shown that PSA can be treated via systematic exposure to public speaking encounters, which can potentially lead to the desensitization of threatening stimuli (Bodie, 2010). VR offers a potential remedy to achieving this through the immersive experience of presenting in various public speaking settings without the risk of public embarrassment (Riva, 1997; Heuett et al., 1999). VR environments differ from traditional displays in that computer graphics and various display and input technologies are integrated to give users a sense of presence or immersion in the virtual environment (Bryson, 1992; Draper et al., 2007; Sheridan, 1992) by enabling them to interact with synthetic worlds through sight, sound, and touch. Using immersive Virtual Reality Therapy (VRT) to simulate public speaking scenarios that are difficult to replicate in real life could be a promising solution to PSA (North et al., 2002; Anderson et al., 2005; Diemer et al., 2014). Research has shown that in a properly designed VRT session, subjects experience significantly high anxiety when exposed to negative VR audiences (Pertaub et al., 2001). It was also pointed out that experiencing multiple VRT sessions can help reduce PSA (Harris et al., 2003). This paper builds upon previous findings by examining the potential of VRT in alleviating FOPS and PSA, as quantified through measures such as self-assessment reports, physiological signals, and third-party evaluations.

2. EFFECT OF ANXIETY ON PHYSIOLOGICAL STATE

In this work, PSA is quantified using physiological signals. In addition to providing insights into current and imminent physiological state, this analysis helps find correlations between physiological state and the presence of high/low stress stimuli. Physiological data used in this research include electrocardiogram (ECG) activity, electrodermal activity (EDA), heart rate (HR) and heart rate variability (HRV), blood volume pulse (BVP), skin temperature, and body acceleration. Physiological markers such as HR and HRV are known to provide a multidimensional assessment of the human body (Kantor et al. 2001), and are used as common noninvasive tools for assessing the autonomic nervous system (Acharya U et al., 2004). Sustained mental stress has been found to impact HRV and increase the likelihood of cardiovascular diseases (Hjortskov et al., 2004; Thayer et al., 2010). Similarly, skin temperature fluctuations are associated with autonomic system activity, and are caused by changes in the flow of blood resulting from arterial blood pressure or vascular resistance. As such, skin temperature is treated as a good indicator of emotional state (Kim et al., 2004). With the availability of wireless EDA sensors (Poh et al., 2010), researchers increasingly utilize EDA signals to monitor arousal levels and changes in affective experiences during real-world interactions and tasks (Chellali and Hennig, 2013). EDA has been closely linked with emotional arousal (Dawson et al., 2000). Previous work has cited skin conductance level (SCL) and skin conductance response (SCR) as distinctive EDA features for detecting stress and cognitive load resulting from threatening stimuli (Fowles et al., 1981).

3. STUDY DESIGN AND DATA DESCRIPTION

A user study was designed to collect data in a series of public speaking presentations in front of both real and virtual audiences. As shown in Table 1, each participant attended three experimental treatments referred to as PRE, TEST, and POST, which were administered in a span of approximately three months. Each participant attended his/her scheduled PRE treatment first, and signed up for a day and time of their choice to attend the TEST and POST treatments several weeks later. Each PRE and POST treatment consisted of one public speaking session during which participants presented in front of a real audience. In contrast, the TEST treatment lasted two days and consisted of 8 public speaking sessions (four per day) in an immersive VR environment in front of different virtual audiences. Each participant was randomly assigned to 8 of 12 different VR settings (Table 2) similar to Figure 1. Each setting comprised a unique combination of environment type and audience characteristics. Background noise was added to each VR scenario to account for ambient sounds such as occasional whispers, papers moving, and items falling off a desk. For each presentation session, participants were given a 10-minute preparation time to read a randomly selected short article covering topics such as history, business, well-being and healthcare, entertainment and culture, science and technology, and travel and nature. This was followed by a 5-minute presentation to real (for PRE and POST treatments) or virtual (for TEST treatment) audiences. Before and after each presentation, participants completed several self-assessment reports, as summarized in Table 3. Wearable devices were used to collect physiological and speech signals before, during, and after all presentations. A total of 10,800 minutes of acoustic and physiological data were collected in 82 real life and 216 VR presentation sessions.

Table 1: Breakdown of the three experimental treatments.

Treatment	PRE	TEST	POST
Type of audience	Real	Virtual	Real
Number of sessions	1	8	1
Average presentation duration (min.)	4.50	4.08	4.24
Number of participants	55	38	29
Male/Female (%)	32/23	22/16	16/13

Table 2: Different combinations of the VR environment used during the TEST treatment.

Setting	Type of VR Environment	Audience Characteristics			
		Reaction	Size	Difficulty	% Female
1	Board Room	Neutral	12	2	50
2	Board Room	Positive	12	1	50
3	Board Room	Negative	12	6	50
4	Classroom	Neutral	25	2	50
5	Classroom	Positive	25	1	50
6	Classroom	Negative	25	6	50
7	Small Theater	Neutral	90	2	50
8	Seminar Room	Neutral	54	2	50
9	Seminar Room	Negative	54	6	50
10	Board Room	Neutral	12	2	30
11	Classroom	Neutral	25	2	30
12	Seminar Room	Neutral	54	2	30

Fig. 1: VR environments (from left to right): classroom, seminar room, small theater.

Table 3: Summary of self-assessment reports completed in each public speaking session.

Timing	Self-assessment	Purpose	Reference
Before presentation	State-Trait Anxiety Inventory (STAI)	General and communication-specific trait-based anxiety	Spielberger (2010)
	Communication Anxiety Inventory (CAI)		Booth-Butterfield and Gould (1986)
	Personal Report of Public Speaking Anxiety (PRPSA)		McCroskey (1970)
	Big Five Inventory (BFI)	Personality traits	John and Srivastava (1999)
	Brief Fear of Negative Evaluation (BFNE)	Feelings of apprehension about others' evaluation	Tavoli et al. (2009)
	Reticence Willingness to Communicate (RWTC)	Reluctance to communicate	Pörhölä (1997)
	Surveys of prior daily experiences and demographics	Caffeine/alcohol/drug intake, age, gender, ethnicity, degree, major	
After presentation	State-Scale of CAI and STAI, and the State-Anxiety Enthusiasm (SAE)	State-based anxiety related to preceding public speaking experience	
	Body Sensations Questionnaire (BSQ)	Body's response under stress	Chambless et al. (1984)
	Presentation Preparation Performance (PPP) survey	Degree of preparation and knowledge on presented topic	

The start and end times of each presentation in the physiological data was marked in two ways: 1) the experimenter marked down the start and end times; 2) two timestamps were added in the E4 device at the start and end of each presentation. These times were cross-checked and no significant difference was found. Signal processing methods were then used to extract bio-behavioral features from physiological data, and compare results with retrospective self-reported state-based PSA. Figure 2 shows a participant speaking to a virtual audience in a presentation simulator (i.e., "Virtual Orator") during TEST treatment. As shown in this Figure, each participant wore (i) an Empatica E4 wristband, which can capture EDA, BVP, body temperature and 3-axis acceleration at a sampling rate of 4, 64, 4 and 32 Hz, respectively (Empatica, 2019); (b) an Actiwave Cardio Monitor (CamNtech, 2019) worn on the chest with two electrodes, which is a single channel ECG recorder at a sampling rate of 512 Hz; and (c) a Creative lavalier microphone with a sampling rate of 16 Hz and 16-bit encoding resolution to record voice.

Fig. 2: Participant speaking to a virtual audience in an auditorium while wearing Actiwave (middle), Empatica E4 (right), and a Creative lavalier microphone.

4. METHODOLOGY

In this Section, data processing, feature extraction, and various individual and contextual factors that potentially contribute to PSA are discussed to investigate whether PSA can be identified using physiological markers, and if continuous exposure to VRT improves public speaking performance.

4.1 Data pre-processing and segmentation

Figure 3 shows user interfaces of E4 and Actiwave devices. The visual inspection of Empatica data provides preliminary insight about the data pattern before extracting features. For instance, in Figure 3(a), clear differences in physiological signal patterns across multiple signals associated with relaxation, preparation, and presentation can be observed. An outlier (i.e., upper and lower extremes) for EDA data is defined as signal samples with values larger than three times the standard deviation from the median considering an analysis window of 48 samples chosen by visual judgement of data patterns (Yadav et al., 2019). Outliers are replaced by interpolating the values of the neighboring signal samples. For ECG data such as the sample shown in Figure 3(b), low pass finite response filter (Papakonstantinou and Gritzali, 1981) with 45-sample length is used, followed by R-peak detection (Papakonstantinou and Gritzali, 1981; Papakonstantinou et al., 1986; Trahanias and Skordalakis, 1990) in BioSPPy toolbox (BioSPPy, 2018). Data segmentation was performed in Matlab and Python with the goal of identifying data for different segment (e.g., relaxation, preparation, and presentation).

4.2 Physiological marker extraction

A total of seven physiological markers are extracted from EDA, BVP, skin temperature, and body acceleration signals captured by the Emaptica E4 device. In particular, skin conductance level (SCL), skin conductance response (SCR) frequency, and mean amplitude of SCRs are extracted from EDA signal using Ledalab software (Benedek and Kaernbach, 2010). In addition, mean heart rate (HR) and inter-beat interval (IBI) are extracted from the BVP signal. Mean skin temperature and l2-norm of the 3-axis acceleration are also calculated. From the ECG signal collected by the Actiwave device, root mean square of successive differences (RMSSD) of R-R intervals, low-frequency (LF) and high-frequency (HF) energy of the ECG, and low-to-high frequency (LF:HF) ratio are extracted. The RMSSD (time-domain feature used to assess heart rate variability) and HF represent human's parasympathetic activity and contribute to self-regulation ability (Laborde et al., 2017). However, while LF and LF:HF ratio represent sympathetic activity (i.e., fight-or-flight reaction), it is not easy to delineate the physiological basis for LF:HF with certainty (Billman, 2013).

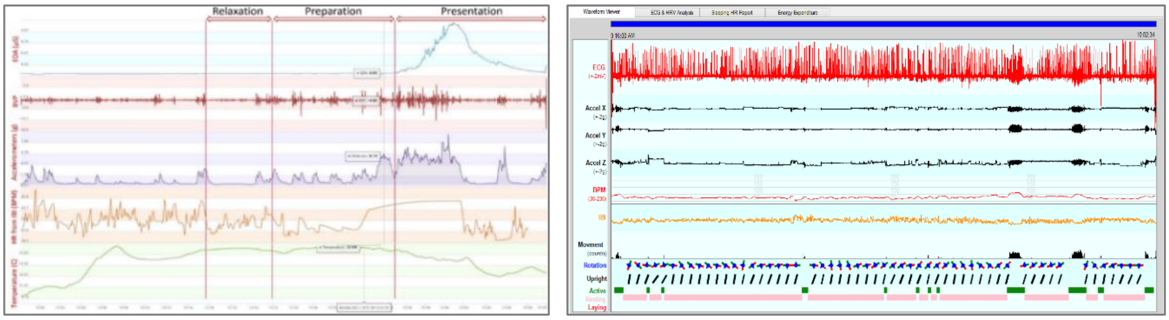

Fig. 3: Data collection interface for Empatica E4 (left), and Actiwave (right) wearable devices.

4.3 Public speaking performance estimation

4.3.1 Audience evaluation

In PRE and POST treatments, real audience observed and rated speaker's performance during presentation. The assessment form asked each audience member to rank the speaker's performance on a 5-point Likert scale of excellent (1: highest score), very good, good, fair, and poor (5: lowest score). During analysis, the average of all performance scores for all participants was calculated, and later used to segment participants into two groups of high performance (those with an average performance score of 1-3), and low performance (those with an average performance score >3). The form also included a separate question where audience members were asked to rate the stress level (not performance) of a speaker during presentation. Audience responses to this secondary question describing stress were used to determine if there was a correlation between performance and stress. Results of the Pearson's correlation test showed a significant correlation between the two (as rated by audience), with Pearson product-moment correlation coefficient (PPMCC) value of 0.869. Stress scores were found to have a strong negative relationship with performance, verifying that high/low stress results in low/high performance, justifying the use of stress (in lieu of missing performance scores) in statistical analyses described in Subsection 5.3.

4.3.2 Participant self-assessment

Statistical analyses between PRE and POST treatments considering participants' self-assessment scores were also conducted. These assessments include data captured by several of the instruments listed in Table 3, including STAI, CAI State, PRPSA, and SAE scores. Details of these analyses are presented in Subsection 5.2.

5. RESULTS AND DISCUSSION

In this Section, a visual comparison between low-/high-stress group in PRE treatment and low-/high-stress group in POST treatment is first presented in Subsection 5.1. This is further expanded in Subsection 5.2 to include a thorough statistical analysis of select features between low-/high-stress group in PRE treatment and low-/high-stress group in POST treatment. Finally, a statistical analysis of PRE and POST treatments (regardless of the distribution of low-/high-stress groups) is carried out in Subsection 5.3, and results will be discussed.

5.1 Visual comparison of low- and high- stress groups in PRE and POST treatments

Figure 4 shows box plots of the stress score (reported by audience), CAI State score (self-assessment), mean EDA, and mean HR that are used to gain more insight into the differences between low- and high- stress group in both PRE and POST treatments. To perform this analysis, the CAI State scores reported by participants are used to divide each of the PRE and POST treatments into two groups, namely low stress (lower than mean value) and high stress (higher than mean value). The number of participants in each group is as follows,

- PRE treatment (mean stress from CAI State = 46.13): 25 low stress, and 27 high stress
- POST treatment (mean stress from CAI State = 39.71): 13 low Stress, and 15 high stress

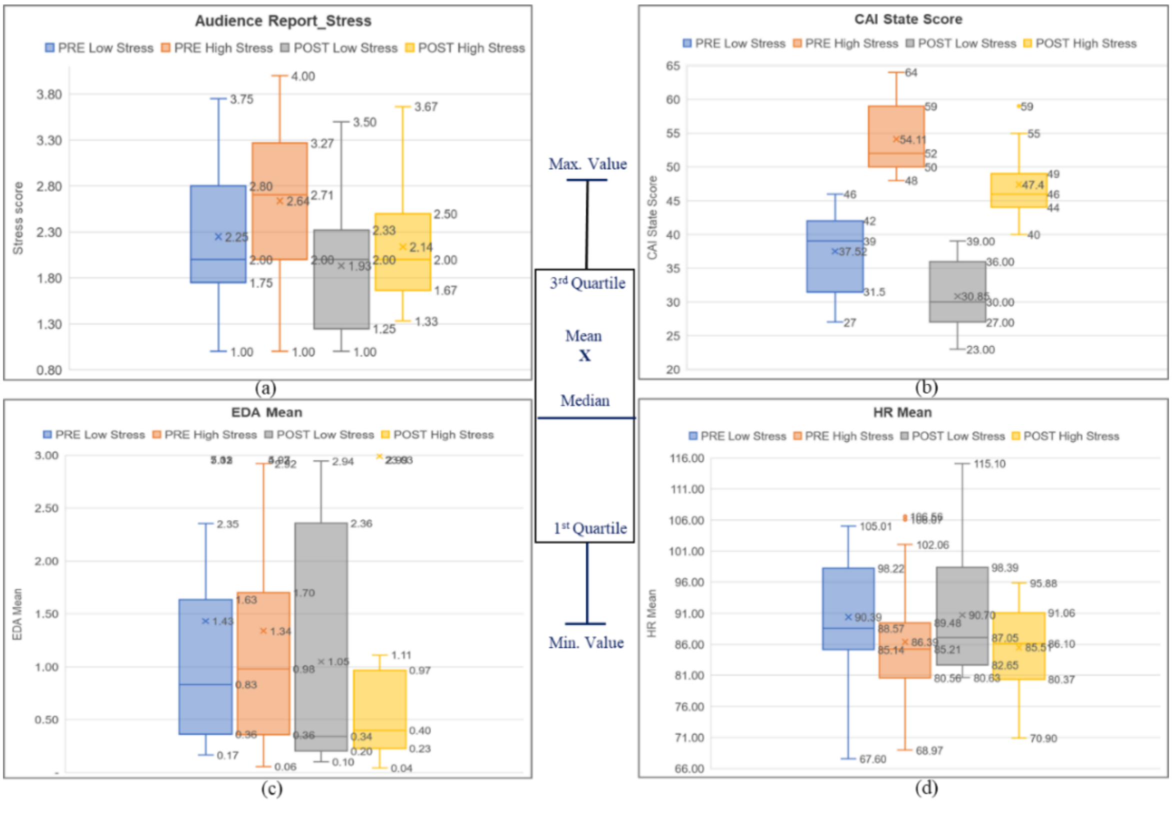

Fig. 4: Box plots of (a) audience report on stress, (b) CAI state self-report, (c) EDA Mean, and (d) HR Mean.

As shown in Figure 4, in most cases, median and mean values are lower in POST treatment compared to PRE treatment, suggesting improvement in participant's public speaking performance due to experiencing with VRT sessions. Specifically, the following observations can be made from Figure 4:

- Figure 4(a): the mean stress values in POST treatment (1.93 for low stress and 2.14 for high-stress groups) is lower than the mean stress values in PRE treatment (2.25 for low-stress and 2.64 for high-stress groups).
- Figure 4(b): the difference in mean CAI State scores between low- and high-stress groups in PRE treatment is 16.59, which is almost equal to the value obtained by comparing low- and high-stress groups in POST treatment, i.e., 16.55.
- Figure 4(c): While the mean EDA value is almost the same for low- and high-stress groups in PRE treatment, in POST treatment, the high-stress group has a mean EDA of only 0.34 compared to the mean

EDA of 1.05 for the low-stress group. Also, mean and median of both low- and high-stress groups in POST are lower than PRE.

- Figure 4(d): the mean HR for high-stress group in POST treatment is 85.5, which is lower than the mean HR of 86.39 for high-stress group in PRE treatment.

5.2 Evaluation of high- and low-stress levels in PRE and POST treatments

For participants belonging to low- and high-stress groups in PRE and POST treatments, t-test analyses of self-assessment, audience evaluation, and physiological markers are conducted. In each analysis, the low-stress (high-stress) group in PRE treatment is compared with the low-stress (high-stress) group in POST treatment. Also, in addition to splitting participants across the mean CAI State score (Subsection 5.1), other segmentation strategies are explored, as summarized in Table 4, to understand if choosing any particular CAI State score other than the mean would lead to statistical significance in any of the comparisons. Each segmentation strategy in Table 4 is described by a value (first column) that represents the percentage of participants that belong to the top and bottom of the list in each treatment, when participants are ranked in ascending order of CAI State score (i.e., from low to high stress). For example, when 20% segmentation is applied to ranked participants in the PRE treatment, 11 participants from the top/bottom of the list will be placed in the low-/high-stress groups, and the remaining 30 are discarded. Furthermore, to avoid splitting participants with same CAI State scores between top-middle or bottom-middle segments, split lines are shifted to include all such participants in top/bottom segments, resulting in a slight change in the number of participants placed in top/bottom segments (as evidenced by initial and final columns in Table 4). In any case, the number of participants in top and bottom segments is kept the same to run the t-test. It is also worth noting that the last row of Table 4 corresponds to 50% segmentation (i.e., based on mean values) of CAI State score, which was explained in Subsection 5.1.

Table 4: Participant segmentation into top-middle-bottom bins based on stress level.

%	PRE (52)		POST (28)	
	Initial	Final	Initial	Final
10	6-40-6	7-40-7	3-22-3	3-22-3
20	11-30-11	11-30-11	6-16-6	6-16-6
30	16-20-16	22-8-22	9-10-9	11-6-11
40	21-10-21	22-8-22	12-4-12	13-2-13
50	26-0-26	25-0-27	14-0-14	14-0-14

Table 5 summarizes the results of t-tests comparing low-/high-stress group in PRE treatment with low-/high-stress group in POST treatment. While these tests are initially performed on 17 features obtained from self-assessment, audience evaluation, and physiological markers, this Table only contains those that yield statistically significant results for majority of segmentation strategies.

Table 5: Significant features for low- and high-stress groups in PRE and POST treatments (**: p<0.01; *: p<0.05; †: p<0.1; ^{ns}: not significant).

Feature	Bottom-top	Low-stress (mean, SD)		$t(df)$	High Stress (mean, SD)		$t(df)$
	(%)	PRE	POST		PRE	POST	
CAI State Score	10%	(29.57, 1.81)	(24.00, 1.73)	$t(8)=1.86^{**}$	(60.57, 1.81)	(55.33, 3.51)	$t(8)=1.86^{**}$
	20%	(31.73, 3.50)	(26.00, 2.45)	$t(15)=1.75^{**}$	(59.27, 2.33)	(51.83, 4.45)	$t(15)=1.75^{**}$
	30%	(36.45, 5.49)	(27.89, 4.61)	$t(31)=1.70^{**}$	(55.41, 4.46)	(49.27, 4.31)	$t(31)=1.70^{**}$
	40%	(36.45, 5.49)	(30.17, 5.55)	$t(33)=1.69^{**}$	(55.41, 4.46)	(48.46, 4.41)	$t(33)=1.69^{**}$
	50%	(38.30, 5.92)	(31.50, 5.87)	$t(39)=1.70^{**}$	(54.11, 4.88)	(47.93, 4.68)	$t(39)=1.70^{**}$
Temperature	10%	(32.94, 0.88)	(32.93, 0.21)	$t(8)=1.86^{ns}$	(32.98, 1.85)	(31.24, 1.69)	$t(8)=1.86^{\dagger}$
	20%	(33.23, 0.88)	(31.26, 2.45)	$t(15)=1.75^{*}$	(32.85, 1.79)	(31.68, 1.42)	$t(15)=1.75^{\dagger}$
	30%	(33.13, 0.95)	(31.12, 2.35)	$t(31)=1.70^{**}$	(32.61, 1.85)	(31.64, 1.52)	$t(31)=1.70^{\dagger}$
	40%	(33.13, 0.95)	(31.70, 2.27)	$t(33)=1.69^{**}$	(32.61, 1.85)	(31.92, 1.69)	$t(33)=1.69^{ns}$
	50%	(33.07, 1.00)	(31.62, 2.19)	$t(39)=1.70^{**}$	(32.69, 1.70)	(31.87, 1.63)	$t(39)=1.70^{\dagger}$
EDA Freq	10%	(13.20, 4.42)	(8.90, 9.14)	$t(8)=1.86^{ns}$	(11.40, 3.39)	(0.32, 0.56)	$t(8)=1.86^{**}$
	20%	(12.22, 3.99)	(8.69, 7.74)	$t(15)=1.75^{ns}$	(11.54, 3.15)	(6.90, 7.77)	$t(15)=1.75^{*}$
	30%	(12.11, 4.69)	(8.08, 6.99)	$t(31)=1.70^{*}$	(12.32, 4.63)	(5.07, 7.14)	$t(31)=1.70^{**}$
	40%	(12.11, 4.69)	(7.84, 6.58)	$t(33)=1.69^{*}$	(12.32, 4.63)	(6.33, 7.28)	$t(33)=1.69^{**}$
	50%	(12.29, 4.56)	(8.00, 6.40)	$t(39)=1.70^{**}$	(12.67, 4.72)	(6.16, 7.03)	$t(39)=1.70^{**}$

From Table 5, it can be observed that for CAI State score, the low-stress group in PRE has a significantly larger value than the low-stress group in POST for all segmentations. Temperature and EDA frequency show similar trends. Also, comparison of high-stress groups in PRE and POST treatments shows significant larger values in PRE than POST. It can thus be concluded that with respect to these three features (i.e., CAI State score, temperature, and EDA frequency), for both low- and high-stress groups, participants in POST treatment exhibited better public speaking performance.

5.3 Comparison between PRE and POST treatments

The key difference in participants' experience between PRE and POST treatments is that between the time they participated in the PRE treatment, and when they participated in the POST treatment, they all had to attend a series of VR sessions in the TEST treatment. Therefore, the comparative analysis between PRE and POST treatments could help understand the effect of the VRT experience in improving public speaking performance. To perform this analysis, several paired t-tests are conducted to compare significant differences in self-reports, audience evaluation, and bio-behavioral measures between PRE and POST treatments. Data from 26 participants (who participated in all three treatments) are used in this step, and include PRPSA, CAI State score, SAE score, STAI score, audience evaluation of stress (in lieu of performance), SCR frequency, and skin temperature. Statistically significant results of t-tests are presented in Table 6, which show that PRE values are higher than POST values, suggesting an improvement after the TEST treatment. Also, since audience evaluation of stress has a negative correlation with participants' performance, observing lower values in POST implies a better performance. The self-assessment and physiological markers also have lower values in POST treatment, confirming this finding.

Table 6: Significant features for participants of both PRE and POST treatments (**: p<0.01; *: p<0.05).

Feature	Measure	All (mean, SD)		$t(df)$
		PRE	POST	
Self-assessment	PRPSA	(104.85, 21.31)	(92, 28.38)	$t(26)=1.71^{**}$
	CAI STATE	(46.26, 10.47)	(39.74, 10.04)	$t(26)=1.71^{**}$
	SAE Score	(55.67, 10.43)	(48.15, 10.06)	$t(26)=1.71^{**}$
	STAI Score	(36.48, 12.77)	(32.74, 12.50)	$t(26)=1.71^{*}$
Audience evaluation	Stress	(2.57, 0.9)	(2.01, 0.65)	$t(27)=1.70^{*}$
Bio-behavioral	SCR Frequency	(11.84, 4.03)	(6.85, 0.66)	$t(26)=1.71^{**}$
	Skin Temperature	(32.72, 1.71)	(31.81, 1.91)	$t(26)=1.71^{*}$

6. CONCLUSION AND FUTURE WORK

This paper examined the effect of VR treatment on alleviating PSA and improving public speaking performance, as evidenced by self-assessments (e.g., CAI, STAI), audience evaluation, and physiological markers (e.g., HR, HRV, EDA, skin temperature, acceleration). Empatica E4 and Actiwave wearable devices were used to collect physiological signals and corresponding markers were subsequently extracted. Leveraging these features in the analysis provided a better understanding of physical and mental state of participants during public speaking, while reducing the effect of cognitive bias in filling out self-assessments. Data was collected in three consecutive treatments, namely PRE, TEST, and POST, that spanned over approximately three months, each consisting of relaxation (baseline), preparation, and presentation sessions. In PRE treatment, participants spoke in front of a live audience. The TEST treatment consisted of 8 successive public speaking sessions in immersive VR with various environmental settings (e.g., large auditorium, small room) and audience characteristics (e.g., reaction, size, difficulty). Finally, in POST treatment, participants spoke again in front of a live audience, to test the effect of VRT in mitigating stress. To document and evaluate improvement in participant's public speaking, self-assessment reports and physiological data were collected before, during, and after each presentation session (in all three treatments, i.e., PRE, TEST, and POST), while audience evaluation was collected only during PRE and POST treatments. Statistical analysis revealed that several of the features (i.e., CAI State score, skin temperature, EDA frequency) extracted from data belonging to low-stress and high-stress groups in POST treatment were significantly lower than those in PRE treatment. Also, paired t-test performed on participants who attended all three treatments indicated some significant reduction of markers in POST treatment, including self-assessment (i.e., CAI State, SAE, PRPSA, and STAI scores), audience evaluation (i.e., stress) and physiological (i.e., SCR frequency, skin temperature). For instance, the mean of SCR frequency in POST treatment was 6.85, which was significantly lower ($t(26) = 1.71$, $p = 0.0007$) than the mean of SCR frequency in PRE treatment, calculated as 11.84. Similarly, the mean of CAI State score in POST treatment was 39.74, which was significantly lower ($t(26) = 1.71$, $p = 0.0001$) than the mean of CAI State score in PRE treatment, calculated as 46.26. Given that participants attended a series of VR sessions between the time they participated in the PRE treatment, and when they participated in the POST treatment, such statistically significant results point to improved public speaking performance as a result of exposure to VRT.

Research in human-computer interaction (HCI) indicates that the effectiveness of performance intervention systems is directly influenced by the extent to which computer-generated (i.e., synthesized) feedback matches human personality (especially for extrovert subjects) (Lee and Nass, 2003). To this end, this paper demonstrated that significant changes in physiological markers can be good indicators of stress and PSA which are related to human personality. As such, the ability to unobtrusively collect and assess physiological data is critical to the design of future intervention systems. Although the experimental setting and procedure described in this paper was intended for public speaking experiences, the designed framework for physiological data collection and assessment can be replicated in other scenarios including situations where humans interact with one another, or interface with technology. In addition, combining bio-behavioral features with performance data obtained from participants in a controlled VR environment can lead to new opportunities in training future workforce to adapt to and work in challenging environments. Future directions of this research include an investigation into the role of external factors (e.g., noise, temperature, habituation), as well as the development of personalized machine learning systems to predict PSA and generate in-the-moment feedback to alleviate stress and improve performance.

7. ACKNOWLEDGMENTS

This work has been supported by the Engineering Information Foundation (EiF) through grant 18.02. The authors would also like to thank Mr. Kexin Feng and Mr. Ehsanul Haque Nirjhar for providing assistance in portions of data preparation and analysis. All opinions, findings, conclusions, and recommendations expressed in this paper are solely of the authors and do not necessarily represent the views of the EiF or the individuals named above.

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POTENTIAL OF VR IN THE VOCATIONAL EDUCATION AND TRAINING OF CRAFTSMEN

Jan Spilski, Christoph Giehl, Sabine Schlittmeier, Thomas Lachmann
Center for Cognitive Science, University of Kaiserslautern

Jan-Phillipp Exner, Alina Makhkamova, Dirk Werth
AWSi-Insitute for digitized products and processes, Saarbruecken

Mareike Schmidt
Innovation Labs, imc AG, Saarbruecken

Martin Pietschmann
KomZet A&F, Rutesheim

ABSTRACT:
Virtual Reality (VR) will lead to a significant change in the way we teach and learn. VR is characterized by immersion, sensory feedback and interactivity. A recent meta-analysis (Merchant et al., 2014) showed that the use of VR (in a broader sense) in primary, secondary and higher education increases learning success, especially with short learning contents. However, Richards and Taylor (2015) found adverse effects of VR on students compared to a classical teaching condition. Generally, studies considering high-immersion VR environments such as those present when wearing VR glasses are relatively scarce (Makransky et al., 2019).
For the area of vocational education and training of craftsmen, there is hardly any knowledge on when and how VR can be used and how it is accepted at German vocational schools although the potential for VR technologies in these learning areas is great. Because the focus of vocational training of craftsmen is on transfer of action-oriented knowledge, VR can particularly support the education with its immersive interaction possibilities, especially in terms of action-oriented content.
In order to analyse the catalysts and barriers in the development and implementation of VR technologies in the educational process, we conducted a design-based research approach with several design loops. We used a mixed-method approach and included qualitative interviews, standardized cognitive tests, standardized questionnaires measuring demands, acceptance and self-efficacy, performance measurement, and assessment of usability of VR prototypes. A total of 55 craftsmen and prospective craftsmen (including 3 teachers) participated in three design loops until now. The results suggested to embed the VR environment into a blended learning context of a vocational training institution for construction workers (KomZet A&F) and the following adapted VR functionalities were implemented: an integrated multiple-choice questionnaire, a gaming approach and a sophisticated evaluation functionality with playback options and questionnaire result analysis.

KEYWORDS: *Virtual Reality; Vocational Education and Training; Craftsmen*

1 INTRODUCTION

In Germany, vocational education and training is mostly organized as a combination of school-based and workplace-based learning. This combination should close the gap between practical competence, action-oriented knowledge, and theoretical knowledge, in the best case, during education and training. Therefore, the paradigm of "Learning in the Process of Work" - Action Orientation (AO) is the paradigm of choice (Howe, 2005). Action orientation (Riedl, 2011), design (Rauner, 2013), and situational learning (Lave & Wenger, 1990; Cognition & Technology Group at Vanderbilt, 1993; Gerstenmaier & Mandl, 2001) also refer to the guiding text method (Nickolaus, Schumm & Pfister, 1990) and project work (Traube, 2012).

The heterogeneity of the learners is important for the design of educational processes in the construction industry. However, existing physical and digital learning content often follows a “one fits all” approach and does not consider the initial knowledge level of the individual learner. The aim of the present article is, therefore, to discuss the potential of digital learning tools to consider this heterogeneity. The challenge is to identify learning statuses for digital learning biographies, to find an appropriate approach to take the individual learning levels into account and to connect the physical and the virtual learning space.

Process orientation is considered the method of choice in the commercial-technical field (Howe & Knutzen, 2013). Lindemann (2013) describes process orientation as an instrument for internal differentiation in structural engineering training. Leisen shows how process orientation is achieved by breaking processes down into auxiliary tasks (Leisen, 2010). Virtual Reality (VR) could enable process-oriented and individualized learning. It may lead to a significant change in the way we teach and learn.

Virtual Reality Methods try to transform existing real situations into a computer-aided simulation and to transfer the data within this environment into a representation of reality, with the potential to manipulate it. The first concepts for VR were based on the concepts by Sutherland in 1965, who pointed out, that the (virtual) world should generally look real, sound real, feel real, and respond therefore realistically to the viewer's actions. In addition, Virtual Reality is not only the implementation of a graphic and an associated visual experience, but it allows also multisensory input (Streich, 2005). VR contains a digital space that is isolated from reality and the user can move through it. To simulate depth perception, common VR systems use a stereoscopic representation with a side-by-side display. By expanding the system to include motion-sensitive control elements, the virtual world receives an additional dynamic component, such as virtual interaction using a data glove. The definition of VR is often multi-layered in the scientific discourse, though it is often considered a technologically generated representation of a three-dimensional environment (Kavanagh et al., 2017).

In order to enable flexible learning and inclusive educational pathways within vocational education and training, technological advances in terms of mixed reality approaches with a special importance to VR can be taken into account. Sherman and Craig (2003) discussed four crucial aspects - virtual world, immersion, sensory feedback and interactivity - that are the reason why VR has such a big potential in the (virtual) learning context. The five main learning potentials of virtual learning environments (VLE) were pointed out by Dalgarno and Lee (2010):

- The three-dimensional environment allows to explore it from various perspectives in a dynamical and interactive way. Based on that, spatial knowledge in the explored domain can be developed.
- With the possibility to experience various real or unreal situations, a VLE can be the basis for experiential learning situations, which are (in reality) not accessible or too dangerous.
- The learner's engagement through VLEs could be increased because of the high level of personalization and the control over the environment, and high fidelity of the experience.
- VLE can be used to facilitate the transfer of knowledge because they correspond to the real world and provide credible sensory feedback. This could be attributed to the high authenticity of learning.
- The potential opportunities to serve as a communication and collaboration mean are a further aspect of the VLEs, because their support is much more effective as in 2D alternatives.

Indeed, in a meta-analysis Merchant et al. (2014) have shown that VR (in a broader sense) leads to an increase in learning success in primary, secondary and higher education, especially with short learning contents. However, Richards and Taylor (2015) found adverse effects of VR on students compared to a traditional teaching condition. Nevertheless, studies considering high-immersion VR environments such as those present when wearing VR glasses are relatively scarce (Makransky et al., 2019).

The present research focuses on the particular area of vocational education and training of craftsmen. There is hardly any knowledge when and how VR can be used and how it is accepted at German vocational schools although the potential for VR technologies in these learning areas is great. Because the focus of vocational training of craftsmen is on transfer of action-oriented knowledge, VR can particularly support the education with its new and immersive interaction possibilities, especially in terms of action-oriented content.
We present an empirical study that analyses when and how VR can generate added value in vocational training and when and how usability, acceptance and persistent implementation can be achieved. We used the design-based research approach based on collaboration among researchers and practitioners in real-world settings (DBRC, 2003; McKenney & Reeves, 2018). This approach is based on several design loops.

2 METHOD

2.1 Participants

All participants were selected by a vocational training institution for construction workers in Germany (Competence Center for Finishing and Facades, Komzet A&F, Rutesheim). In applying the design-based research approach, a total of 55 craftsmen and prospective craftsmen (including 3 teachers) participated in three design loops until now. In loops 1 and 2, a total of 37 prospective master craftsmen (3 female) were selected from a master preparation class of plasterers. For the third loop, we selected 15 trainees in plastering (second year of training) in order to make statements about a significantly larger target group. Mean age for participants from the target group of prospective masters was 27 years (range 21 to 39) and for trainees 22 years (range 17 to 34).

2.2 VR environment

The VR environment being developed in the project has the aim to involve the participants into a virtual site inspection which was implemented as a learning station inside of a bigger Learning Management System (LMS). The learning goal of the VR learning station is to better understand and to determine the actual state of a built structure, with prospective planning and identification of the scope of repairing and finishing works, as crucial part of the education for craftsmen, especially in construction and plasterwork.
The virtual environment was developed based on static 360-degree photos taken around a house from various perspectives. Participants can navigate between the perspectives with the aim to identify spots in the house exterior that are to repair. Multiple-choice items aimed to reflect on the essence of the identified issues and corresponding repair works were integrated directly into the environment (see Figure 1).

The VR environment also makes it possible to choose between different levels of difficulty and can be aligned to the defined competency levels based on the previous knowledge of the learners. This feature was introduced after design-loop 2 based on the feedback (more details will be given below). The measurements during the last iteration loops were taken, however, only in the medium level of difficulty, which was designed for approx. 25 minutes of gameplay. The used hardware varied between Oculus Rift, Go and Quest. The choice of these technologies was mainly because of affordability of the mentioned hardware and, consequently, their potential use within the educational setting. A basic distinction is the portability of head-mounted displays (Oculus Go and Quest are wireless), whereas Rift is wired to a PC, along with the quality of the image and positional tracking. This also allowed us to try out different settings for the integration into class. Whereas Go and Quest are very suitable for self-learning experiences, the use of the Rift coupled with a PC and additional screen allows the teacher to show the respective content from his VR world to the students, or also to follow the student being ready to help.

In order to support VR novices and to develop media competency, a tutorial was developed to facilitate the handling of VR within this application. The tutorial introduces the participants to the controllers and head-mounted display (see Figure 2). Based on quantitative and qualitative feedback from participants, the user interface of the VR environment has been developed iteratively.

Fig. 1 Gameplay and multiple-choice items integrated in the VR environment (green = question, orange = multiple-choice answers)

Fig. 2 VR controllers' tutorial

2.3 Learning Management System (LMS)

The LMS platform provides trainers and students a learning environment to work on the learning stations. It is designed as a responsive easy-to-use interface which allows users to access their material and exercises on different mobile devices (e.g., laptops, tablets or smartphones). Currently, VR content is embedded within the curriculum of a learning station as information with task descriptions and instructions how to use the VR application. Results of the VR can be manually transferred back to the LMS by trainers or students to document the learner progress. In parallel, we are working on a solution to obtain a deep integration of VR scenarios that allows to switch easily from the LMS to VR tasks and storing results back to the LMS automatically. Thus, progress of the students could be saved and mapped to their competencies in a fine-granular manner. Then all results of the learning station could be used in overall reports and statistics to support students in improving their skills. Additionally, a comprehensive collection of these data empowers trainers to adapt their lesson plans based on the strengths and weaknesses of their class.

2.4 Tests and Procedure

We used the design-based research approach based on collaboration among researchers and practitioners in real-world settings (DBRC, 2003; McKenney & Reeves, 2018). While conducting several design loops, we applied qualitative interviews, standardized cognitive tests (e.g., processing speed, working memory span), standardized questionnaires measuring demands, acceptance and self-efficacy, measurement of performance, and assessment of usability with prototypes. In this contribution we focus on the first three design loops and present the chosen methodology.

The participants were invited by the course instructor for each design loop and informed about the general conditions. In principle, participation was voluntary for each participant and could be stopped at any time without any disadvantages for the individual. Participants who did not want to take part in the exams could stay in the training workshop (which is also located in the competence center) and apply manual techniques under guidance. The studies were approved by the ethics committee of the University of Kaiserslautern.

2.4.1 Design loop 1 (cognitive and acceptance measurement)

Within design loop 1, cognition and acceptance measurements were performed in order to get the participants' individual baseline values (e.g., the individual processing speed, attitude towards learning and technique affinity). For the measurements, standardized scales and cognitive tests were used as far as possible. Questionnaires covered media literacy (e.g., Aufenanger, 2003; BMBF-Commission of Experts, 2010; Gapski, 2006), job-related learning transfer factors such as "learning-related self-esteem" (Schyns & Collani, 2014), "fear and uncertainty in learning" (Patzelt & Opitz, 2014) and attitudes to technology (Neyer et al., 2016).

Cognitive tests were used to record individual cognitive abilities in terms of personal characteristics. Those characteristics are mental speed measured by a number connection test (ZVT, see Oswald, 2016 or, for a digital version, Rodriguez et al., 2019), working memory span measured with the AOSPAN-test (see Unsworth et al., 2005), the (visual) attention measured with the Frankfurt Attention Inventory 2 (FAIR-2, Moosbrugger et al., 2011), and the visual-spatial imagination measured with a digital version of the 3DW-test (see Gittler 1990).

The results of this design loop were mirrored to the developers of the VR environment in order to enable the most accepted and user-friendly learning solutions.

2.4.2 Design loop 2 (qualitative survey, think aloud)

In this design loop, we tested the use of digital learning stations in the group as well as the VR environment in a setting of two participants in the training workshop (see Fig. 3).

A qualitative approach was chosen, and the first VR prototype was tested. In order to record general processes and teaching phases, a standardized observation protocol was used. In addition, think-aloud protocols were used to collect assessments of the participants during use.

Fig. 3. Design loop 2

2.4.3 Design loop 3 (Usability, UX, Attitudes towards VR)

In design loop 3, both the LMS and the VR environment were tested and evaluated. In this contribution, however, we focus on the VR, as already indicated. An example of the VR test setting is shown in Fig. 4. Standardized questionnaires were used, which included the following aspects:

Different dimensions of the subjectively perceived workload were measured with the NASA Task Load Index (NASA-TLX; Hart & Staveland, 1988). The NASA-TLX measures the subjectively perceived workload in six dimensions, namely mental demands, physical demands, temporal demands, (satisfaction with) performance, effort, and frustration. Different aspects of visual fatigue and eye strain were measured with the Visual Fatigue Questionnaire (VFQ, Bangor, 2000; adaption of the German translation by BAUA, 2016). Self-constructed items were given to evaluate the perceived usability of the VR and user experience (UX).

Fig. 4 Design loop 3

We also used the same scales as in design loop 1, such as "learning-related self-esteem" and "fear and uncertainty in learning". In addition, acceptance factors from the Technology Acceptance Model 3 (TAM 3, Venkatesh & Bala, 2008) were assessed, e.g. “Perceived fun while using VR", "Ease of use", "Perceived usefulness of VR" as well as the “intention to use VR”.

3 RESULTS

In our empirical studies we analyzed when and how VR can generate added value in vocational training and when and how usability, acceptance and persistent implementation can be achieved.

3.1.1 Design loop 1

Our sample of potential masters in the cognitive tests tended to show above-average performance (*M* = 0.31 to *M* = 0.77 standard deviations above norm values, depending on the test), however, there was a high heterogeneity of individual performances. For example, the mean z-value for mental speed was *M* = 0.77 (*Min* –1.7, *Max* 3), attention performance was *M* = 0.31 (*Min* –0.84, *Max* 1.65) and for concentration ability *M* = 0.37 (*Min* -0,74, *Max* 1.56). In terms of learning attitudes, the mean self-efficacy perception of respondents was *M* = 3.76, (scale of 1 to 5; *Min* 2.57, *Max* 4.29), while the feeling of fear and uncertainty of learning is relatively low with a mean of *M* = 2.53, (scale of 1 to 5; *Min* 1.67, *Max* 3.5).

The attitude toward technology that, according to the dimensioning of Neyer et al. (2016), can be differentiated into technology acceptance, technical competence conviction and technology control conviction, is also above the scale-midpoint. The acceptance of technology has an average of *M* = 3.36 (scale from 1 to 5; *Min* 1, *Max* 5) and measures the general interest in and use of new technologies. The technical competence conviction has a mean of *M* = 4.00 (*Min* 2, *Max* 4.75) and reflects the perception of the own competence in dealing with (new) technology. The technique-control conviction has a mean of *M* = 3.56 (*Min* 2.50, *Max* 5) and reflects the perception of one's own control over technology (Does the machine do what I want or am I helplessly exposed to technology?). There was also a high degree of heterogeneity in the sample for the attitude factors.

3.1.2 Design loop 2

As already reported in the methods section, a qualitative approach was used in design loop 2. In the following we present some statements by the participants, which give an impression of their experiences during the VR use and the subsequent evaluation of the VR solution. The results were then used to improve the VR prototype.

There were comparatively many positive statements about the VR prototype. Statements were, for instance e.g.:

> *“Made me curious and I liked it!“; “It's the future, very positive!“; "I like a lot of things!"; “It's like being right by the house”; “Do I really have to stop?”*
>
> *"Switching between self-learning and plenary can work. But technology is very important! “*

Many participants feel strongly immersed into the virtual reality. While they were sitting on chairs at the beginning of the training workshop, many participants unconsciously adapted their positions and movements to the virtual environment. Some examples:

> *"I didn't notice at all that I was lying on the chair like this"; "F_ _ _, I'm slipping off the chair"*

However, there were also critical remarks, for instance, regarding the technical language used or the competence of the trainers in dealing with VR.

> *“To the information: ... Who wrote this? That doesn't sound like a plasterer!”; “Wrong terminology!”*
>
> *“Will the instructors be abolished now?”; “You can handle it, but can our instructors handle it too?”*

Other observations regard the direction of gamification, in particular, that merely providing points as results was not enough:

> *“Feedback on my performance would be great, best in percent”; “Are there different levels?”*

Finally, we would like to list a statement made during the use of the VR that illustrates the current limitations of VR applications, as this technology has so far concentrated primarily on visual perception.

> *“I'd have to feel the wall here. So, I can't tell if there is anything. I mean whether it is cold or wet. Whether rough or smooth. Plaster is different. I must always feel.”*

3.1.3 Design loop 3

In design loop 3, the improved prototype of the VR environment was extensively evaluated. We used a quantitative evaluation approach, as already described.

Perceived workload: The results from the survey with the NASA-TLX on a scale of 0 (very low) to 20 (very high) indicate that the average level of physical demands was *M* = 5.0 (95% *C.I.*: 2.53, 7.47), of frustration-related demands *M* = 6.62 (95% *C.I.*: 3.92, 9.32), effort-related demands *M* = 6.62 (95% *C.I.*: 4.12, 9.12), of mental demands *M* = 12.37 (95% *C.I.*: 10.54, 14.20) and of performance-related (satisfaction with) performance *M* = 13.44 (95% *C.I.:* 11.16, 15.72); suggesting that physical-, frustration-, effort- and temporal-related demands were relatively low, whereas performance- and mental-related demands were slightly higher. Figure 5 illustrates the corresponding mean values.

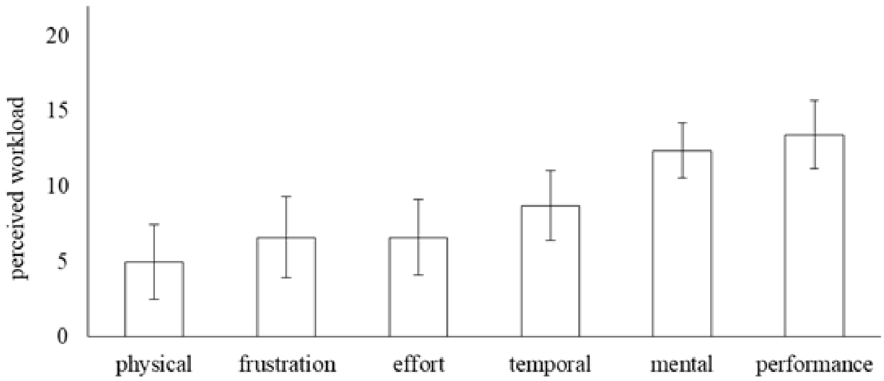

Fig. 5 Mean values of the load assessments. Whiskers = 95% confidence intervals of the mean values.

Discomfort after use (visual fatigue and eye strain): There were no abnormalities after using the VR solution across all 17 items. This means that our VR solution can be used in education and training by a large number of learners without physical discomfort. The mean values were between *M* = 1.97 (95% *C.I.*: 1.30, 2.58) for "difficulties to see clearly" and *M* = 1.27 (95% *C.I.*: 0.88, 1.66) for "mental fatigue" (scale 1 “refuse completely” to 5 “fully agree”).

Fear and uncertainty in learning with the VR learning environment: The participants rarely felt fear and uncertainty in learning with the VR learning environment, which was reflected in averages that were always below the value of 3 ("sometimes") on a scale of 1 = " never" to 5 = "always".

Usability Ratings were made on a rating scale of 1 “refuse completely” to 5 “fully agree”. Table 1 lists the descriptive statistics for 10 items. Most of the assessments of the VR solution were very positive (values greater than 4). Whether moving the head to see the tasks completely is really a shortcoming ("I had to keep moving my head in order to see the tasks completely", *M* = 3.82; 95% *C.I.*: 1.58, 3.12) is determined in loop 4.

Table 1: Descriptive Statistics Usability

	Min to Max	*M*	*95% C.I.*	
I could see the tasks clearly and distinctly	3 to 5	4,18	3,78	4,58
The VR glasses responded quickly to my input	3 to 5	4,63	4,23	5,03
The VR glasses immediately recognized my gestures (e.g., head movements)	2 to 5	4,35	3,93	4,77
I trusted the information in the VR glasses, e.g. in the introductory texts	3 to 5	4,19	3,82	4,56
I got along well with the control of the VR glasses	3 to 5	4,47	4,16	4,78
I got along well with the way the tasks were presented in the VR glasses	3 to 5	4,24	3,91	4,57
I always knew what to do to get ahead in the VR station.	2 to 5	4,24	3,76	4,72
At the beginning I would have needed more practice to operate the VR glasses	1 to 5	2,88	2,26	3,50
I had to keep moving my head in order to see the tasks completely	1 to 5	3,82	3,19	4,45
I sometimes had the feeling that the VR glasses no longer reacted	1 to 5	2,35	1,58	3,12

Note. M = Mean, 95% C.I.: 95% confidence interval of the mean

Acceptance factors from Technology Acceptance Model 3 (TAM 3, Venkatesh & Bala, 2008) were assessed with three items per factor. The results from the survey with the TAM factors on a scale of 1 “refuse completely” to 5 “fully agree” indicate that the average level of “*Perceived fun*” were *M* = 4.56 (95% *C.I.*: 4.15, 4.96), “*Ease of use*” were *M* = 4.21 (95% *C.I.*: 3.83, 4.58), “*Perceived usefulness*” *M* = 4.09 (95% *C.I.*: 3.68, 4.50), and “*Intention to use”* were *M* = 4.34 (95% *C.I.:* 3.93, 4.76).

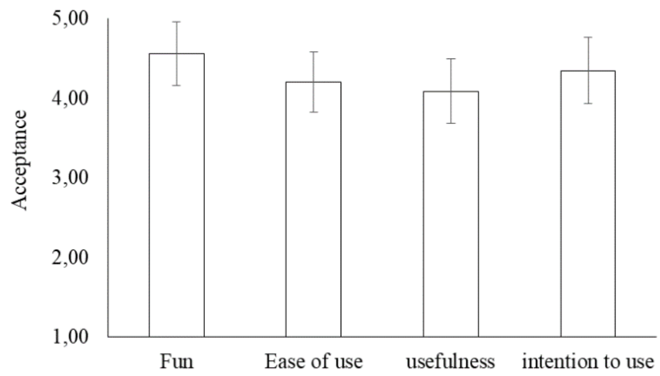

Fig 6. Mean values of TAM 3 acceptance factors. Whiskers = 95% confidence intervals of the mean values.

4 DISCUSSION AND CONCLUSION

The present research analyses potential of digital learning technologies to improve the vocational education and training for craftsmen. Our sample contained 55 craftsmen and prospective craftsmen. Based on collaboration among researchers and practitioners in real-world settings, we applied a design-based research approach (DBRC, 2003; McKenney & Reeves, 2018). We argued that considering the heterogeneity of learners is important for the design of educational training tools in the construction industry; however, existing tool often follow a “one fits all” approach.

In the first research design loop of the design-based research approach, we indeed found great heterogeneity among learners in terms of, for example, their individual processing speed, attitude towards learning and techniques affinity. We argued that digital learning technologies have the potential to take these heterogeneities into account. For this reason, we have implemented a VR solution. The three-dimensional VR environment with its interactive and immersive characteristics seems to be particularly able to consider different starting levels of building craftsmen, to give them the possibility for a deep experience and understanding of the learning content while focusing on action-oriented and authentic learning processes. In research design loop 2, this VR solution was qualitatively evaluated and, while taking the evaluations and experiences of the learners and teachers into account, iteratively improved. Here, we relied on a qualitative approach that gives us spontaneous, authentic and unstandardized reactions from the learners. In research design loop 3, we tested further experiences with the VR technology, such as perceived workload, discomforts, fears and uncertainty as well as usability ratings.

In sum, the results suggest that VR applications have the potential to be included into curricula of craftsmen, and, more importantly, to be accepted by learners and teachers as a learning media and content. This application has the potential to be integrated into the classroom and even used remotely, with or without a head-mounted display. We also included learning analytics reports in form of view- and selection-heatmaps with the option to replay the run with the aim to evaluate own performance and identify weak spots and moments of uncertainties and disorientations.

The gained experience will not only help the students while their craftsmen education. It may also sensitize them in the long run as future business owners in the construction sector in terms of which potentials technologies can have for daily business. This embraces potentials for virtual site inspections as well as methods for inhouse training, to name a few applications. The gathered results indicate a great potential in this context.

There were some rare moments of motion sickness and inconveniences occurring for some learners while they were wearing the head-mounted displays. However, we expect those to gradually decrease because of the improvement of resolution, latency and wearing comfort of the glasses. With increasing media literacy, uncertainties in the use in digital vocational training will disappear. However, we recommend to constantly consider how different present technologies and methods (e.g., also AR, MR) could be integrated into the learning concepts in order to achieve the most adequate environment for both learners and teachers.

5 ACKNOWLEDGEMENTS

This study is part of the D-MasterGuide research project. The study was funded by the German Federal Ministry of Education and Research (Bundesministeriums für Bildung und Forschung, BMBF), # 01PZ16010.

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PEDAGOGICAL TRANSFORMATION IN BUILDING STRUCTURES' CLASSROOM: IMMERSING STUDENTS INTO A VIRTUAL WORLD FOR IN-DEPTH UNDERSTANDING OF STEEL CONNECTIONS

Amna Salman
McWhorter School of Building Science, Auburn University, Auburn, AL, USA

ABSTRACT: *Virtual Reality (VR) is a three-dimensional, computer-generated environment which can be explored and interacted with by a person wearing a VR headset. That person becomes part of the virtual world or is immersed within the environment, while being at his/her home/classroom/office etc. VR is being integrated in many ways in various architecture/construction schools and industries around the world. One can create virtual objects and step inside to see, hear, touch, and modify them. Currently, at McWhorter School of Building Science, Auburn University, 2D drawings and/or field trips are used to teach students about design complexities in steel structures especially various types of steel connections. Teaching through field trips has been very effective as students learn more when they see the objects in reality. However, it is not always feasible to take a large class to field trips due to time, safety, and cost constraints. Creating 3D VR models and immersing students in the virtual world could provide an engaging and meaningful experience to both Building Science and Architecture students. This research study focuses on creating different 3D VR enabled steel connection models and testing them using a VR headset called Oculus Go. Having this concept in mind, the project has three goals: 1) Creating a VR model of a steel sculpture showing different steel connections; 2) Deploying the VR model in BSCI 3440: Structures of Building-II course; and 3) Evaluating the efficacy of the VR model through students' feedback. Though the full study is expected to finish in late October 2019, the paper will discuss the development phase of the VR App and preliminary results. The full results will be shared with the conference attendees in the presentation. It is hoped that this study will be valuable to instructors teaching building structures courses to Civil Engineering, Architecture, and Building Science students.*

KEYWORDS: *VIRTUAL REALITY, CONSTRUCTION EDUCATION, FLIPPING CLASSROOM, PEDAGOGICAL CHANGES, STEEL STRUCTURES*

1. INTRODUCTION

Structures of Building I and II are two core courses taught to architecture and building science students at the McWhorter School of Building Science, Auburn University, USA. In Structures of Building-I, we teach forces, different kinds of loads, strength of materials etc, whereas in Structures of Building-II, we teach the design of steel, timber, and concrete members. In order to design members in steel, timber or concrete, it is important to fully understand shear and moment forces, their critical application points, and the connections provided to resist these forces. It has been observed by the author that students have great difficulty understanding and visualizing the structural connections. The ability to visualize the built environment and learn the building construction processes is critical for students in the architecture and building science disciplines. For students lacking field experience, visualizing the construction processes and thus making informed decisions is difficult (Nikolic et.al, 2011).

The aim of the practical application of the Virtual Reality (VR) models, presented in this paper, is to provide support to building science and architecture students particularly in understanding onsite steel connections in a classroom-based education. The topic of steel connections was chosen to start with because of its inherent complexity. In a steel building, connections play an important role in the integrity of a structure, and many structural failures are attributed to connection failures (Moaveni and Chou, 2015). The recent failures of I-35W Bridge in Minneapolis in 2007 was due to the connection failure. In the past, many schools in the USA have used a steel sculpture model for explaining connections. A steel sculpture is a physical system that shows different types of connections found in standard construction practices as shown in Figure 1. However, not all architecture and building science programs have the steel sculpture. Those schools which have the steel sculpture are unable to bring it in class due to its size and weight (eight feet tall, weighs nearly 2500 pounds and usually erected outdoor) (Moaveni and Chou, 2015). Creating 3D VR models and immersing students in that virtual world could provide an engaging and meaningful experience to both building science and architecture students. For this reason, through McWhorter Fund for Excellence award, we have created an interactive VR Oculus Go app, the "Steel Sculpture

App" to teach steel connections. We started off by making a sketch up model of the steel sculpture and shortlisted the connections we wanted to teach. We made seven different modules representing seven different connections. When this visualization tool was being designed human perceptual and cognitive capabilities were taken into account. NASA TLX test was applied to measure the workload of the app. The NASA Task Load Index (TLX) is a popular technique for measuring subjective mental workload. It relies on following six subscales: mental demand, physical demand, temporal demand, performance, effort, and frustration level (science.gov). Moreover, the Steel Sculpture App created, is a self-explanatory interactive app which is also designed to cater people who have hearing impairment. In addition, to allow student's better understanding of the steel construction process, videos of the various assembly and erection processes are included in the final product. This VR app allows students to see modules repeatedly, by pausing or exiting at any time. This interaction allowed by three-dimensional (3D) geometric models could also bring an end to passive leaners' attitude, which are often found in traditional academic teaching situations (Sampaio et.al, 2010). This paper presents the steps and challenges in the development phase of the steel sculpture prototype and creating the Steel Sculpture App. The app will soon be available free of charge to all educational institutions to use in their curriculum.

Figure 1: Steel Sculpture erected outside of McWhorter School of Building Science

2. LITERATURE REVIEW

Teaching steel structures and connections to building science and architecture students is particularly challenging because of its spatial configuration. It is hard for them to comprehend from the 2D drawings and photos. Site visits, while valuable, are difficult to implement extensively due to limitations of time, cost, safety, and availability. Moreover, while planning for the site visit to teach steel connections, it is important that the framing of the building is visible. This adds to the difficulty of selecting a productive site visit. Visualization skill acquisition is an important aspect of engineering education. Along with math and science disciplines, engineering instruction has been identified as a discipline in which students have the most difficulty visualizing and understanding complex and abstract information. The importance of visualization skills in construction engineering education stems from the inherently spatial nature of construction projects (Nikolic et.al, 2011). Construction education requires the development of various skills to contribute efficiently in the professional field. VR and Augmented Reality (AR) technologies have proven beneficial in various disciplines. Technologies that add to the learning environment have gained popularity and have become the subject of even further studies.

At present many construction schools are establishing VR/AR laboratory for research and education purposes: The Faculty of Electrical Engineering of the Czech Technical University in Prague established a Virtual Reality Laboratory (VR Lab) to serve both for research and education. It supports teaching and research by carrying out projects funded by commercial organizations. VR Lab contains equipment for experiments in virtual and augmented reality as well as tests of advanced rendering and interaction techniques. In particular, it has at disposal a stereoscopic projection wall, a tracking system, and two types of augmented reality setups. The members of computer graphics group conduct active research in the field of real-time and realistic rendering (global illumination, visibility computations), advanced data structures for computer graphics, and also in the field of content creation and 3D reconstruction for images and video (Berka et.al. 2011).

Many researchers and scholars are working on developing modules for construction education and industry. Azhar (2017) research introduces some case studies that show effectiveness of Virtual Reality in the construction industry. The researcher argued that the traditional safety planning relies heavily on manual observations. The case studies proved that the safety planning using Virtual Reality is more effective than the traditional safety training (Azhar et.al, 2017). Dawood et al. (2014) aims to utilize 4D enabled games for construction safety based on some created scenarios. The main purpose of the research was to demonstrate effectiveness of the 4D game for trainees to prevent hazards on the job site.(Dawood et.al, 2014).

San Diego State University (SDSU) has started a Virtual, Immersive, Teaching, and Learning (VITaL) program, which provides a variety of VR, AR, and mixed reality (MR) immersive tools for use across the pedagogical spectrum. The VITaL program has served as an incubator to enable experiences that would otherwise be out of reach in a traditional learning environment. This program has resulted in increased student understanding, knowledge, skills and motivation (Huaze, et. al, 2019).

Another study by Sampaio et.al. (2014) created two VR models related to activity of bridge construction. One model presented the cantilever method of bridge deck construction and the other model presented the incremental launching method of bridge deck construction, both frequently used construction techniques. They developed interactive applications which made it possible to show the physical evolution of the construction work, the monitoring of the planned construction sequence, and the visualization of details of the form of every component of each construction. The introduction of these VR techniques resulted in better student understanding.

The literature review shows that many schools are using VR tools in different forms to aid both instructors and students. VR technology provides an opportunity to students to visualize the concept they are learning in the classroom. Creating VR models provides a very positive contribution towards improving pedagogy and student understanding of spatial configuration of construction processes.

3. RESEARCH METHODOLOGY

After a thorough literature review on VR applications in construction education, a framework was developed to create some modules to teach steel connections to building science and architecture students. We initiated the project by creating a sketch up model of a steel sculpture. Although, McWhorter School of Building Science has a model of steel sculpture outside its building (Figure 1) but due to time limitations, instructors often fail to take the class to the model location and, instead, teach using 2D drawings and pictures. The creation of interactive VR app will help students to visualize and learn steel connections in a 3D environment. In order to create this educational app several steps were involved. Below is a step-by-step explanation of the app development process.

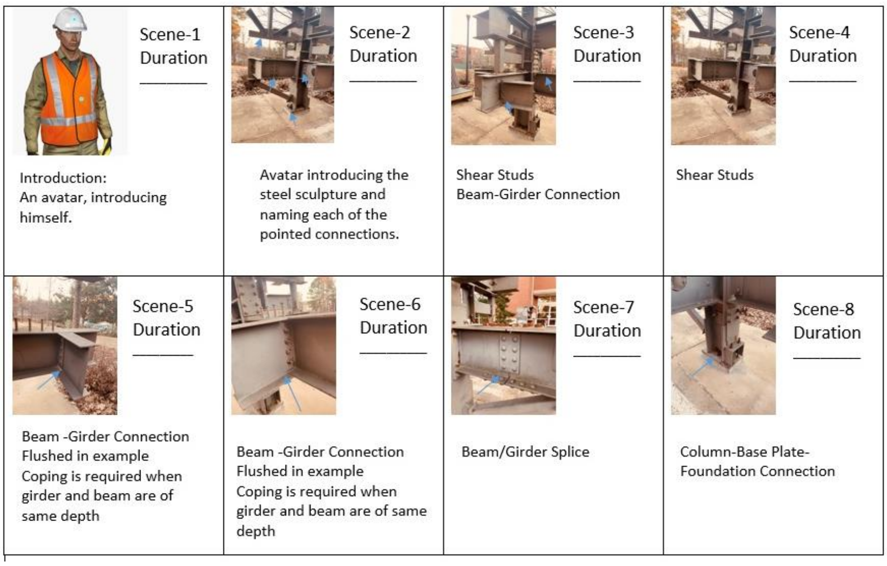


Figure 2: The Steel Sculpture App Story Board

3.1 Story Board

Several story boards were created to initiate the project and develop the related scenes (Figure 2). To develop the storyboard, we shortlisted seven basic connections from the steel sculpture. Each VR module explains a specific connection, where it is used and provides a field example. The app starts by explaining the steel sculpture, a menu bar then appears and user can select the modules one by one and learn about them.

3.2 Creating Oculus Go App

There were several steps in creating the "Steel Sculpture App" for Oculus Go. It was made sure that the contents presented are easy to comprehend. The steps involved in the app development are explained below:

3.2.1 Creating a 3D Model of the Steel Sculpture

We started off by creating 3D model of the steel sculpture in Sketch-up using 3D Warehouse (Figure 3) tools. Once the model was completed, it was converted into an .fbx file.

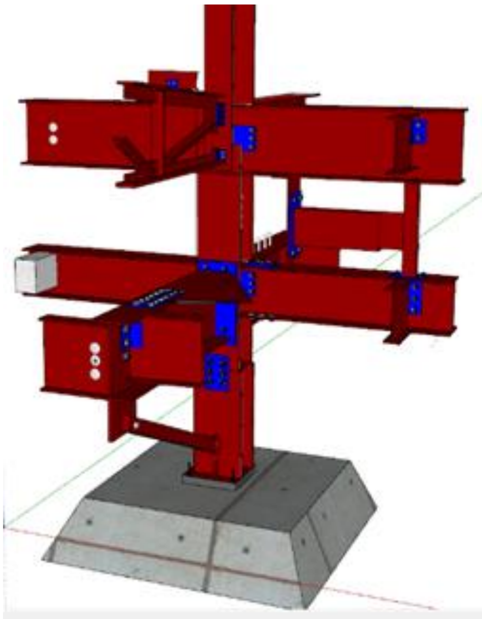


Figure 3: Sketch-up Model of Steel Sculpture

3.2.2 Importing the Sketch-up Model into Unity and Creation of Animation

The .fbx file was imported to Unity engine to create the animation. Unity asset store was used to create the surrounding elements. Voice maker program was used to add the voice which explained the modules in Unity. The placement, speed, and movement of cameras were designed very carefully.

3.2.3 Transfer of Animation from Unity to Oculus-Go

Once the animation was completed it was transferred to Oculus Go in the developer mode. Several changes were made to improve visibility and sound. After these changes, the icon logo and a short summary of the App were created.

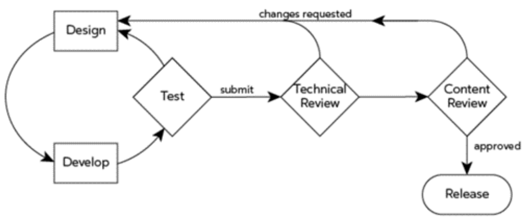


Figure 4: App Lifecycle for Oculus Go (oculus.com)

3.2.4 App Testing

Once the Steel Sculpture App was ready, it was tested in the Release Channel of Oculus Go. Release channels allows distribution of early versions of the built app to limited audiences for testing. One can invite different groups of people to different channels for testing (oculus.com).

3.2.5 Publishing the App

Once the Steel Sculpture App was tested in the release channel with a small group of audience, it was sent to the Oculus publisher. In Oculus, apps goes through design, development, and testing phases in order to be published. A detail evaluation of content and app performance is evaluated before it is released to the public for download. Figure 4 demonstrates the typical app lifecycle whereas Figure 5 summarizes the whole app development process.

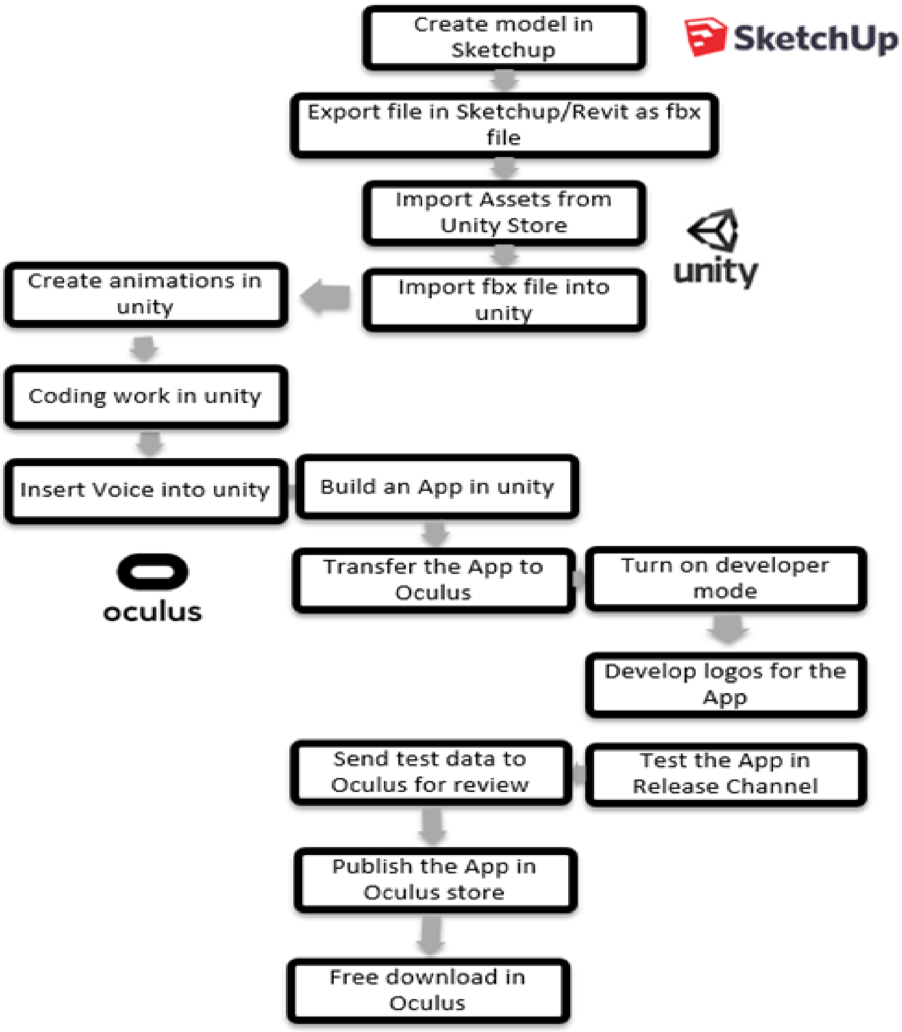


Figure 5: Steps Involved in Development of App

4. STEEL SCULPTURE APP AND CONTENT PRESENTATION

The app starts off with a welcome note and inquires if you want to keep the subtitles. Subtitles were included for people with hearing impairment. It then gives an introduction of the steel sculpture and goes around it, so one can look at it closely from different angles. This part can also be skipped and one can go directly to the connections. The selection menu helps select any connection to learn about its details. Figure 6 shows some screenshots of the app.

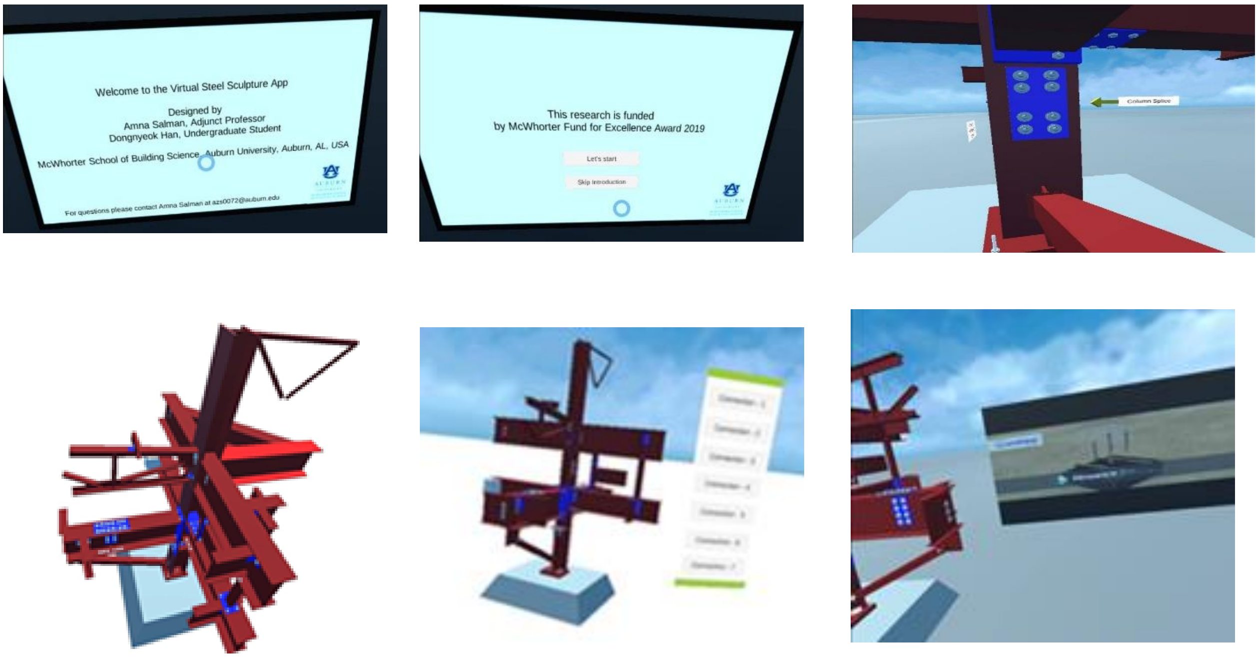
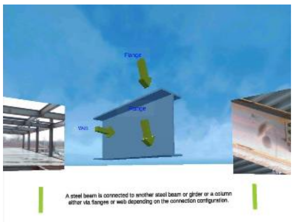
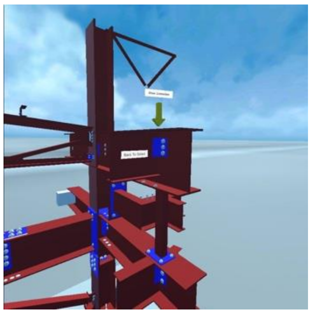
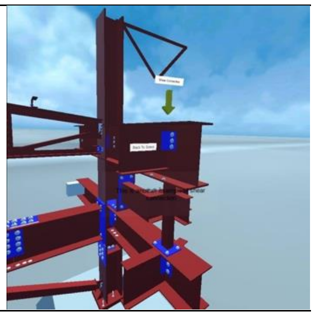
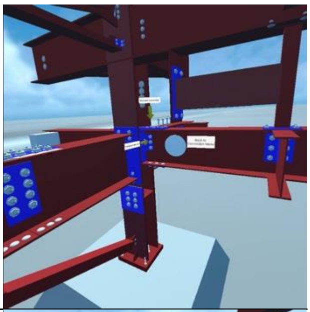
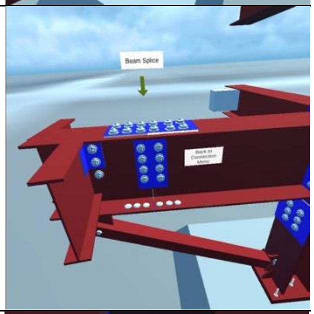
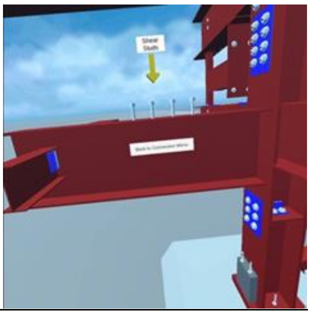


Figure 6: Images from the Steel Structure App

There are seven different modules in the app explaining a unique connection. As one click the connection number it takes him/her closer to that particular connection and teaches in detail about it. A brief description of connections in the app are given in Table 1.

Table 1: Modules and its Educational Benefits with Scenes/Images

Module	Connection	Educational Benefit	Scenes on Oculus Go
	W-section Beam	Students learn about W-section beam and its parts along with some field example on the right and left. Students have the option of including or excluding the subtitles. This pictures includes the subtitles.	
1.	Shear Tab	Once students go through the introduction, they can select different connections. In connection-1, student learn about shear tabs, where to use it and when to use it.	
2.	Shear Connection	The app talks to the students and tells them about the shear connection. It says, "The type of connection which joins only the web of the beam, but not flanges, to the column or girder is known as a shear connection. It does not transmit any bending moment from one member to another".	

3.	Moment Connection	The app tells the listener about moment connection and says, "Moment connections are designed to transfer bending moment and shear forces. The design strength and stiffness of a moment connection can be rigid or semi-rigid depending on the stiffness of the connected members".	
4.	Beam Splice	Students learn about beam splices. The app explains, "It is often required to divide structural members along their length due to their lengths, transportation challenges and erection constraints. Such joints are called splices".	
5.	Column Splice	The explains about column splice, "It is often required to divide structural members along their length due to their lengths, transportation challenges and erection constraints. Such joints are called splices".	
6.	Shear Studs	Shear studs are designed to effectively tie concrete slab to the steel beam. They also resist shear loading between the slab and beam in composite construction.	
7.	Column-Foundation Connection	Student learns about the construction of steel column and baseplate. The app also shows a short video of steel column erection.	

5. EVALUATION FRAMEWORK

In order to determine the benefits and limitations of the VR app, 15 students were chosen for a pilot study. These students were all architecture students enrolled in BSCI 3440: Structures of Building-II in summer 2019-. They were in their junior year. These students had learnt about the properties of steel in the earlier class. The instructor spent 20 minutes explaining the use of Oculus Go and how to interact with the app. Students learnt about the steel connections through the Oculus Go app. After a short break, students were given a survey to collect feedback about the workload of the app. Some informal interviews were also conducted to understand its benefits and limitations.

5.1 Evaluation Results

The main focus of the study was to examine if the transformation to VR driven educational tools is beneficial to improve student understanding and knowledge retention. For this purpose, we first tested the cognitive workload of the app using the NASA TLX questionnaire. The questionnaire covers six criteria (1) Mental Demand, how much mental activity was required in the VR App. Was the app easy or demanding, simple or complex? (2) Physical Demand, how much physical activity was required in the learning process? (3) Temporal Demand, how much pressure did you feel during due to the pace of the app? (4) Performance, how successful were you learning the VR connections (5) Effort, how hard did you have to work? (6) Frustration, how irritated, stressed, and annoyed versus content, relaxed, and complacent did you feel during the task (nasa.gov). They had to choose on the scale of 1 to 10 where 1 was least demanding and 10 was most demanding. Table 2 shows the average of the student responses:

Table 2: Average of Student Response

	Mean	Comments
Mental Demand	4.46	Satisfied
Physical Demand	2.46	Highly Satisfied
Temporal Demand	3.86	Satisfied
Performance	4.50	Satisfied
Effort	4.01	Satisfied
Frustration	4.00	Satisfied

The student response from the NASA TLX test was overall satisfactory. The average of all the criteria's was below 5 out of 10, which was reasonable. The workload encountered was mostly mental and we needed to achieve whether the content presented is at a pace which can be easily understood. The higher averages of Mental Demand and Performance was due to environment of the app being fuzzy and motion sickness from Oculus Go. We will work on the environment of the app, however, the motion sickness is a lot reduced in Oculus Quest. We plan to get more data in future semesters especially with building science students. Some informal feedback was also taken from the students concerning the app use, visibility, and learning of the subject matter. Students agreed that the virtual content had sufficient content to learn about steel connections. Most students agreed on creating more educational tools in VR because they can see the image closely and through different angles. This was a pilot study through which we wanted to measure workability of the Steel Sculpture App. Preliminary results do confirm that this app could be used to assist educators in teaching steel connections. We have made another questionnaire which will measure the effectiveness of the app, whether such VR apps could replace field trips or not? We also plan to create a quiz which will measure the learning assessment of the students after watching the app. These evaluations will be conducted in the coming weeks and full results will be shared with the conference participants in the paper presentation.

6. DISCUSSION AND CONCLUSIONS

The main purpose of creating the Steel Sculpture App was to provide an additional tool to students which they can use at any time and learn at their own pace. The paper presented the development phase of the Steel Sculpture App designed for teaching steel connections to building science and architecture students. We made seven different modules representing seven different connections. All the programming and voice over was done in the Unity engine. The launch of the app has to go through series of content and technical review sessions. However, we were able to share the app with limited audience and completed a pilot study. Students viewed the Steel Sculpture App in Oculus Go. It was important to ensure that students were able to retrieve accurate and appropriate information to learn about the desired connections. In this respect, there was a need to balance the complexity of the material presented to get the desired learning outcome. To determine and measure the workload of the app, NASA TLX test was used. The initial findings suggest that the app could be used to assist instructors and students in teaching the steel connections and content is presented at a pace that students can easily comprehend.

Further development of this work is suggested to incorporate similar connection details for concrete and timber. The VR technology can be used for the elaboration of teaching material for increased student interest, knowledge retention, and conceptual clarity. Developing such powerful interactive design and visualization applications can help student understanding, especially in the design phase of any structural systems. However, a significant time commitment and technical expertise are required for development of any similar app. At the same time, the continuous advancement in VR software's is making the app development process more effective and efficient.

The Steel Sculpture App will soon be published for Oculus Go and Oculus Quest. Instructors will be able to download it from the Oculus Store. The next step is to create similar VR app for Apple and Android phones for students to download and view it directly from their smartphones.

Acknowledgement

This research was funded by McWhorter Fund for Excellence Award 2018. I would like to appreciate the College of Architecture, Design, and Construction, Auburn University, USA for providing this funding opportunity to develop innovative teaching content.

I would also like to gratefully acknowledge Mr. Dongnyeok Han, an undergraduate student of Building Science who substantially assisted in the creation of the app.

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STRATEGIES AND LESSONS LEARNED TO CREATE VIRTUAL REALITY IMMERSIVE GAMES FOR CONSTRUCTION SAFETY TRAINING

Dongnyeok Han
McWhorter School of Building Science, Auburn University, Auburn, Alabama, USA

Swarnali Ghosh Dastider
Robert R. Taylor School of Architecture and Construction Science, Tuskegee University, Tuskegee, Alabama, USA

Salman Azhar & Amna Salman
McWhorter School of Building Science, Auburn University, Auburn, Alabama, USA

ABSTRACT: *This paper aims to demonstrate the strategies, lessons learned, and the decision-making process in creating three Virtual Reality (VR) games to aid in construction safety education and training. The presented research is a direct result of an earlier pilot study conducted to measure the effectiveness of VR technology for teaching Construction Safety to undergraduate students. The study concluded that immersive VR technology has a huge potential as an alternative teaching pedagogy for construction safety and similar courses that requires hands-on training. The most significant advantage is real-life experience without exposing the students to the dangers of a jobsite. The earlier pilot study also recognized the need to develop customized VR construction safety content; therefore, the current research study focuses on this goal. For this study, a team of researchers from Auburn and Tuskegee Universities collaborated to identify the most needed areas based on the feedback collected from two regional construction companies. A conceptual framework for design efficiency, execution, and method of delivery was laid out to improve pedagogical and participation experience of students. Three different topics, namely confined space safety, scaffolding safety and jobsite clean-up safety were chosen as initial platform to test the strategies. Unity gaming engine was used as the developing platform and VR modules were created for Oculus Go head mounted display. The team found that the gaming modules less than 10-minute long are most effective to address the selected topics. Each module contained demonstration of the hazards and mitigation methods based on the OSHA standards. At this stage, the three gaming modules are complete and tested by a group of undergraduate and graduate students enrolled at the Building Science Program of Auburn University and few construction professionals. A questionnaire survey was used to collect feedback and related assessment data. The team will continue to collect additional data until the end of October 2019 and share with the conference participants during the paper presentation.*

KEYWORDS: *Virtual Reality, Gaming, Construction Safety, Education and Training, Head Mounted Display*

1. INTRODUCTION

This paper is a continuation of an earlier research study completed at Tuskegee University to investigate the application of Virtual Reality (VR) based games for teaching construction safety to Generation Z (GenZ) students (Dastider, 2019). As part of this research, the students enrolled in the Construction Safety class at Tuskegee University were first exposed to the traditional 2D teaching aids, demonstrating construction hazards, and then to few commercially available Virtual Reality games. Their responses were recorded through written reports and oral interviews followed by a survey incorporating comparative analysis between 2D visual aids and VR technologies. The results indicated that the GenZ students greatly welcomed VR Construction Safety exercises over the traditional 2D visual aids and were interested in exploring more. The research concluded that VR technologies have huge potential as an alternative teaching methodology for GenZ students because they can provide the real life experience similar to jobsite visit without the potential liability that may arise on a construction site. However, the paper also noted that, one major challenge with implementing VR in a classroom is lack of customized construction safety related VR content. In order to create customize VR construction safety content the team reached out to several developers; however it became quickly evident that commercial developers are too expensive for pedagogical modules development. Therefore, the authors of this paper decided to join forces together to create customized construction safety VR modules, more suitable for teaching and current construction industry needs.

2. SAFETY TRAINING USING VIRTUAL REALITY (VR)

It is a well-known fact that inadequate safety training in the construction industry may lead to fatalities or injuries on a jobsite. Research has shown that absence of proactive and preventive measures like workforce training, risk source identification and control, safety awareness and education have considerable influence in controlling risk and safety on site (Vitharana *et al*., 2015). Given all these facts, teaching construction safety remains a great challenge, both at the university and industry levels. Several research studies conducted in this regard indicate that Virtual Reality (VR) could provide an alternative with better efficacy (Azhar, 2017). VR allows spontaneous interaction to users within a virtual environment thus providing a real life experience (Fernandes *et al*., 2006). Education through VR also results in improved efficiency as users are learning by doing and they can develop an emotional reaction to almost real environment, which may help retain more knowledge when compared to the 2D media like textbooks and slides. Moreover, VR contents may also be more effective to foreign workers due to its emphasis on visual learning experiences.

3. RESEARCH AIM

The goal of this research is to create interactive safety training VR modules that could enhance Occupational Safety and Health Administration (OSHA) training for the construction students and workers. The research objectives are as follows: (1) Investigating and identifying the most needed safety education topics which will benefit from an immersive learning environment; (2) Creation of three construction safety training VR modules based on OSHA rules and regulations; and (3) Testing the VR safety modules for time management and learning effectiveness by conducting a questionnaire survey.

4. LITERATURE STUDY

To begin with, the research team focused on a thorough literature study with variety of topics related to safety and safety education in the construction industry. Most influential papers that have shaped this research are mentioned in this section. A study by Azhar (2017) examined several case studies to show effectiveness of VR in the construction industry. The researcher argued that the traditional safety planning relies heavily on manual observations. The case studies point out that safety planning using VR is more effective than the traditional safety planning. Another paper by Dawood *et al.* (2014) aimed to utilize 4D enabled games for construction safety based on multiple scenarios. The main purpose of the research is to investigate effectiveness of 4D games for training about construction safety hazards management at the jobsites. A paper by Fernandes *et al.* (2006) outlines the current barriers in adoption of VR technology in the UK public sector construction. Using a three-phase factor analysis approach, the researchers argue that a champion in the company, top management interest, internal needs along with competition, and resources have great influence on the VR adoption. A scholarly book by Hinze (1997) also supports the positive influences of visualization on construction education. Another related research done by Wang *et al.* (2018) investigated the influence of engaging and immersive environments on construction engineering education and training in recent years. The researchers acknowledged the positive influence of VR technology on education and training programs to improve the participants' performance.

Sacks *et al.* (2013) investigated the feasibility and effectiveness of construction workers' ability to identify and assess safety risks using VR. Sixty-six subjects were provided training in construction safety and their safety knowledge was tested prior to the training, immediately afterward, and one month later. The research subjects were divided between traditional classroom training with visual aids and 3D immersive VR power-wall. Their findings indicated significant advantage when using VR training for stone cladding work and for cast-in-situ concrete work, but not for general site safety. VR training was more effective in terms of maintaining trainees' attention and concentration. Their researched also emphasized that VR safety training was more effective over time, especially in the context of cast-in-situ concrete works and strongly recommended. Zhao and Lucas (2014) reviewed the gap between the VR status and industry expectations on construction safety. Their work demonstrated the development and application of a training VR simulation program where users can experiment with electrical tasks and hazards and ultimately accrued cognition and intervention related to electrical safety in a safe environment. They mentioned that the visualization and simulation features could also help to remove the training barriers caused by of invisibility and dangerousness of tasks.

Rita (2018) discussed the advancement of technology for construction safety and especially how VR technologies have become affordable over the past years. She reviewed the popular VR games around the globe and the costs and benefits of VR technology in the construction industry. Her work focused on real-life applications of the VR tools in Hong Kong for safety training. Xie *et al.* (2006) used a VR safety training system to assess the perceptual and behavior impacts of the VR environments on a user to investigate its effectiveness. The investigations found that a streamlined, scenario-developing pipeline is important to support flexible, computer-generated variations of the VR world. The research team created a reconfigurable and reusable system of 3-dimensional virtual images of various virtual objects and virtual environmental factors including temperature, air composition, and visibility. They tested the developed VR training in multiple testing environments and found it significantly effective as compared to the traditional training systems.

Though the review of the published literature shows significant effort in developing and testing VR technology for construction safety education and training, however most of the developed VR systems are prototypes and not readily available to other users for continuous use in the academia and industry. The thrust of our research is to develop easy-to-use VR construction safety training apps based on OSHA standards that are available free of cost to any user.

5. RESEARCH METHODOLOGY

This research study was completed in three parts. The team started with interviewing the regional construction firms, followed by creation of three VR safety modules, and development of a survey to collect the necessary feedback for improvement. It was a known fact that the commercially available VR safety games are predominantly related to Fall Protection, and there is hardly anything available for other OSHA's critical safety categories. Moreover, most of the available games fall short to provide the reactive real life decision-making experience. Driven by these factors; the research team decided to focus on the underdeveloped arears to better serve the purpose.

The research was initiated by contacting and interviewing two regional construction companies (Doster Construction and Holder Construction LLC) followed by brainstorming sessions amongst the involved parties to identify the most needed arears for VR safety modules. These sessions resulted in three focus areas namely Confined Space Safety, Scaffolding and Ladder Safety, and Jobsite Clean-up Safety. The team then formulate the scene-by-scene sequence for the three VR gaming modules. The cross-platform gaming engine Unity was selected for development of the VR gaming modules. Unity was a natural choice given that it can create three-dimensional VR environments, as well as simulations and other interactive experiences (Samuel, 2016; Dean 2018). It is also a popular choice for game developers in the Architecture, Engineering and Construction (AEC) industries. The following systematic method was followed to create the VR gaming modules (see Figure 1):

1. A storyboard for each module was created during brainstorming sessions of the team members.
2. Based on the storyboards, multiple 3D construction models were created in Sketchup/Revit 3D.
3. Sketchup and Revit 3D models were exported as .fbx files.
4. The .fbx files were imported into the Unity software program for preparing the simulations.
5. Associated assets (e.g. PPEs) were imported from the Unity Asset Store.
6. Animations, characters and major equipment were created within the Unity engine.
7. Essential voice was inserted in VR modules by using voice maker program.
8. Necessary coding was done in Unity to create the interactive digital environments.
9. Three VR Apps were created and transferred to the Oculus Apps store.
10. Test data was sent to the Oculus team for review and approval so that these apps are available to the public.

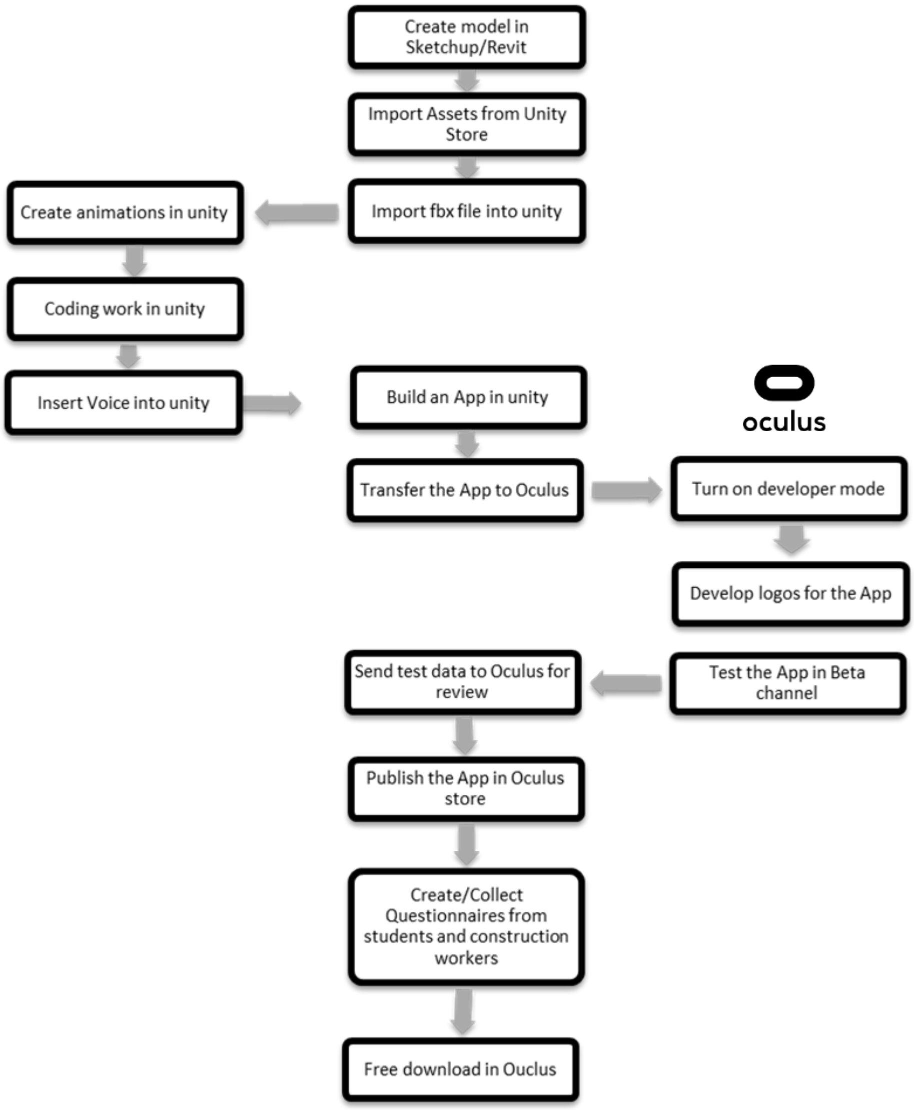

Fig. 1: Construction safety VR gaming modules workflow

6. DESCRIPTION OF THE VR GAMING MODULES

6.1 Module 1: Confined Space Training

Confined space inspection game provides an imaginary environment such as walking inside an underground utility tunnel to inspect the damage to the electrical lines post a heavy rain. This VR game consists of two steps; first one is selection of the appropriate Personal Protective Equipment (PPEs) followed by hazards identification inside the confined space. The first step starts inside a locker room where the user is prompted to select the appropriate PPEs from the given choices. The PPEs selection includes LED hardhat safety helmet, rubber insulating liner gloves, full body harness with lifeline and appropriate footwear. Figure 2 shows the first step of the confined space VR module.

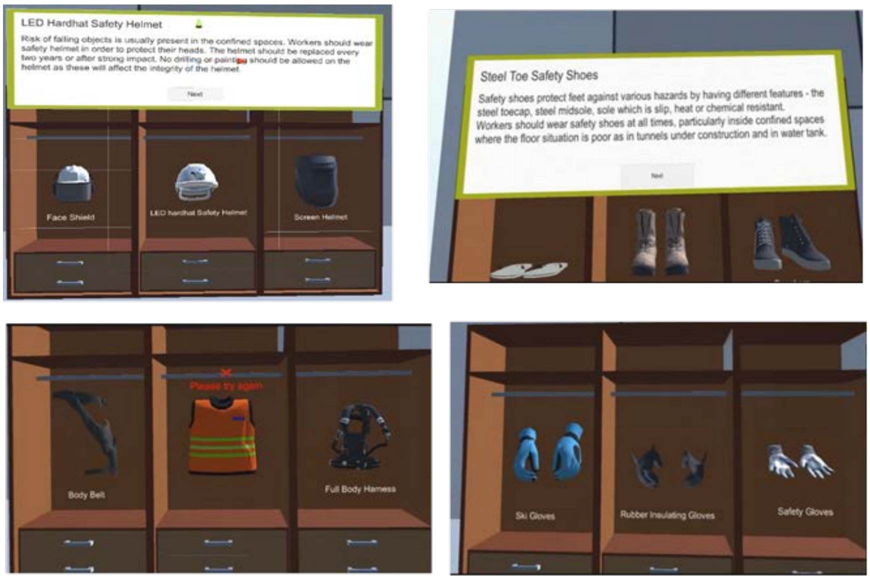

Fig. 2: Confined Space Training VR game: Selection of appropriate Personal Protective Equipment (PPEs)

The second phase of the game is initiated after successful selection of PPEs, which leads to the confined space work area. Inside this water-damaged tunnel, the user needs to identify six (6) carefully designed hazards that could be fatal for the oblivious worker. These six hazards are smoke hazard, chemical hazard, electrical hazard, struck by hazard, slippery fall hazard, and free fall hazard. The VR game also indicates the acceptable oxygen level by OSHA standards inside the confined space. Figure 3 shows few images from the simulated confined space.

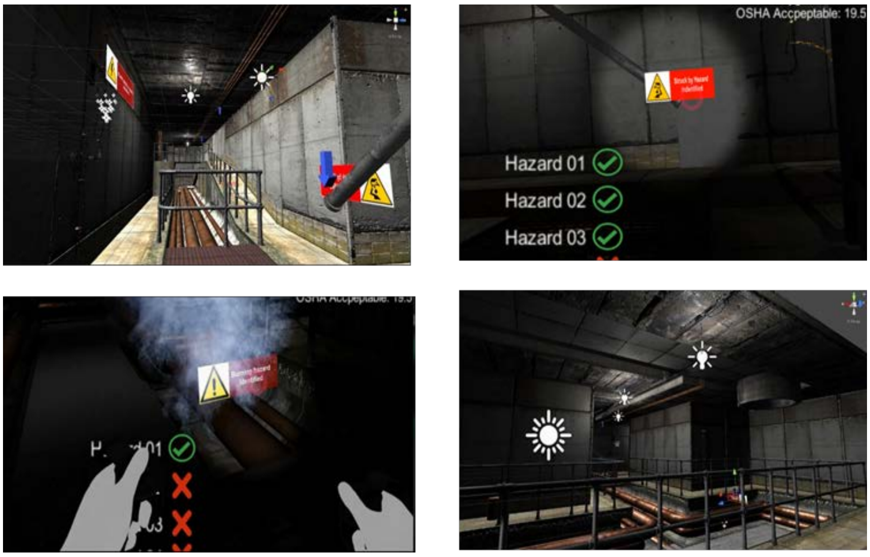

Fig. 3: Confined Space Training VR game: Simulated hazards in the confined area (tunnel)

6.2 Module 2: Scaffolding and Ladder Safety Training

According to Rubio-Romero *et al.* (2013), about 40% of serious construction jobsite injuries are caused by falls from height, and about 30% of these incidents are related to falls from temporary structures such as scaffolding used to work at heights. Thus, hazards associated with unsafe scaffolding remain as most frequently cited in the construction industry. It is a challenge to teach scaffolding safety to a little-to-no experience worker/student using mere PowerPoint slides and/or videos. The research team addressed this issue in this VR module, Scaffolding and Ladder Safety Training.

Similar to confined space, this module also starts with a description of the proper PPEs needed for installation of windows on a three-story building that requires working at a height more than 6 feet. The game continues on to identify seven (7) safety observations based on the OSHA standards. These safety observations include a detail description of how to install scaffolding, its support system, height restrictions, and guardrail and fall arrest system. The games ends with a short quiz to better reinforce the knowledge gained. Figure 4 shows some scenes from the Scaffolding and Ladder Safety Training VR game.

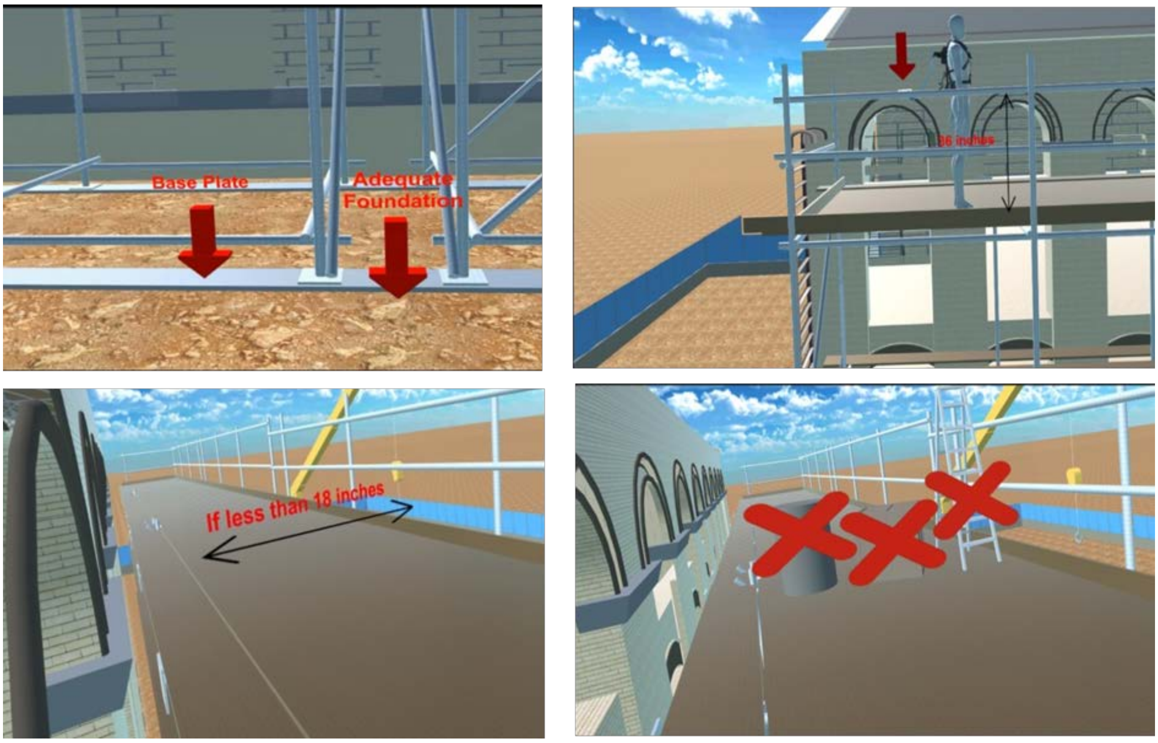

Fig. 4: Scaffolding and Ladder Safety Training VR game: Selected screenshots depicting hazards/standards

6.3 Module 3: Jobsite Cleanup Safety Training

Construction jobsite cleanup is a very important task that is often overlooked. This deficiency prompted the research team to create a VR gaming module to bring focus to this area by demonstrating proper handling and disposal of construction debris. The module begins on a jobsite cluttered with scrap plastic/metal pieces, paints, and other hazardous substances that could lead to tripping, fall, or other hazards. The goal of this module is to train a worker/student on how to dispose or recycle the construction waste using appropriate disposal methods.

In the VR game, users must pick up all unused material such as light bulbs, paint, scrape metal and lumber, and dispose them into the right recycling bin provided adjacent to the site. This module further reinforces the experience of the user using a short quiz. Figure 5 shows some scenes from the Jobsite Cleanup VR game.

Fig. 5: Jobsite Cleanup Safety Training VR game: Selected screenshots depicting various hazards

6.4 Challenges Encountered

During the VR gaming modules development process, the research team encountered several challenges that indeed helped to shape up this research. Some important lessons learned are as follows:

- Length of a module is very important to keep the user engaged and alert. A 5-7 minutes duration is found to be most appropriate. Anything above 10 minutes results in user disengagement.
- Motion sickness is a big concern in the VR games. The research team paid special attention to the speed and change of environment to make it easier on the users.
- The VR modules were enhanced with both audio and visual aids to create a more realistic experience.
- The research team also learned about the quality control challenge during transfer of the Unity VR modules from a tethering Head mounted device (such as Oculus Rift) to a standalone head mounted device (Oculus Go). Although there was no loss of computation power, a moderate visual/screen resolution quality loss was noted.

7. SURVEY RESULTS

After completing the three modules, the research team tested their effectiveness for construction safety education/training through a questionnaire survey. As of now, 25 undergraduate and graduate students enrolled in the Building Science program at Auburn University and 5 VDC experts from a regional construction company have tested the modules. Overall, the users' feedback about the learning experience is very positive. The team will continue to test these modules by engaging more students and industry professionals. The preliminary findings of the survey are shown in this section (Figures 6-10) whereas complete survey results will be shared with the CONVR2019 participants during the paper presentation.

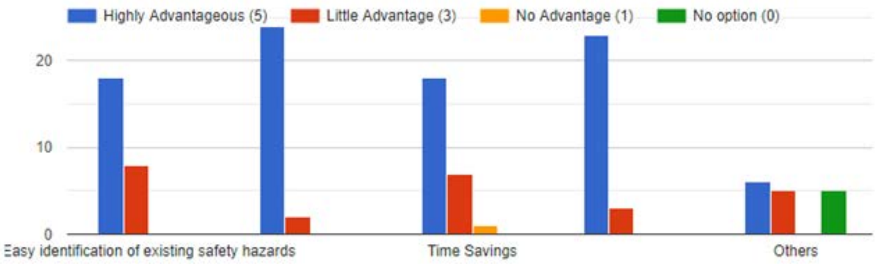

Fig. 6: Is a VR safety training system advantageous as compared to the traditional safety training systems?

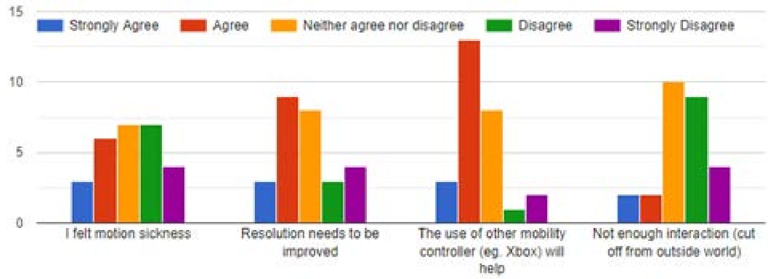

Fig. 7: Issues associated with a VR safety training system

The users' feedback about each of the VR gaming modules is as follows:

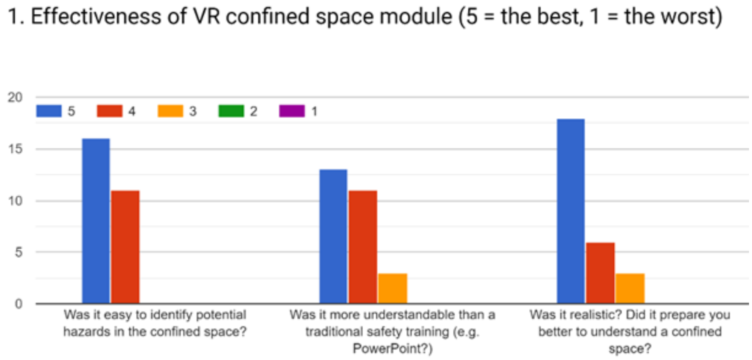

Fig. 8: Users' feedback about effectiveness of the Confined Space training module

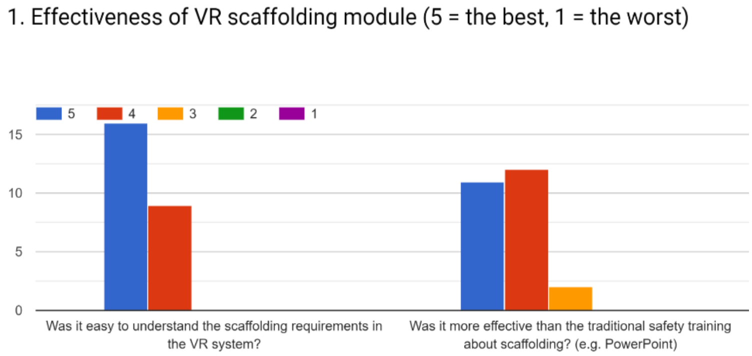

Fig. 9: Users' feedback about effectiveness of the Scaffolding and Ladder training module

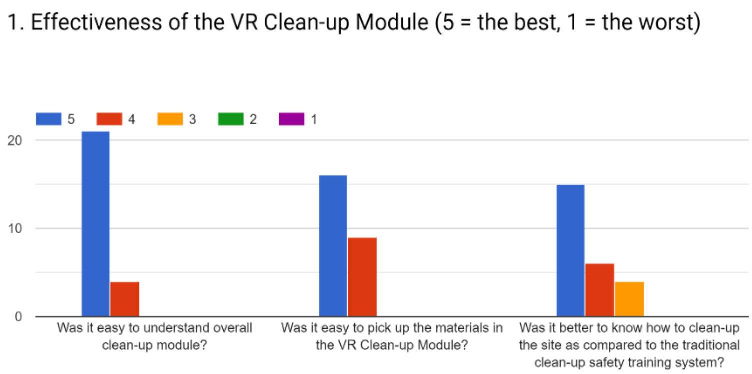

Fig. 10: Users' feedback about effectiveness of the Jobsite Cleanup training module

8. FINAL THOUGHTS

The research team is continuing to collect data for the developed VR modules. So far, the users have specified positive learning experiences. They found the VR based learning for construction hazards as being more realistic and effective than the traditional methods. This is a good indicator of improved pedagogical approach to teach construction safety in an innovative way. However, the team does recognize that a more in-depth investigation is needed to push adoption of these modules in the academic curricula as well as OSHA safety training courses. The team aims to improve the current modules based on the feedback received from the participants and plans to develop new training modules in the next year. All modules shall be available on the Oculus Store for download.

9. ACKNOWLEDGEMENT

This research study is supported by the Auburn University's Office of Undergraduate Research through Undergraduate Research Fellowship program. The authors appreciate their financial assistance. The research team also thank Holder, Doster and Brasfield & Gorrie Construction companies for their generous time contribution towards this research. Appreciation is due to undergraduate and graduate students enrolled in the Building Science program at Auburn University for participation in this study. Finally, the research team extends gratitude towards Building Science program at Auburn University and College of Art and Science at Tuskegee University for their support towards this research.

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VIRTUAL REALITY APPLICATION TO AID CIVIL ENGINEERING LABORATORY PREPARATION FOR UNDERGRADUATE STUDENTS

Sokkeang Try & Kriengsak Panuwatwanich
Sirindhorn International Institute of Technology, Thammasat University, Thailand

ABSTRACT: *Virtual reality (VR) technology simply emerged from just an abstract concept and gradually revolutionizes into an authentic technology. While the architecture, engineering, and construction (AEC) industries are desperately growing across either developed and developing countries, a huge trend in architectural and construction education is presented. This research is looking at building a VR application to aid civil engineering laboratory preparation for undergraduate students. By exploiting the benefits of VR technology and smart handheld devices, this research is aiming at supplementing construction training education to enhance the quality of learning. To be more specific, this study will be carried out under the context of "Virtual training on concrete compressive strength testing" as a case study in which learners will be able to visualize and learn within an immersive virtual environment parallel to reality. By adopting low-cost head-mounted devices (HMDs) powered by smart handheld devices, this research will be done under three the purposes including (1) To facilitate learning process by providing briefing of information to learners for a better preparation prior to conducting actual laboratory experiment, (2) to simultaneously provide learners with both experimental and experiential learning regarding laboratory testing procedure and inform learners with safety precautions while performing the experiment, (3) to determine the impact and effectiveness of VR training application on construction education. The following results are expected to be generated from the study: (1) The VR application could provide effective briefing of information to enhance learners' understanding prior to conducting the experiment, (2) The VR application could provide a user-friendly training environment and insight into safety awareness while performing actual task, (3) The VR application could provoke learners' interest and motivation to learn.*

KEYWORDS: *virtual reality, visualization, simulation, construction training, laboratory preparation, supplementation, head-mounted devices.*

1. INTRODUCTION

In relation to the advancement of technologies, the feasibility of information to some extent provides people with opportunities to invent, store and retrieve information. One of the most recent technologies "Virtual Reality (VR)", a computer-generated three-dimensional virtual environment represented actual world and objects (Craig, 2013, Farshid et al., 2018) gradually becomes more and more mature and is considered as an essential tool for enhancing various sectors, especially education. Due to the potential of this technology, VR has been adopted for facilitating and enhancing the visualization of complex systems. A number of researches have been done in terms of adopting Virtual Reality into various fields involving training and education, public health, entertainment, tourism, the gaming industry and others (Carmigniani et al., 2011, Craig, 2013).

From another perspective, the demand for the development of the construction sector is gradually increasing due to the demand in raising a country's economic, alleviating expense, time, safety issues and mobilization problems. As a result, it leads to the increase of more human resources in the field of construction engineering. To be a well-qualified construction engineer, both theories and hand-on training activities are needed in realizing technical understanding, working phenomenon, and the correlation between theoretical knowledge and actual practice. While the construction sector has been marching rapidly forward, additional training, specifically hand-on training is considered as an essential source of experiential and experimental learning for construction students. Although on-site training can provide learners with useful, unique and applicable experiences in actual working environments, risks are likely to be encountered ranking from a minor injury to fatality during the training. Furthermore, the following limitations have been identified. Firstly, there is a time constraint for on-site training (Lucas, 2018). Secondly, there is high exposure to construction safety hazards where insufficient safety training, lack of construction safety awareness, inadequate safety risk assessment are regarded as the root causes of accidents in construction sites (Park and Kim, 2013). lastly, on-site training activities are limited for learners to absorb in-depth knowledge and understanding of construction-related tasks.

To deal with construction training and education issues, VR technology is seen as a possible solution to either deal with existing learning constraints and enhance the current state of training and learning methods. VR not only provides learners with unique experiences, but it also generates risk-free training scenarios that allow users to experience hand-on training activities as if they are physically present in the actual training session. Additionally, VR application can provide users opportunities to learn accordingly at their own pace while triggering their interest to learn. Further study is needed in realizing the full potential of VR technology.

2. LITERATURE REVIEW

2.1 Overview of virtual reality (VR)

The continuity study upon virtual reality technology by different researchers lead to the differences in its definitions. To some extent, VR is defined as a computer-generated environment in the form of three-dimensional graphics in which interaction between a human entity and virtual objects within a virtual environment can be done through input/output devices (Pantelidis, 1997, Wickens, 1992). According to Sherman and Craig (2003), Virtual Reality consists of four key elements including Virtual World, Immersion, Sensory Feedback, Interactivities.

- Virtual World simply refers to a computer-based simulated environment stem from either mimicking the real world or an imaginary.
- Immersion is depicted as a sense or feeling of being presented in a non-physical world. The immersive system can be classified into physical and mental immersion where physical immersion simply refers to the synthetic stimulus of physical senses using technology while mental immersion emphasizes on emotion and feeling.
- Sensory feedback can be illustrated as computerized sensing of positions including orientation and location tracking of an object.
- Interactivities refers to users' ability to interact and navigate within the virtual world.

2.2 Virtual reality use-cases

The dissemination of VR technology sophistication has become a trend in the digital world. It encourages and attracts numerous researchers to critically investigate its potential benefits and usages.

The concept of virtual reality has been used by entertainment productions and shown in Hollywood movies, for example, Ready Player One, which received significant support and reputation from audiences around the world. Meanwhile, "The museum of Bruttians and the Sea" located in Cetraro, Italy, hosted a virtual museum (VM) that allows visitors to involve physically, psychologically, and emotionally in visualizing and navigating in a virtual world where all necessary contents have already been manipulated into VR system. Consequently, the VM development program capable of providing audiences educational and enjoyable experiences (Barbieri et al., 2017).

Additionally, VR has also been adopted in the educational sector. The adoption of VR technology can provide users educational and enjoyable experiences as well as foster students' engagement in the learning process (Barbieri et al., 2017, Zhou et al., 2018). Existing researches indicate that the adoption of VR technology helps avoid potential risks, reduce expense compared to the cost of the original training method (Haluck and Krummel, 2000). Significantly, there is a noticeable improvement in the effectiveness of teaching (Tarng et al., 2019).

Meanwhile, within the construction sector, a variety of researches has been done by incorporating VR with the construction field of study. For example, a study was done on immersive VR in the construction classroom regarding the sequence assembly of wood frame construction to scrutinize the potential introduction of HMDs-VR powered by mobile devices (Lucas, 2018); the result shows that users had an overall favorable view of implementing VR into the construction education curriculum. Another study was done by reviewing virtual reality applications in construction safety due to the increasing concern regarding construction safety thus establish useful insights and necessary information regarding VR/AR technology (Li et al., 2018).

2.3 Challenging factors

It has been notified that VR technology has tremendous advantages due to its real-time visualization and interaction capability. Although the advantages outweigh the disadvantages of utilizing VR technology, potential issues have been identified and yet to be solved. The major problems involve the users' ability to adapting to VR technology and cyber-sickness (Lucas, 2018). Cyber-sickness can be depicted as physically and emotionally discomfort that stems from a prolonging exposure to the virtual environment using head-mounted devices. This kind of sickness produces the following symptoms including dizziness, spew out, eye strain, facial pallor, headache and so on (LaViola Jr, 2000). Consequently, users could be demotivated and lose their satisfaction in using VR.

2.4 Construction training and education integrated VR

2.4.1 Overview of conventional construction training and education

The current construction learning method depends heavily on theoretical learning. It is an instructive process and a contents-based learning method where lectures are given in a chronological order to provide detail information and foster learners to construct knowledge. This learning process indeed contains excessive information although practical learning is not substantially provided. Some institutions including but not limited to vocational learning centers can provide adequate hand-on learning activities while some others can only provide theoretical knowledge plus a partial amount of actual practices to learners; thus, make learning a lack of realistic and practicality.

2.4.2 VR capability and potentiality

Virtual reality is built with tremendous benefits which is beneficial to be adopted into various fields. VR is equipped with highly potential real-time 3D visualization and immersion capacity that allows users to visually see and manipulate objects within a specific 3D virtual space using specific tools. Some other specific capabilities of VR including performing risky and inconvenient tasks, experiencing trial and error scenarios, eliminating risks of unintended property damaging, avoid environmental conflict. Most importantly, besides providing powerful training scenarios, this technology may help private and public organization reducing expenses on training courses and learning equipment, ultimately produce a better and faster learning process.

2.4.3 Bridging VR with educational pedagogical contexts

In accordance with cognitive learning theory, knowledge is acquired through a process of thinking, experiencing, and sensing (Lucas and Thabet, 2008). It seeks for converting working memory which deals with daily activities' performances awareness (Baddeley and Hitch, 1974) into long-term memory (Shiffrin and Atkinson, 1969) where information is stored permanently. This long-term memory later can be used to apply in real-life contexts. Overall, cognitive learning theory can be processed using virtual reality.

Dewey (1944), stated that learning should be real and practical in actual living conditions and should be both experimental and experiential; thus, VR is seen as a solution to deal with this theory. According to Zhou et al. (2017), to link VR to educational pedagogical context, four main key factors are considered including "learning objectives, learning styles, learning activities and tasks, motivated learning outcomes" (Zhou et al., 2018). To define the four key factors, two main theories are adopted "constructivism and bloom's taxonomy" (Bloom, 1956, Huang et al., 2010). Meanwhile, constructivism learning is viewed as a pedagogical factor driving construction of VR learning environment in which the design of learning tasks is based on several principles including learning from interacting within a virtual world, problem-solving to promote creativity, motivating learners to learn, and VR as a scaffolding tool for learners to learn (Huang et al., 2010).

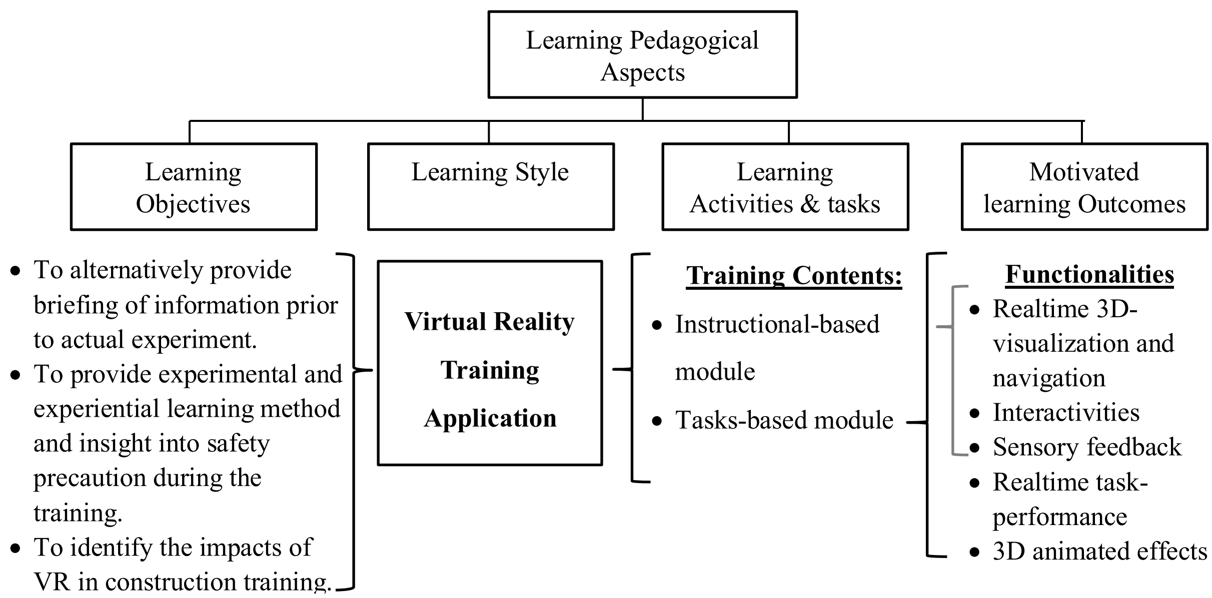

Fig. 1: Designing virtual training application based on learning pedagogical aspects.

3. RESEARCH METHODOLOGY

3.1 Research setting

This research mainly emphasizes on the construction of laboratory training which essentially reckoned as beneficial for civil engineering students to proof the learning theories and enlarge their knowledge. Upon the completion of the prototype, the testing experiment will then be conducted at SIRINDHORN INTERNATIONAL INSTITUTE OF TECHNOLOGY with third-year undergraduate civil engineering students who basically prepared for the laboratory study within the semester. To be precise, all participants must be nonexperience students. Basically, this research seeks to measure the efficacy of VR learning method over the traditional means of learning.

3.2 Research apparatus

Virtual Reality application prototype will be developed and used for construction training concerning technical understanding as well as safety awareness. Hence, certain tools, both hardware, and software are required to be used within the research process. Technically, the required software may involve Microsoft Visual Studio, C-Sharp Program Language, a variety of design software including Autodesk AutoCAD2D&3D, Sketch-UP, and SolidWorks, most significantly UNITY-Game Engine are being used as a based program for developing VR application. UNITY is a multi-platform game engine that allows developers to build and deploy applications across different types of devices including computers, handheld devices as well as consoles.

While a variety of software is being used to build the training prototype, low-cost head-mounted devices (cardboard headsets) and smart mobile devices which are compatible with virtual reality application are considered compulsory for this research study. Initially, Samsung Galaxy S9-Plus is being used for testing the prototype.

3.3 Research development phases

To achieve the objectives of the research and reach the determined milestone, this research will proceed through the following phases while the objectives of each phase are diverse from one phase to another.

- *Phase 1: Literatures review: T*he study will be focusing on reviewing existing works of literature to further expand users' overall understanding regarding virtual reality. By doing a literature review, potential benefits and gaps of research on virtual reality applications can be identified. Consequently, this study will help in formulating and sharpening the research topic as well as avoiding any repetition of the existing works. Within the proposed research topic, two main scenarios were determined including an instructional-based module where content-based learning can be done during the simulation, while the second scenario is the task-based module where practices can be done upon the completion of the first training scenario.
- *Phase 2: Proof of concept:* This phase mainly emphasis on proofing the training concept through the development of VR prototype and consequently deploy on an android mobile device to test the possibility, workability and potentiality of VR integrate construction training. The prototype will be partially developed accordingly based on the objectives of the research in an attempt to measure the possibility of the study and its usefulness in supplementing the traditional means of construction training. In this phase, 3D models were established by using Autodesk AutoCAD2D&3D and SketchUp then exported to UNITY as a FILMBOX file (.fbx extension). Additional functions including interactivities will be designed to form a partial prototype.
- *Phase 3: Exploratory Study:* the study will focus on gathering essential information and investigating the current state of training method and to figure to what extent VR technology can help improving the conventional training methods. The study will be conducted with experts who have experience in the concrete materials testing field while other essential information will be obtained from the literature review and standard testing code. The preliminary information relevant to the study to be accumulated may involve the current method and materials adopted in teaching concrete compressive strength testing, issues and limitations of the current training method found during teaching and training period,
- *Phase 4: VR prototype development:* the study will focus heavily on the development of the prototype to generate a complete VR training application where all compulsory contents and characteristics of VR gathered in the previous phases are manipulated to be used as a training prototype. The clarity of training information and procedure is to be guaranteed and organized sequentially and significantly avoid confusing information. Furthermore, it is to ensure that errors and major lags that affect the VR training process are eliminated
- *Phase 5: Testing and evaluation:* Phase number five will be begun by conducting an assessment on VR application to measure learners' efficacy as well as the potential and usefulness of VR technology on

construction training. The application will be first evaluated by experts and modified accordingly prior to conducting the experiment with the undergraduate students. The following factors will be considered including sample size, testing criteria, and procedure in testing the application. The testing will be done thoroughly to avoid subjective results, thus generate an accurate output.

- *Phase 6: Finalizing research report:* The results obtained from the participants will be critically analyzing to see whether the outputs meet the expected results responded to the research objectives. All comments from participants will be checked thoroughly and modification will be made accordingly. Then, all collected information from phase one to six together with the final version of the prototype as well as the concluded results will be accumulated and compiled as a research report.

3.4 System architecture

Among all the research development phases, the VR prototype development phase is considered the most challenging part due to its complexity. within this phase, 3D assets are needed to be built while scripting is required to build a complete training scenario. Additionally, UNITY engine is a professional game engine that is considerably complicated to be used; thus, an extensive amount of time is needed to deep dive into how to manipulate the software.

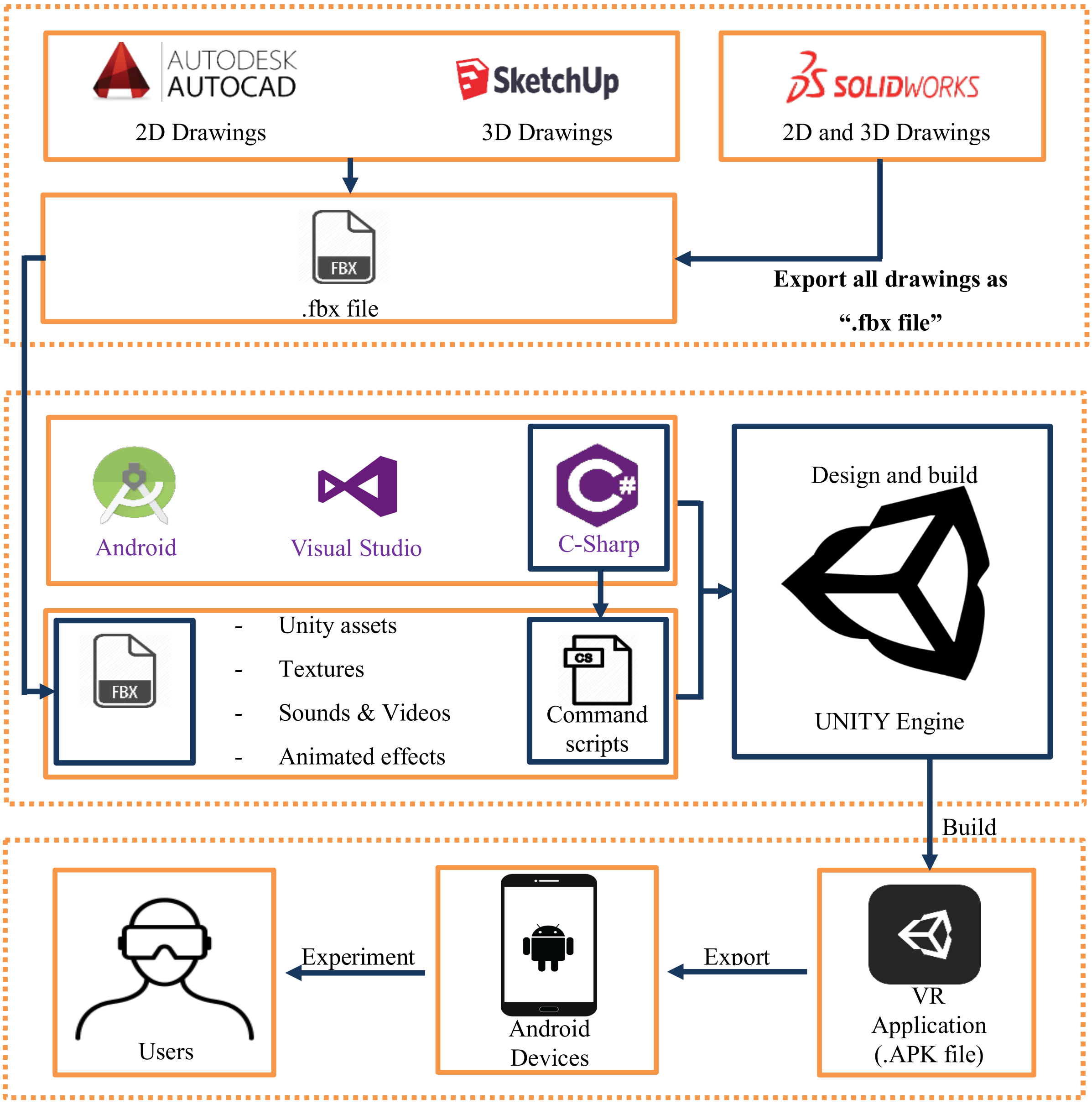

Fig. 2: Prototype development diagram.

The prototype development consists of three vital parts: the 3D-assets development, the design of VR integrated training scenarios using UNITY game engine and finally deploy the prototype on android devices for the experimentation. 3D models of the laboratory and compressive machine will be sketched thoroughly using Autodesk AutoCAD for 2D drawing which later will be exported to SketchUp and Solidworks for 3D modeling. Precisely, these models indeed needed to be converted into a .fbx extension prior to exporting to UNITY Engine.

The second part focus on the development of the prototype using UNITY Engine. Prior to the development of the training prototype, all associated software is needed to be installed including Android Studio, Visual Studio, and C-sharp program language. The prototype will be built thoroughly from scratch by compiling all necessary components including UNITY assets, 3D models, textures, sounds and videos, animated effects to form a complete prototype. More importantly, C sharp script plays an important role in creating the simulation prototype. Each of the interaction takes part in the application are controlled by various scripts.

Finally, in the last part, the built prototype will be deployed on android devices to make sure the operation of the application performs smoothly prior to initiating the experiment. Any modification will be done subsequently due to experts' comments.

4. PRELIMINARY WORK

To achieve the objectives of the research, the prototype must be built thoroughly according to the contents of the lesson. Most significantly, the prototype will consist of four critical characteristics including 3D modeling, interactivities, animations, finally the display of the information. To avoid any confusion, each function will be designed separately and merge with one another upon the successful development of each function.

4.1 3D assets modeling

Preliminarily, the 3D laboratory model asset has been drawn on SketchUP2019 and successfully exported and deployed into UNITY as .fbx extension. Initially, the imported model in UNITY cannot be interacted with unless the collider function is added to the 3D model. Within UNITY Engine, texture materials can be added and adjusted accordingly to make the models looks more realistic.

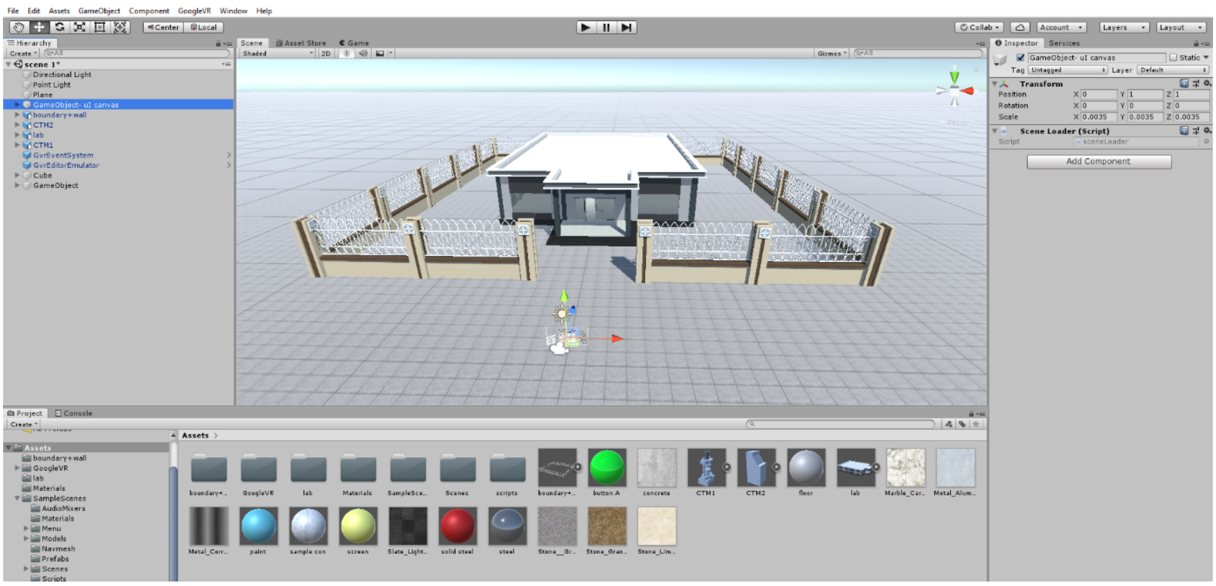

Fig. 3: Importing 3D models to UNITY Engine.

4.2 User interface

Preceding the importation of 3D models into UNITY, the prototype interface (UI) was designed accordingly. Basically, UI is designed using the available function in UNITY software which later integrates with command scripts written in Visual Studio using the C-Sharp program language. Each UI function may diverge from one to another; thus, different types of command scripts are needed to attach to each and every button. In the first version of the prototype, the user interface consists of five interactive buttons and a description canvas that indicates the guideline regarding the training simulation.

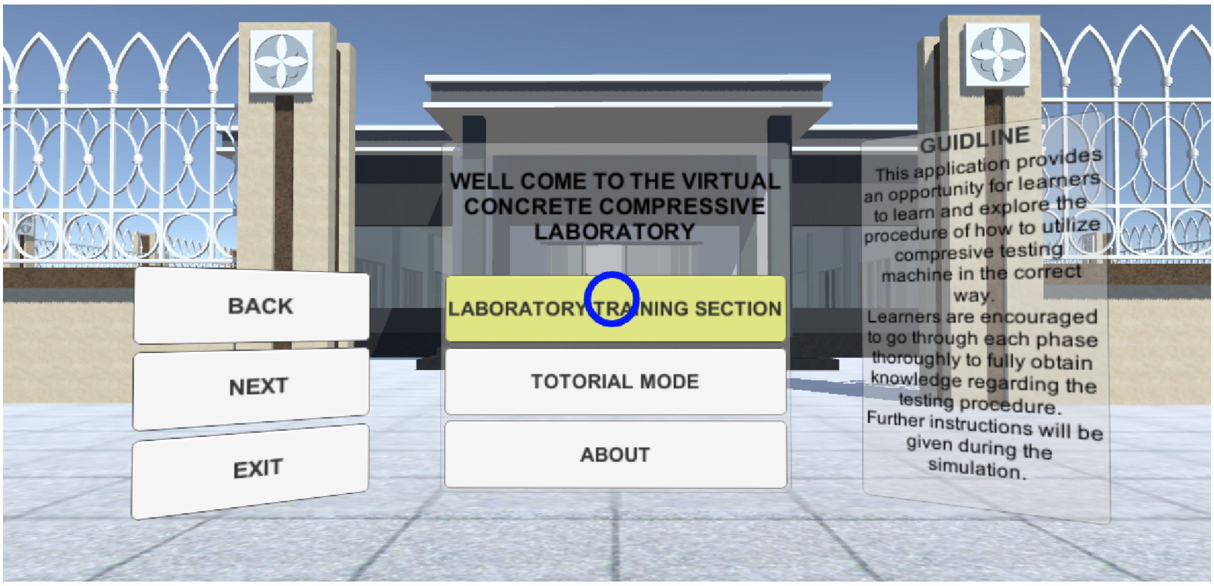

Fig. 4: Initial user interface with clickable UI pointer.

4.3 Interactivities

Interactions are being built including navigation and teleportation functions which allow users to simultaneously navigate around the virtual space using gaze function and button on the cardboard. The current prototype allows users to either teleporting from one position to another while the distance of the teleportation is set at an exact value to make the movement looks more realistic. Another type of movement can be done by using a controller (both Bluetooth and cable connected controllers can be used) connected with the mobile phone. Meanwhile, drag and drop functions allow users to interact with virtual objects in the 3D space. These functions have been built and tested in the Android Samsung Galaxy S9 Plus device. Additional interactivities include scenes switching, hover-text where information pop-up whenever a user gaze directly into a specific object. Each and every interactivity and VR components were then integrated with one another to form a partial prototype.

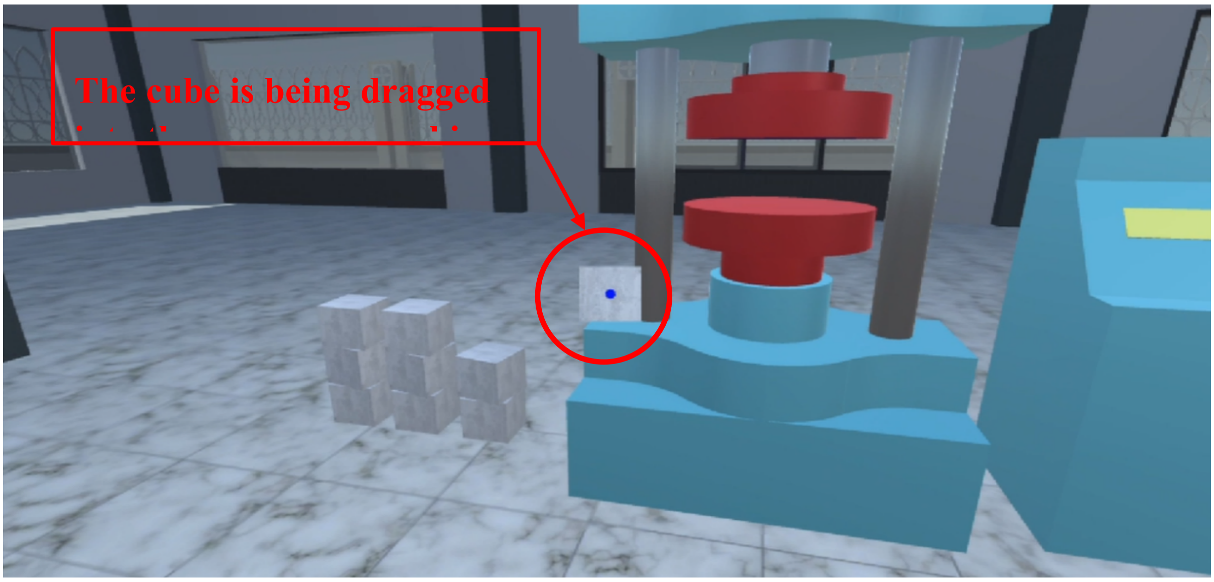

Fig. 5: Drag and drop object functionalities.

5. FUTURE WORK

While the training prototype is being developed, the testing procedure is simultaneously being done. Thus, by the time the prototype is fully built, the experiment can be performed subsequentially. To guarantee the accuracy and efficacy of this research, the following factors are critically considered:

- *Materials and testing requirement:* The experimentation will be conducted mainly at Sirindhorn International Institute of Technology (SIIT) with three different groups. The first group consists of concrete technology expertise participants who will be invited to test the application to identify contents-errors and major improvements. The other two groups are non-experience participants recruited specifically from year three civil engineering class at SIIT. During the main experiments, one group will be assigned to engage with virtual learning using the final version prototype while the other group will proceed with the learning using traditional learning materials. This test will be done to measure "learners' understanding ability, application usability, users' satisfaction, and application efficiency. The testing and learning materials will be prepared thoroughly including the final version of the prototype, the original learning handouts as well as the questionnaire surveys.
- *Testing criteria and procedure:* The testing will be initiated with the expertise participants group in an attempt to evaluate the quality of the application prior to conducting further experiments. The expertise participant group will be arranged to go through the following criteria including (1) experiencing the training prototype, (2) engaging in semi-structured interviews. Based on the feedback from the participants, the application will be modified accordingly.

  Upon the completion of the modification, one of the nonexperience groups will be assigned to perform the learning using the VR training application to measure how effective the VR integrated training application would help students learning. Thus, four steps will be adopted in the experiment including (1) providing a brief illustration of how to utilize the training tools and how to proceed the prototype simulation, (2) performing the VR training simulation within a limited timeframe, (3) conducting survey questionnaire to measure application efficiency, users' satisfaction and the usability of VR prototype, (4) perform actual training in the concrete laboratory in which time and result of the training will be recorded for further comparison with the result conducted by the third group to see the effectiveness the training using VR application.

  Last but not least, the last group of nonexperience participants will be assigned to proceed with the training using the traditional method. This group will be asked to conduct the training through the following sequence begin with (1) the learning using a laboratory learning manual in which learning time parameter is fixed at a certain length, (2) perform actual laboratory training in which time and result will be recorded.

Finally, the recorded time and results from both of the nonexperience groups will be analyzed to see which of the two learning methods is more effective. Hence, the final result can be generated and placed in the final report.

6. Conclusion

By exploiting benefits of virtual reality technology, this research aims at developing a VR integrated construction learning method by offering a real-time visualization in which the environment is done by mimicking real-world environment where users can navigate and interact with objects during the simulation. By way of illustration, this application is designed by integrating theoretical learning with a virtual presentation of learning objects where learners can learn through the theory and sequentially clarify and extend their understanding of the topic through virtual practice. The learning task in the VR integrated learning contains a procedure designed based on actual hand-on training where learners can conduct testing, recording, and evaluating testing results within the simulation. Presently, Phase one to four is being under progressed while phases five and six will be conducted subsequentially upon the completion of developing the prototype. Consequently, the objectives of the research is expected to be achieved with positive results that could enhance users understanding by providing effective briefing of information with user-friendly training environment as well as insight into safety awareness prior to actual training session, most importantly, the VR integrated learning method is expected to be able to provoke learners' interest and motivation to learn.

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A COMPARATIVE ANALYSIS OF NON-IMMERSIVE AND IMMERSIVE VR ON IMPROVING STUDENTS' UNDERSTANDING OF BUILDING SYSTEMS

Gulbin Ozcan-Deniz, and Carmen Cordero

Thomas Jefferson University, 4201 Henry Ave, Philadelphia, PA, USA

ABSTRACT: *The rapid development of hardware and software applications, as well as improved digital information platforms have directed architecture, engineering, and construction (AEC) users towards the use of innovative visualization tools. Virtual Reality (VR) has been at the center of attention, as the technology allows transferring computer generated 3D models into a virtual environment. With the option of non-immersive and immersive VR, users can step into the design and understand and apply design changes as necessary even at the early stages of a construction project. In this context, future construction graduates pose a need to be equipped with the VR knowledge to keep up with the emerging technologies and the needs of the industry. This study aims to compare two types of VR applications, as non-immersive and immersive, to verify the ability of each application in providing a better understanding of construction building systems (e.g. mechanical). The methodology includes using Keyboard-based and Head Mounted Display (HMD) technologies for VR in actual construction projects to compare users' perception of building systems. Findings will state the strengths and weaknesses of both non-immersive and immersive tools in relation to Building Information Modeling (BIM) and education. Discussions will be included to explore the uses and benefits of two VR applications for construction management (CM) education.*

KEYWORDS: *Virtual reality, construction education, non-immersive VR, immersive VR.*

1. INTRODUCTION AND BACKGROUND

Virtual Reality (VR) has been very valuable for the construction industry and Construction Management (CM) education for the past years. VR in education has been used for simulation of complex systems, visualization, high levels of interactivity, and its characteristic flexibility and adaptability (Kalawsky, 1996). In construction education, VR was practiced for future project implementation including construction scheduling and interactive site experiences (Messner et al. 2003), visualization of project designs (Messner et al. 2002), visualization of construction plans and schedules (Haymaker & Fischer, 2001), performing civil engineering processes (Sampaio, 2010), and designing and analyzing construction equipment (Lipman & Reed, 2000). VR allows students to step into 3D building models and proposes an active learning environment (Sala, 2016). Navigating freely in a 3D virtual model and interacting with the virtual environment increase students' engagement and motivation in learning (Winn et al., 2002).

AEC education was further improved with the integration of Building Information Modeling (BIM) and VR. Visualization was stated as being one of the most important characteristics of BIM (Wang et al., 2014). VR has been utilized in simulations and role-playing environment for collaboration as well as training. It was pointed out that a systematic investigation of the development and implementation of VR in construction education and training was still needed (Guo et al., 2012). Considering VR technologies, non-immersive VR was improved through the introduction of V-REALISM (Li et al., 2003) and the Interactive Construction Management Learning System (ICMLS) (Sawhney et al., 2000). V-REALISM was created as an object-oriented prototype desktop VR-enabled system for maintenance training. ICMLS was proposed as an instructional tool to better prepare graduates for managing the complex dynamics, pressures, and demands of construction sites. Immersive VR was believed to be advantageous over the non-immersive VR due to its real-time capabilities and spatial immersion (Sacks & Pikas, 2013). There are also limited studies on evaluating Heating, Ventilation, and Air Conditioning (HVAC) systems with the help of VR technology (HPAC, 2018). This research will enable students to interact with building elements through the use of both non-immersive and immersive VR systems to observe which VR system, non-immersive or immersive, enhances students' learning experience better.

There are various levels of immersion with VR. A non-immersive system refers to a desktop-based VR, where a keyboard and a mouse are main controllers and users view the virtual environment from a PC/laptop screen. An immersive VR refers to the use of special display systems like Head Mounted Displays (HMDs) and hand-hold controllers to connect and immerse users to the 3D model. Immersive VR improves the engagement and interactivity with the 3D model, as users do not see the real world outside and perform actions in a virtual environment. As mentioned in literature, both systems benefit education and student learning with different levels of interactivity and learning. As an example, Roussou et al. (2016) found the positive impact of immersive VR in problem-solving skills of students.

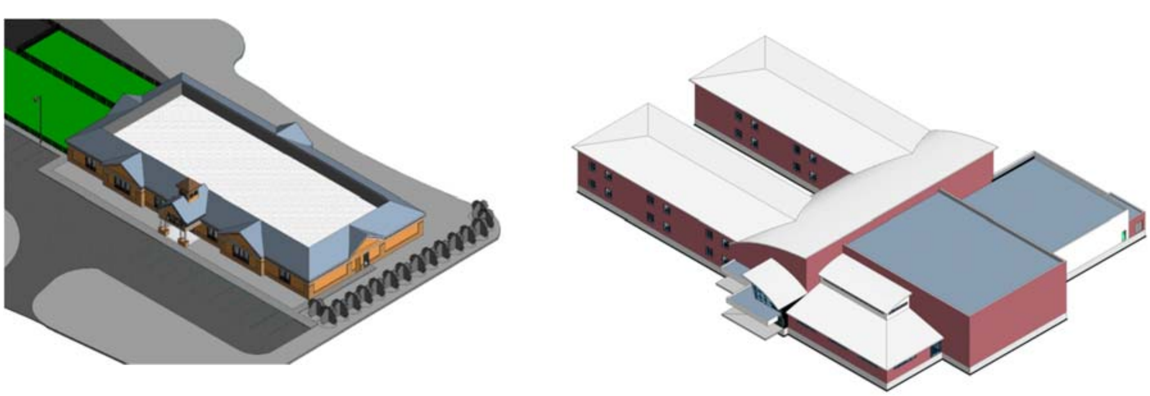
With the increase in the use of VR in the AEC industry, it is no longer a need, but now a necessity to implement VR in the CM education. CM graduates need to be equipped with VR knowledge to keep up with the needs of the industry. With various VR types, it is important to select the most feasible one considering their applicability to CM education and building systems. This research aims to investigate and compare two distinct types of VR systems: non-immersive and immersive in relation to improving users' perception of building systems. Mechanical systems will be the main focus of this research, as they possess a high percentage of cost compared to other systems in a construction project. Improper understanding, design, or application of building systems would increase the total construction cost as well as duration of a project drastically. Additionally, mechanical system requires collaboration between project participants such as architects, engineers and construction managers to be able to fully apply its potential in a project. VR simulations were analyzed by many researchers and reported to improve students' understanding of construction projects and plans (Messner et al., 2003). Consequently, VR offers users improved visualization and understanding of mechanical elements. Although VR's potential for education is apparent, it is not clear on which VR system, non-immersive or immersive, is most beneficial for construction students. This study compares the use of non-immersive and immersive VR for CM undergraduate students' education in terms of developing understanding of building mechanical systems.

2. METHODOLOGY

The methodology includes three (3) areas:

1. Background Preparation
2. Experiment and Data Collection
3. Data Analysis

The Background Preparation was composed of selection of case studies, creation of 3D building models with Autodesk *Revit*, training of the Research Assistant (RA), and creation of pre and post-surveys. As two different VR tools were compared in this study, two case studies were chosen to perform virtual walk-throughs. One daycare center and one elementary school building were used as case studies (Figure 1). The daycare center was a prototype building to be replicated in different locations with an area of 10,000 SF on one level, while the elementary school was a two-level building with an area of around 75,000 SF. Both buildings had central HVAC system with 2' by 2' air diffusers connected by flex ducts, round ducts and rectangular ducts, which were common for duct systems in commercial buildings in the U.S. The daycare center had a roof top unit with bottom supply and return duct connections. Details of mechanical plans and typical duct connections were available when creating the HVAC ceiling and floor plans in Revit. A sample HVAC plan is presented in Figure 2. The elementary school had indoor Air Handling Unit (AHUs) for every two rooms to sustain air flow. Both buildings' duct systems were installed on compound ceiling systems of 2'x2' or 2'x4' sizes. The most important aspect of the creation of the 3D building model included placing some intentional clashes in the daycare center. The elementary school was kept as a correct example of mechanical systems' design.



a) b)

Figure 1. 3D Revit Models of a) Daycare Center and b) Elementary School

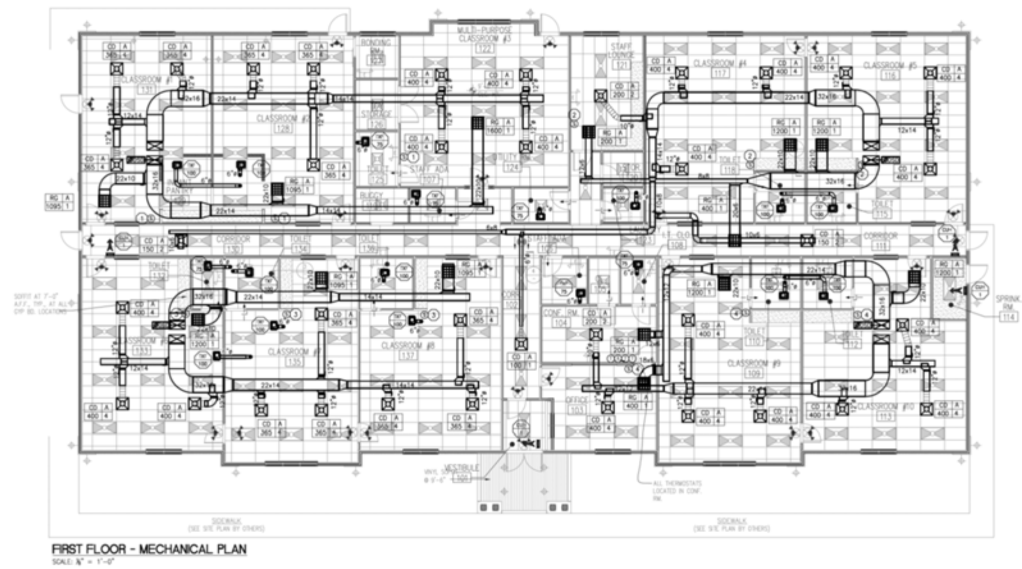


Figure 2. Sample HVAC Plan View

The RA of the project was trained with the basics and details of the BIM software *Revit* (Autodesk-Revit, 2019) to be able to place and modify HVAC systems. Additionally, non-immersive VR and immersive VR training were performed with the use of *HTC Vive HMD* (Vive, 2019). For non-immersive, a keyboard and mouse system were used to virtually navigate in the sample buildings. Meanwhile, an experiment plan was prepared to walk students in the building on a certain path. The entrance door to start the virtual walk-through and classrooms to visit in the sample buildings were planned ahead for the actual study. Similarly, *HTC Vive HMD* system was practiced with the RA by using the same virtual walk-through path.

The pre and post-surveys were created before the RA training and were modified during the training sessions to better reflect the pros and cons of both non-immersive and immersive VR systems. Each survey had ten questions and took students around fifteen to twenty minutes to answer all questions. Pre-survey included three sections: (1) questions related to the students' current knowledge of HVAC building systems and to the students' current knowledge of VR (both non-immersive and immersive), (2) questions related to duct systems of 2D plans of the elementary school and the daycare center, and (3) questions related to clashes in the 2D plans of the elementary school and the daycare center. Pre-survey was designed to test students' understanding of HVAC systems from 2D plans of both buildings before using the VR technology. Post-survey included similar sections as: (1) questions related to ease of use and navigation in the non-immersive and immersive VR, (2) questions related to duct systems in the VR of the elementary school and the daycare center, and (3) questions related to clashes seen during the VR walk-throughs of the elementary school and the daycare center. Post-survey was designed to ask the same technical questions related to the HVAC systems as the ones in the pre-survey to see students' understanding after the non-immersive and immersive VR experiments.

Experiment and Data Collection included using pre and post-surveys to evaluate the understanding of CM students' building systems knowledge (Figure 3). Student groups of fifteen were used for pre-survey and post-survey data collection. First, a group of CM students were selected based on their ranks and previous knowledge of building systems. Junior level students were targeted with an aim that the student body had taken a related building systems course before the VR experiment. As a result, 100% of students had taken a course related to building systems before the experiment. The pre-survey was distributed to the CM students to record their current knowledge of VR technology and the results state that 80% of the students had not used VR before. Students' current knowledge of mechanical systems were also observed through the pre-survey. Students were asked specific questions about the HVAC systems of two sample buildings by using only 2D plans as mentioned before. Data collected from the pre-survey was stored to be analyzed later. Then, students used non-immersive and immersive VR to visualize the same sample buildings.

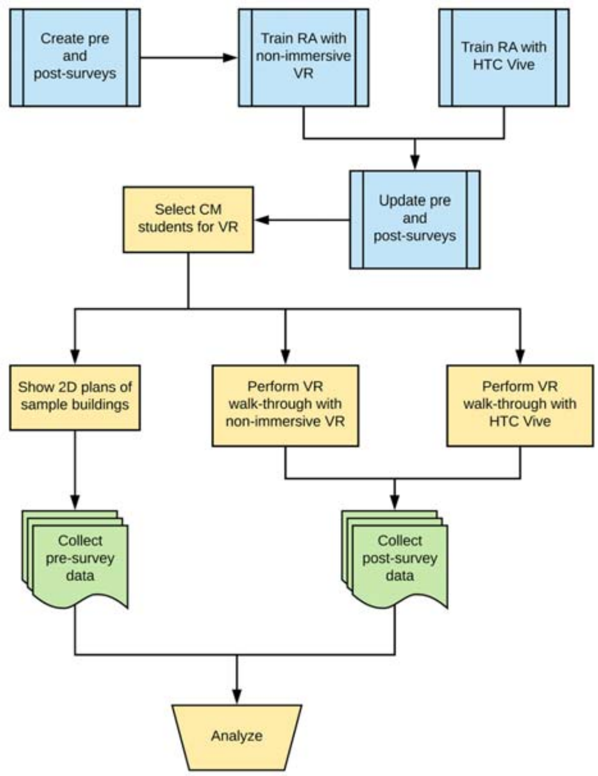


Figure 3. VR Experiment and Data Collection Flowchart

The setup of the non-immersive system was straightforward and took around five (5) minutes, while the setup of the immersive VR was much more detailed and took around thirty (30) minutes. The classroom included a projector and a screen to make sure all students could be involved in the experience. The classroom also had available plugs and extension cords, as many cables would be around for the immersive VR setup. Immersive VR setup included a virtual room setup with enough maneuver space (i.e. 6.56ft by 6.56ft). This step included creating a virtual room boundary with imaginary lines (Figure 4). Although students could not see the lines directly, users could realize the virtual room boundary through the appearance of green dashed lines when in VR. *HTC Vive HMD* and accessories were placed in the classroom within the virtual room boundary. *HTC Vive* had goggles and two hand-held controllers to navigate in the virtual environment. Two base stations allowed to transfer the signals from HMD to the laptop. Laptop was a special gaming laptop to be able to operate three software applications simultaneously. *Revit* was operated to view the 3D model of the sample buildings, SteamVR was used as the VR software of the *HTC Vive* system, and IrisVR (IrisVR, 2019) was used to connect *Revit* and SteamVR (SteamVR, 2019) to virtually walk-in 3D building models.

Figure 4. Virtual Room Setup

During the non-immersive VR, RA and the Professor helped students with the control and navigation with the mouse and keyboard (Figure 5). Students visualized the air diffusers, duct types and sizes, and clashes in the daycare center.

Figure 5. Non-immersive VR View

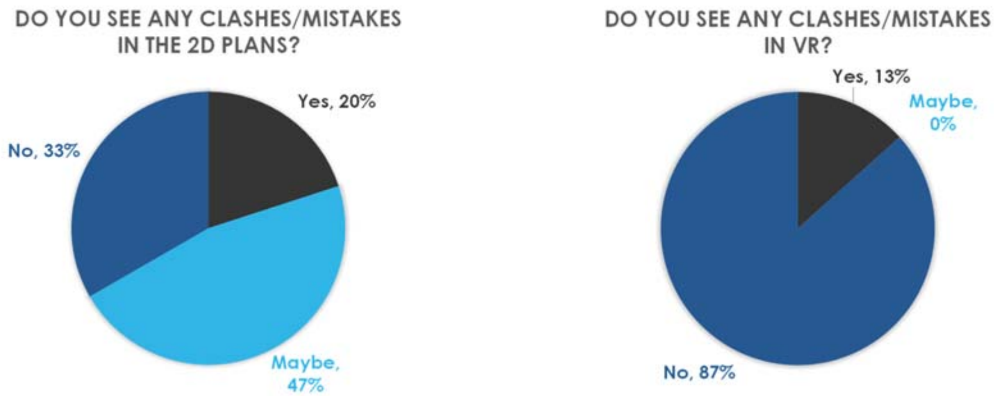
During the immersive VR, students used *HTC Vive HMD* with the professor's directions. With the ability to hide ceiling systems and teleport themselves up above the ceiling systems, students had extended view of the HVAC systems (Figure 6a). Questions related to clashes/interferences in the sample building were found and marked using the mark-up tool available in the immersive VR system (Figure 6b**Error! Reference source not found.**).

Figure 6. a) Immersive VR View from Laptop Screen, b) Immersive VR Clash Detection

Data Analysis was performed through several steps by using quantitative and qualitative data collected from student observations to distinguish the changes in the learning pattern of students for mechanical systems. Hypothesis testing was used to see whether immersive VR performs better than non-immersive VR in terms of construction students' learning and observation of mechanical systems. To test the causality or link between the VR system and students' performance, the experiment maintained a level of control of the different variables that may influence the relationship, such as similar HVAC systems were viewed in two different 3D building models. Descriptive statistics provide absolute numbers in relation to students' performances. Quantitative data is converted into percentages to identify which technology, keyboard-based (non-immersive) or HMD (immersive), was more feasible to be used in CM education to improve users' perception of building MEP systems. Qualitative data analysis was performed to learn pros and cons of both systems from students' perspectives. Collected data was transcribed and filtered to identify patterns and connections. The most common responses were selected to find areas that can reflect the pros and cons of both systems in a comparative manner. Analysis of data will be shared in the next section.

3. FINDINGS AND DISCUSSIONS

As mentioned before, pre-survey focused on students' understanding of mechanical systems by only using 2D mechanical plans. Students first viewed the 2D plans of the elementary school and were asked if they had seen any clashes in 2D plans. Elementary school was the case with no clashes, however 2D plans were not detailed enough to surely state that. Therefore, the correct answer to "By reviewing the 2D plans of the Elementary School, do you see any clashes?" would be 'maybe'. As results show (Figure 7), only 47% decided that 'maybe' there would be clashes as 2D plans were not thorough. When students had immersive VR walk-through, they were asked the same question. This time, 87% stated that there are no clashes in the elementary school, which is the correct answer. It was interesting that 13% of students still answered the question incorrectly, although all students were involved in the mark-up process of clashes during the VR experiment.



a) b)

Figure 7. Clash Detection Answers

Another question to compare students' understanding was "Do all supply diffusers fit onto ceiling grids?". Although all supply diffusers fit in well, 80% said 'Yes' by using 2D plans and 100% (all students) answered correctly as 'Yes' after immersive VR. Similar results were obtained for questions related to the size of mechanical items. For example, only 20% of students found the size of supply diffusers correct by using 2D plans, while 67% of students found the size correctly after immersive VR (Figure 8). It should be noted that sizes of elements were not directly shown in VR and students had to use the measure tool to measure elements correctly. From a pedagogical perspective, this process brings in critical thinking into the picture during the VR experiment.

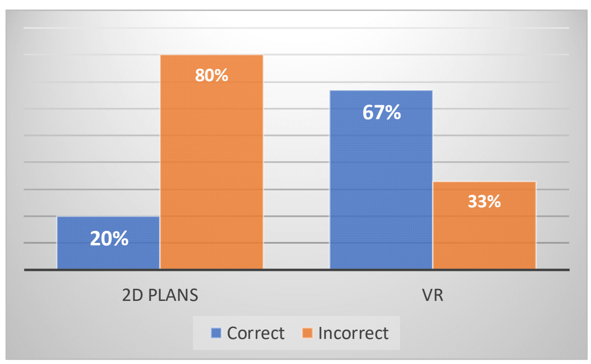


Figure 8. Correct vs Incorrect Answers to Mechanical Element Sizes

Similar questions were asked about the daycare center by using only 2D plans and then by using non-immersive VR. Daycare center was the sample project with clashes. When students were asked if they had seen any clashes only 20% found clashes in the 2D plans, while this rate was improved to 87% after non-immersive VR. Interestingly, answers to questions whether all supply diffusers fit onto ceiling grids and questions related to the size of mechanical elements were very close in percentages of students, who answered correctly for both 2D plans and non-immersive VR.

After the technical questions related to the elementary school and the daycare center, it was time to ask questions to compare non-immersive VR and immersive VR systems. According to the pre-survey results, 80% of the students have not used VR before. After using non-immersive VR, 50% of students found it easy/very easy to use (Figure 9). On the other hand, 80% of students found immersive VR easy/very easy to use (Figure 10).

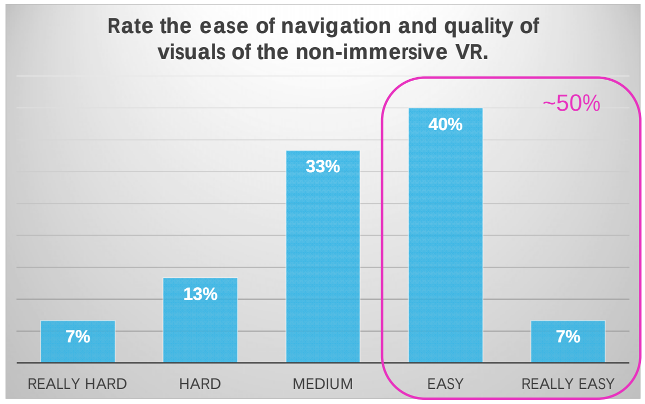


Figure 9. Ease of Navigation and Use of Non-immersive VR

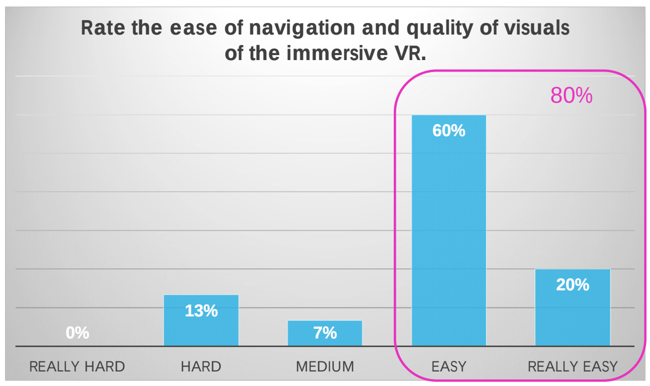


Figure 10. Ease of Navigation and Use of Immersive VR

Students were also asked to rank the use of 2D plans, non-immersive VR, and immersive VR to find relevant mechanical systems information. In the overall, 87% of students found VR better than using 2D plans in locating information. Among this 87%, 74% were in favor of immersive VR. It was interesting to see that 13% of students ranked 2D plans higher than either immersive or non-immersive VR. That states that there are still traditional students, who would like to use 2D plans instead of virtual visualization technologies.

Post-survey included open-ended questions to identify pros and cons of non-immersive and immersive VR systems. Pros of immersive VR were stated as:

- Being able to see real perspectives and feel of space
- Visualize building better
- Easy to see clashes/mistakes
- Easy to navigate for a 1st time user

Although immersive VR was found as a successful method for visualizing mechanical systems, students mentioned that non-immersive VR had pros such as:

- Not getting lost in the building
- Being able to reference plans
- Being practical

As mentioned in previous studies (Ozcan-Deniz, 2018), it is a necessity to have a co-pilot outside the VR system to help immersive VR user to navigate around the building. As students were aware of this fact, they stated that one might get lost in the building in the immersive VR, but not in the non-immersive as users have had the ability to reference to 2D plans during the non-immersive virtual walk-through. Considering the cost associated with the immersive VR system, students found non-immersive being practical and feasible from both a cost and accessibility perspective.

Cons of both systems were asked. Finding dimensions was found difficult in both non-immersive and immersive VR. Non-immersive VR was found hard to navigate due to the use of keyboard and mouse. Although having goggles and controllers eased navigation in the immersive VR, not being able to reference drawings was found as a weakness. In addition to being more expensive than non-immersive, immersive VR was reported to have another disadvantage. Students realized the cybersickness potential of immersive VR and having a time limit was stated as another weakness.

Considering the results, both non-immersive and immersive systems were found to improve students' understanding of mechanical systems in comparison to traditional visualization methods such as 2D plans. Students benefited from the improved visualization potential in especially finding clashes of building systems. Although both VR systems found useful by the professor and students, non-immersive VR was more practical in terms of affordability and ease of setup. Immersive VR technology requires a first cost to purchase, cost and manpower for maintenance of hardware and software, and additional time to setup the system, while non-immersive VR requires a minimum first cost to start up such as the license cost of the software and takes less time to setup. It does not require additional manpower from IT due to being less complicated than immersive VR as the whole system. As it would not be possible to use immersive VR in all classes, it may be beneficial to focus on upper level CM courses to adopt immersive VR.

4. Conclusions

This study compared two types of VR applications, as non-immersive and immersive in developing CM students' understanding of building mechanical systems. As it VR's potential for teaching and education was well-known, the intention was to see whether non-immersive or immersive VR would be more beneficial for CM undergraduate students. With a VR experiment setup, students' understanding of mechanical systems by using 2D plans, non-immersive VR, and immersive VR was analyzed to verify the ability of each application in providing a better understanding of mechanical systems. Students viewed actual construction projects and answered pre and post-survey questions related to their background of building systems and VR, technical knowledge of mechanical systems, clash detection, and use of VR systems.

Results showed a significant increase (from 47% to 87%) in observing clash detection in between 2D plans to VR. Similar results were observed for technical questions related to mechanical systems, as students' understanding was improved from 20% to 67% in immersive VR. For clash detection, there was only a slight increase (from 80% to 100%) in immersive VR. Results were even more interesting for non-immersive VR. The understanding of students of clash detection was improved from 20% to 87% after non-immersive VR, while the percentage of success of students in observing sizes of mechanical elements were exactly the same before and after non-immersive VR. That may be the most unexpected result of the study, as it was expected both non-immersive and immersive VR would improve students' understanding of mechanical systems.

Findings suggest that immersive VR improves students' learning better than non-immersive VR in terms of both observing clash detection and locating mechanical systems information. The strengths of immersive VR were stated as being able to see real perspectives and feel of space and visualize building better. Student also stated that it was easy to see clashes, which is also apparent in quantitative results. Considering the study was performed with a student group that was majorly new to the VR technology, immersive VR's controls allowed students to navigate in the virtual environment easily after a short orientation. Despite the cost associated with the immersive VR system, it is still the most beneficial one in CM students' learning.

The fact that students' understanding of mechanical system was exactly the same by observing 2D plans and after using non-immersive VR diminishes the impact of non-immersive VR for building and construction industry. As non-immersive VR improved observation of clash detection for CM students, it is suggested to use non-immersive VR in introductory CM courses to: (1) Introduce VR technology to students, and (2) Show how virtual walk-throughs can be used in the construction industry. Including non-immersive VR to lower level CM courses would familiarize students with VR systems within a limited budget and without the requirement of a detailed setup process. As immersive VR performs better in improving students' understanding, it is suggested to include immersive VR in upper level CM courses to make sure students benefit from VR knowledge, considering its extensive use in the construction industry. Immersive VR can be implemented horizontally through several courses to make sure its use in different subject areas are practiced in the CM curriculum. With the combination of BIM and VR, CM graduates would be successfully equipped with VR knowledge to keep up with the needs of the industry.

5. ACKNOWLEDGEMENT

This research was conducted with the support of Thomas Jefferson University with associated Honors Research Grant entitled: A Comparative Analysis of Non-Immersive and Immersive VR on Improving Students' Understanding of Building Systems (2019-2020).

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AN APPLICATION OF VIRTUAL ENVIRONMENTAL TECHNOLOGY FOR REDUCING THE PROBLEMS OF CONSTRUCTION WORKS CHANGE ORDERS.

Noppadon Jokkaw, Tanit Tongthong, Somjintana Kanangkaew
Chulalongkorn University, Thailand

ABSTRACT: *The objective of this research is to propose an application of Virtual Environment (VE) technology in the construction focused for change orders in the construction project. The possibility of Virtual Environment technology to apply for reducing the problems of change order in the construction project was studied. The assumption of this research is the feeling of users measured by using VE applications and the real situations are not different. The assumption was tested by the respondents' feeling using the questionnaire that compared between the feeling measured by VE applications and the real situations. The two cases studies in the real construction project were used for the experiment. The 20 respondents were selected to visit the construction site and compared the feeling between using VE application and the real situations. The statistical analysis was applied to analyze the data from the questionnaires. The results of the research show that the feeling of the respondents who applied the VE applications and the real situations in the construction project for both case studies are not significant difference. Therefore, it can be concluded that the VE technology is possibly applied in order to reduce the problems of change orders in the construction project.*

KEYWORDS: *Virtual Environment, Change Orders, Construction Project.*

1. Introduction

1.1 Background and objective

In the construction projects, the change orders occur due to the misunderstanding of the construction drawing among the parties such as owners, the contractors, and the designers. The change orders can make the problems which have high impact to the construction projects. The effects of the problem of change orders in the construction projects are such as cost overrun and time delay. Nowadays, 3-D software can be applied in many construction projects that can help the owners or the users to enhance their understanding and imagination when they look at the construction drawing. However, the 3-D application cannot build the users' feeling as the real situation so the change order problems are not reduced as much as expectation. However, Virtual Environment (VE) technology is the technology that has high efficiency to build the users' feeling as real as in the real situations. It can build the users' feeling that involve the dimension changing (the width, length, and height) such as comfortable, tight, safety, and dangerous feeling. The designer can apply the VE technology to measure the users' feeling during design process and may adjust the dimension in the design drawing before construction process or project complete. Thus, the VE technology may apply to the construction projects to help reducing the change orders. This research is to propose the experiment of Virtual Environment (VE) technology application for reducing the problems of change order in the construction project.

2. Literature Review

2.1 Types of construction drawings

2.1.1 Two-dimensional (2-D) drawing

The two-dimensional (2-D) drawing is too simple. It shows only its length and width that can be measured along the X-axis and Y- axis. The purpose of two-dimensional (2-D) drawing is intended to describe the size and shape of an item and may provide information regarding acceptable variations, materials and any other information that can help a complete understanding of an item.

2.1.2 Three-dimensional (3-D) drawing

The three-dimensional (3-D) drawing is a virtual plan that simulates the structure such as the width, the height and the depth of the building to look as close to reality as possible including the decoration work, the interior work, along to the landscape work. [1]

2.2 Concept of Virtual Reality

2.2.1 Virtual Reality (VR)

Virtual reality is usually implemented using computer technology to enhance user's imagination and feeling such as three-dimensional (3-D) model. There are a range of systems that are used for visual reality such as Head-Mounted Display – HMD, Omni-directional treadmills and special gloves. These are used to stimulate our senses such as vision, hearing, touch, even smell together in order to create the illusion of reality. [2] There are 5 types of Virtual Reality [3] can be described as follows:

1. Desktop VR or Window on a world (WoW) is an application developed for a computer monitor to display in a Virtual screen to support and enhance the user to understand the information.

2. Video Mapping is a projection technique used for specialized software. Three-dimensional (3-D) model is spatially mapped on the virtual program which mimics the real environment it is to be projected on.

3. Immersive System is a VR system that the user to use a data glove and Head-Mounted Display – HMD and tracks the user's movement when they change the view.

4. Tele-presence is a range of technologies that enable one person to appear present to another from a remote location such as a video conference, holograms, and robots.

5. Augmented Reality (AR) is an upgrade of VR where synthetic stimuli (computer-generated visual, audio or haptic information) are superimposed onto real-world stimuli [4]. Augmented Reality applied to develop users to understand and perceive the displayed invisible information such as in the medical field, during the surgery.

2.2.2 Virtual Environment (VE)

Virtual Environment is a computer simulation to create a realistic environment for users and perceive by senses vision, hearing, touch, smell, and taste. All the feeling processes and display by a computer and accessories that give users access to the virtual environment. Accessories that use in virtual environment consist of Head-Mounted Display (HMD) and Cave Automatic Virtual Environment (CAVE) can be described as follows:

1. Head-Mounted Display (HMD) is a Virtual Reality headset attach straight to the user's head as shown in Fig.1 and present visuals directly to eyes and peripheral vision as well. There is a display divided into 2 parts for both eyes and the images shown as simulated within different angles allow the user to see the image display in a three-dimensional (3-D) model as a real object [5]. In addition to displaying images, motion detection devices can be added and show the direction of sight in the virtual environment in accordance with the direction of the user.

Fig.1: Head-Mounted Display (HMD)

2. Cave Automatic Virtual Environment (CAVE) is an Augmented Reality (AR) and scientific visualization system. CAVE uses stereoscopic pictures on the walls of the room instead of using Head-Mounted Display – HMD. [5]. CAVE consists of the 3^{th} walls and the 1^{st} door as the 4^{th} wall as a flat screen with the projectors to form 4 projection surfaces. In the CAVE projection on 6 surfaces of a room as shown in Fig. The 2 allows users to turn around and look in all directions and interact with a virtual environment in ways with a better sense of full immersion. [6]

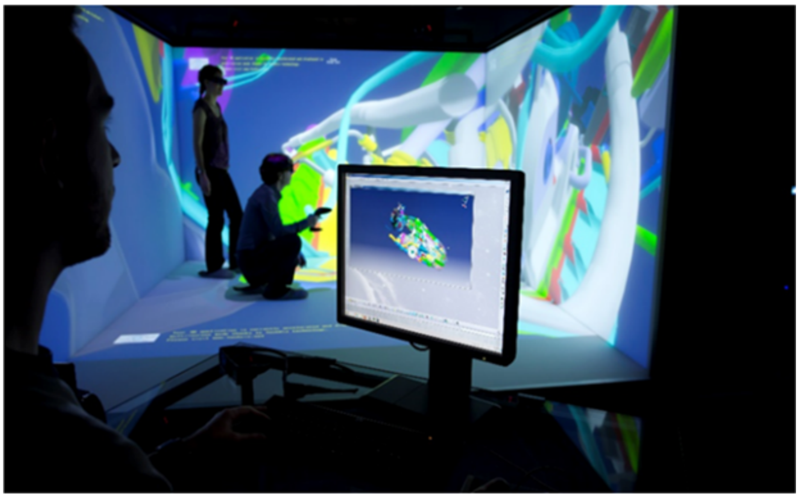

Fig. 2: Cave Automatic Virtual Environment (CAVE)

2.3 Causes of revise for construction drawing (Change orders)

Cause of revised for construction drawing have 2 main causes such as change order by the owner and conflict due to uncompleted drawing and specification [7]. First main cause is change order that refers to the changes in the scope of work by the owner agreement. There are 2 minor causes such as the need for user changed and the uncertainty of the construction drawing and specifications.

3. Methodology

This research is to propose an application of Virtual Environment (VE) technology for reducing the problems of change order in the construction project. The assumption of this research is the feeling of users measured by using the VE application is not different from the real situation. The assumption was tested by the questionnaire that compared the feeling by VE application and the real situation. The methodologies that were used to verify the user's feeling measurement can be described as follows:

3.1 Selecting the case studies

This research focused on As-built drawings of the real construction project that have improper dimension and unsafe user's feeling. The two cases studies in the real construction project were selected for testing such as Nursing' student bedrooms and stair halls.

3.2 Developing the models for testing

In this research, there are two types of models were applied to test the user's feeling such as three-dimensional (3-D) model and Virtual Reality (VR) models in Virtual Environment (VE). The details of each method are described as follows.

3.2.1 The three-dimensional (3-D) models

The three-dimensional (3-D) model of Nursing' Student bedroom and stair hall were created by Autodesk Revit 2019 for illustrated in virtual environment as shown in Fig 3.

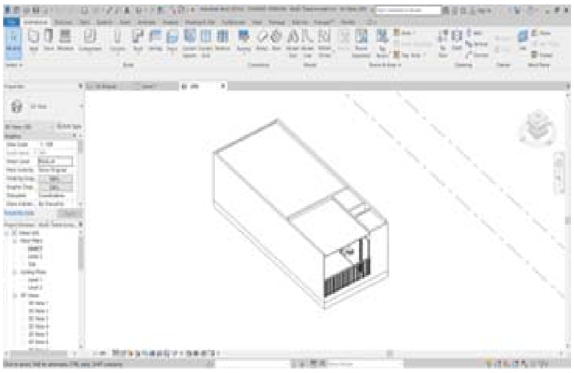

Fig.3: The three-dimensional (3-D) model created by Autodesk Revit 2019

3.2.2 Virtual Reality (VR) models

For enhancing the reality of the construction site environment, Enscape software as shown in Fig.4 was applied to develop the Virtual Environment models. The users have to use Head Mount Display and run by Enscape software for looking at the virtual reality (VR) models as shown in Fig.5 and Fig. 6.

Fig. 4: Enscape software

Fig. 5: The Reality Environment of construction site by using Enscape software

Fig. 6: A user is using the Head Mount Display for looking at the virtual reality (VR) models

3.3 The experiment of feeling measurement

In this research, the experiment of feeling measurement was investigated by the user's feeling of responding in 2 case studies such as student bedroom and stair hall in a nearly completed building construction project which have improper dimension. The project owners prefer to change the dimensions but it will make the project cost overrun. The respondents were tested their feeling that responded by Head Mount Display in Enscape software for looking at the virtual reality (VR) models compared the feeling in the real situation in the construction site. The questionnaires were applied to obtain the respondents' feeling.

3.3.1 Samples

The respondents are the students who will be the users of the building after the construction project completed. The 20 respondents were randomly selected to be the respondents for the experiment. In part of testing, they were divided into 2 groups such as 10 respondents for testing the proper dimension of student rooms (measure comfortable feeling) and 10 respondents for testing the proper height of stair handrails in the stair hall (measure the safety feeling).

3.3.2 Data Collection

The experiment of feeling measurement was investigated by the respondent's feeling between the feeling in the real situation and in the virtual environment displayed in Head Mount Display. Questions in the questionnaires are the rating scale with 5 levels of feeling such as comfortable feeling with the dimension of the room (width, length, and height) and safety feeling in each case study, respectively. The users will respond their feeling level from 1 to 5 scaling of comfort and safety feeling.

For case study No. 1: The student rooms in the dormitory were divided into 4 rooms such as bedroom, balcony, bath room and toilet, respectively. The respondents were tested by their feeling between the feeling in the real situation and in the virtual environment by used Head Mount Display one by one room as shown in Fig.7 (a) and Fig.7 (b). After that, they responded their feeling levels from 1 to 5 such as appropriate room width (5 = very wide, 4 = wide, 3 = medium, 2 = small, 1 = very small) and the room height (5 = very high, 4 = high, 3 = medium, 2 = low, 1 = very low) for each room in the questionnaires.

(a) The feeling tested in the real situation

(b) The feeling tested by VE tools

Fig.7: The feeling measured by the real situation and virtual environment for dimension of the rooms

For case study No. 2: in the stair hall, the stair levels were divided into 4 levels such as the 4th, the 5th, the 6th the 7th floor level, respectively. The respondents' feeling were tested by the real situations and virtual reality (VR) environment using Head Mount Display one by one location as shown in Fig.8 (a) and Fig.8 (b). After that, they responded to their safety feeling levels from 1 to 5 for the height of the handrail and type of handrail (5 = very safe, 4 = safe, 3 = normal, 2 = unsafe, 1= very unsafe) for each level by using the questionnaires.

(a) The feeling tested in the real situation

(b) The feeling tested by VE tools

Fig.8: The feeling measured by the real situation and virtual environment for height of stair hand rail

3.3.3 Data analysis

The levels of the respondent's feeling on comfortable and safety in each case study between the real situation and virtual environment were analyzed by 2 statistical analysis. There are such as Paired-Simples test to obtain the Mean of feeling level in real situation$(\bar{\mu}_{pre})$, Mean of virtual environment$(\bar{\mu}_{post})$, Mean of difference level$(\bar{D}_{ij})$, Standard Deviation$(S.D.)$ of feeling level by using Eq.(1), Eq.(2), Eq.(3) and Eq. (4) and Sample T -Test to obtain the null hypothesis (H_0) and alternative hypothesis (H_1). Then, the probability of observing the test statistic under the null hypothesis comparing *t* to a *t-distribution* with (n − 1) degrees of freedom were calculated.

$$\bar{\mu}_{pre} = \sum_i^n \frac{X_i}{N} \quad (1)$$

$$\bar{\mu}_{post} = \sum_i^n \frac{Y_i}{N} \quad (2)$$

$$\bar{D}_i = \sum_i^n \frac{D_i}{N} \quad (3)$$

$$S.D. = \sqrt{\frac{N\sum_{i=1}^{N} D_i - \left(\sum_{i=1}^{N} D_i\right)^2}{N(N-1)}} \quad (4)$$

Where X_i = Level of user's feeling in the real situation

Y_i = Level of user's feeling in virtual environment

D_i = Difference level of user's feeling between the real situation and virtual environment

N = Number of users

Sample t-test was used to determine whether a sample of observations could have been generated by a process with a specific mean to test hypothesis such as the null hypothesis (H_0) and alternative hypothesis (H_1). In this research the null hypothesis (H_0) assumes that the mean of respondent's feeling measured in the real situation $(\bar{\mu}_{pre})$ is not different measured by using virtual environment $(\bar{\mu}_{post})$ and the alternative hypothesis (H_1) assume that the mean of respondent's feeling measured in the real situation $(\bar{\mu}_{pre})$ is different the mean measured by using virtual environment$(\bar{\mu}_{post})$. The null hypothesis and the alternative hypothesis are defined below:

$$H_0 : \bar{\mu}_{pre} = \bar{\mu}_{post}$$

$$H_1 : \bar{\mu}_{pre} \neq \bar{\mu}_{post}$$

Once the assumptions have been verified and the calculations are complete, all that remains is to determine whether the results provide sufficient evidence to reject the null hypothesis in favor of the alternative hypothesis.

4. Result of the experiment of feeling measurement

4.1 Comparision the difference between the the feeling in real situation and VE

4.1.1 Case study 1: The room dimension

From the pair-wise comparison of the level of respondents' feeling by the real situation and virtual environment of 10 respondents in case study No.1 that analyzed by Paired-Simples test and Sample t-test method, all levels of the comfortable feeling in part of the width and the height of each room can be presented in Table1 and Table 2.

Table 1: The Mean, Standard Deviation of comfortable feeling level for room width ($\alpha = 0.05$)

Pair No.	Mean	S.D.	Sig. (2-tailed)	H_0	H_1
Pair No. 1	-0.800	1.398	0.104	Accept	Reject
Pair No. 2	-0.100	0.994	0.081	Accept	Reject
Pair No. 3	-0.800	0.632	0.758	Accept	Reject
Pair No. 4	-0.500	0.707	0.052	Accept	Reject

In Table 1, the level of comfortable feeling in part of the room width in the real situation and virtual environment of each room obtain the Sig. (2 tailed) values such as 0.104, 0.081, 0.758 and 0.052, respectively that higher than critical value ($\alpha = 0.05$). Therefore, the null hypothesis were accepted which can be concluded that the feeling that measured by the virtual environment and the real situation for the room width are not significant difference.

Table 2: The Mean, Standard Deviation of comfortable feeling level for room height ($\alpha = 0.05$)

Pair No.	Mean	S.D.	Sig. (2 tailed)	H_0	H_1
Pair No. 1	0.100	0.316	0.343	Accept	Reject
Pair No. 2	-0.300	0.568	0.081	Accept	Reject
Pair No. 3	-0.100	0.561	0.561	Accept	Reject
Pair No. 4	0.000	0.000	1.000	Accept	Reject

In Table 2, the level of comfortable feeling in part of the room height in the real situation and virtual environment of each room obtain the Sig. (2 tailed) values such as 0.343, 0.081, 0.561 and 1.000, respectively that higher than critical value ($\alpha = 0.05$). Therefore, the null hypothesis were accepted which can be concluded that the feeling that measured by the virtual environment and the real situation for the room height are not significant difference.

4.1.2 Case study 2: Stair handrail

From the pair-wise comparison of the level of respondents' feeling by the real situation and virtual environment of 10 respondents in case study No.2 that analyzed by Paired-Simples test and Sample t-test method, all levels of the safety feeling in part of the stair handrail height can be presented in Table 3.

Table 3: The Mean, Standard Deviation of comfortable feeling level for stair handrail height ($\alpha = 0.05$)

Pair No.	Mean	S.D.	Sig. (2 tailed)	H_0	H_1
Pair No. 1	0.500	0.527	0.150	Accept	Reject
Pair No. 2	0.200	0.632	0.343	Accept	Reject
Pair No. 3	0.200	0.422	0.168	Accept	Reject
Pair No. 4	0.000	0.667	1.000	Accept	Reject

In Table 3, the level of safety feeling in part of the stair handrail height in the real situation and virtual environment of each room obtain the Sig. (2 tailed) values such as 0.150, 0.343, 0.168 and 1.000, respectively that higher than critical value ($\alpha = 0.05$). Therefore, the null hypothesis were accepted which can be concluded that the safety feeling that measured by the virtual environment and the real situation for the stair handrail height are not significant difference.

5. Conclusions

The objective of this research is to propose an application of Virtual Environment (VE) technology in the construction focused on change orders in the construction project. The possibility of Virtual Environment technology to apply for reducing the problems of change order in the construction project was assumed. In two cases studies, the experiment of feeling measurement was investigated by 20 respondent's feeling such as comfortable feeling for the dimension of the room (the width and the height) and safety feeling for stair handrail height were made in the real situations and virtual environment by used Head Mount Display. Two cases of studies were designed and compared by pair-wise comparison. Statistical methods were used to analyze the feeling level such as Paired-Simples test and Sample t-test.

From the statistical analysis of the feeling measured by the real situation and virtual environment, the results show that the comfortable for room dimension and safety feeling for stair handrail height that measured by the virtual environment and the real situation are not significant difference. It can help the owner and the designer to clear the dimension of room and stair handrail height for the users' comfortable and safety feeling. Therefore, it can be concluded that the VE technology will be possibly applied to reduce the problems of change order in the construction projects.

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A Novel Solution of Workload Management Based on Tunnel Worker's Physical Status Using Wearable PPG Heart-Rate Detection Wristband and BLE IoT System

Wei-Cheng Chen Ph.D. Candicate and Hui-Ping Tserng Ph.D.

Department of Civil Engineering, National Taiwan University, TAIWAN

Jiasheu Josh Huang Ph.D

Gini Bio-Technology Corporation Limited, TAIWAN

ABSTRACT: *According to the latest statistics revealed by International Labor Organization (ILO), 33.7 million accidences happened around the global with USD1.2 trillion lost consequently. Safety management has been acting as the most important role in all national construction projects, that encourages innovative technologies to be introduced to many construction projects to save more precious lives. This paper proposes wearable heart rate detection devices and senor networks to instantly assess worker's workload, that can prevent accidents caused by worker's unintentional errors. Heart rate is commonly recognized as human's physical and psychological index used to assess one's fatigue status in clinics. Thanks to the advance of micro photo-electronic technologies, the Photoplethysmography (PPG) device is popularly used as the heart rate monitor in the athletic training program. To extend the value-added application of wearable PPG devices, we've developed a novel IoT system incorporated with the bioinformatics theory. Therefore, we can continuously monitor and collect construction worker's heart rate without interfering their routine work. In our experiment, 16 volunteer workers from a shield tunnel construction project have joined our field test. However, the result of our first field test was not satisfactory. Modification work of wearable PPG devices and IoT gateways were conducted successfully to fulfill the expected data availability of 80%. We increased the data transmission rate of the PPG device, and increased the number IoT gateways installed in the shield tunnel. Finally, we have successfully achieved 85% of the data availability in our second field test conducted in October and November 2018. In this paper, we demonstrate the PPG heart rate detection device, Bluetooth sensor network and application system used in the shield tunnel construction projects. In order to analyze worker's workload, we've established the standard procedure of measuring worker's Resting Heart Rate (RHR), the assessment method of Percentage of Reserve Heart Rate (%HRR) and Workload (%L), which can be used as the guideline for arranging worker's shifts and tasks in the shield tunnel construction projects.*

KEYWORDS: *PPG, RHR, HRR, Workload, BLE, IoT.*

1. INTRODUCTION

In every 10 minutes, one labor's life is taken away by accidence and sadly there are more than 60 thousand of casualties caused every year (Yi, W., Chan et al., 2016). Construction workers are involved in the highest casualty rate industry, which has 3 to 4 times higher casualty rate compared to other industries (Yilmaz, F. et al., 2015). According to statistics published by International Labor Organization (ILO), 33.7 million accidents happened around the global with USD1.2 trillion lost accordingly. Due to such a high casualty rate happened in construction projects, safety management has been included by the Project Management Body of Knowledge for years. NIOSH has been promoting Total Worker Health (THW) to inspire and encourage construction companies and workers to be more cautious and vigilant to safety related matters including off-duty times. (Wonil Lee, 2017) (Lee, Lin, Seto, &Migliaccio, 2017). It is known that construction projects are versatile but extreme hazardous. Especially the tunnel construction sites are the most dangerous construction sites of all. In the tunnel, workers are not only constrained by the limited space but also limited fresh air and light, furthermore workers are burdened with psychological pressures caused by closed-by noisy machine, smelly air and blurred sight. Tunnel construction workers have more workload due to the both physical and psychological burdens, which may cause worker's cognitive obstruction or even damage if fatigues strike them. These cognitive obstructions are the main factors of causing fatigue to those workers and likely lead them to fatal accidents. This paper seeks for innovative solutions to facilitate the safety management of tunnel construction projects. We found wearable devices and IoT sensor networks are potential solutions to monitor worker's physical status and to prevent accidents caused by unexpected fatigue usually happened to tunnel construction workers.

In this paper, we propose an innovative solution to monitor worker's heart rate and workload in the near real-time fashion. With the help of wearable PPG sensor and IoT technology, a real-time worker's workload monitoring system is soundly designed and installed in the shield tunnel construction site. Shield tunnel construction workers wearing the heart rate monitor device so that their heart rate data are collected and analyzed instantly. Therefore, the Percentage of Reserved Heart rate (%HRR) known as the index of human workload or fatigue level, can be measured and accumulated workload of each worker is calculated automatically. We expect these analytical data can be further processed using Big Data or Deep Learning theories, so that the prevention algorithm based on Hear Rate Reserve (HRR) and Heart Rate Variability (HRV) can be developed in the near future. Such a prediction and prevention algorithm will bring great benefits to all construction workers as well as to construction companies, because we trust construction worker's safety is the top priority in all construction projects.

2. DEVELOPMENT AND VALIDATION OF HEART RATE MONITERING SYSTEM

To meet the rigid requirement and constrain for any electronic device or system in the harsh tunnel construction environment, this research integrates wearable PPG heart rate detection devices, IoT sensor networks, and cloud computing applications, to come up with a total solution of worker's heart rate and workload monitoring. The core technical breakthroughs in this research are the customized PPG heart rate detection device and the adaptive IoT sensor network, which are reliable and durable deployed in the hazardous shield tunnel construction site.

2.1 Experimental Site and Volunteer Workers

The tunnel construction site designated for our experiment locates in the suburban of Taipei, which is a standard trenchless tunnel construction site with a shield tunnel of 2,255 meters in length and 2.1 meters in diameter. The launching shaft is built by RC caisson with 10 meters in diameter and 22 meters in depth. Arriving shaft is built by RC with 8 meters in diameter and 23 meters in depth. Most tunnel construction activities surround the drill machine; therefore, workers are all around the drill control station during the working hours. There are 2 shifts a day, day shift and night shift, and six working days a week excluding Sunday. Each tunnel construction team has seven members, one is drill control station operator, two are shield segment installers, two are cement filling operators, one is material transporter, and the seventh member is the crane operator working on the ground.

The field experiment was token place for 30 days starting from October 15 until November 14, 2018. Volunteer construction workers in the day shift wear the PPG heart rate detection wristband from 7am until 7pm. When workers finish their daily work, they leave the wristband at the construction office for charging. The experiment has successfully collected the heart rate data from 15 workers and gathered 199 data sets in total. Before the experiment began, all volunteer workers had signed up the privacy agreement, and the experiment program was approved by the IRB Committee of University of Taiwan.

2.2 Design of Heart Rate Senor Network

In this search, Bluetooth v4.2 (BLE) is adopted as the data communication protocol of the heart rate senor network. BLE has many advanced features like low energy secure connection, bulk data high exchange rate and fast data advertising interval, which are advantageous for developing such an affordable and accountable senor network. The PPG heart rate detection wristband has built-in BLE v4.2 chipset which transmits heart rate data to the BLE IoT gateway continuously, then the heart rate data are routed to the application system built on the cloud computing platform for further processing.

The heart rate sensor network used in tunnel construction site shall meet the following requirements (T. Y. Ho et al., 2009):

1. Wearable and high accuracy and resolution of heart rate detection.

2. 24 hours continuously heart rate data collection and transmission.

3. Location-based and identification awareness.

4. Open data-exchange interface to be connected to other system.

Table 1. Customization of the PPG heart rate wristband

No.	Management Requirements	Specifications	Descriptions
1	Full range detection of heart rate	Sampling rate >500 times/second	Heart rate detection range from 30 to 200bpm.
2	Continuous detection	Heart rate detection and transmitting rate >10 times/second	Heart rate data can be received by application system at least in every second.
3	Full working hour power duration	Battery life before next charge>12 hours	A full operation period of one shift.
4	Environment sustainability	IP66 Standard	Water, dust, and shock proof.
5	Mobility	Bluetooth Low Emission version 4.x	Full coverage of heart rate senor network in tunnel construction site.

2.3 PPG Heart Rate Sensor and Validation

Construction operation for field workers is very intensive and fast calories consuming. Workers having long working hour without sufficient rests can be easily led to fatigue and low work efficiency, or even diseases in some worst case. Papers indicate human's heart rate can be analyzed to assess worker's physical and psychological health status. In order to meet the requirements of heart rate analysis, the PPG wristband must be customized to meet the specifications listed in Table 1.

In order to validate the PPG wristband, a test program of 6 volunteers and 20 minutes exercise was conducted in a gym. Each volunteer wears a PPG wristband and an ECG tag (US FDA approved) and then running on jogging machine for 20 minutes. Each tester is required to run for three times and have a 10 minutes break before the next exercise. Heart rate data generated by PPG and ECG are collected simultaneously. Unfortunately, one tester is overweight and causes the jogging machine unstable, that results his heart rate data abnormal and must be discarded. We took the heart rate data from the other 5 testers into account and proceeded the data analysis work.

Figure 1 and 2 illustrate heart rate data of the two testers generated from ECG tag and PPG wristband during the 20 minutes of exercises.

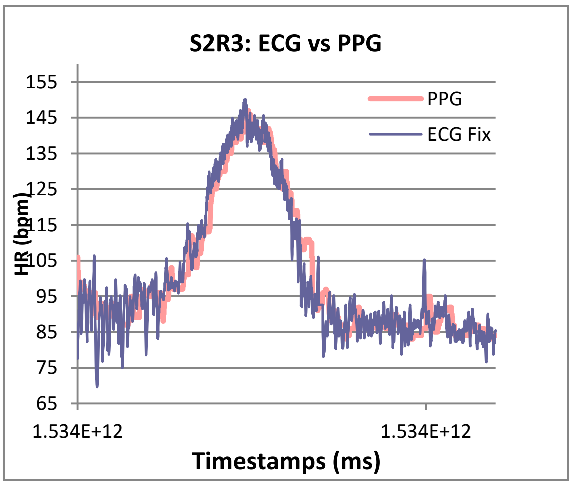

Figure 1. ECG vs. PPG from the first tester

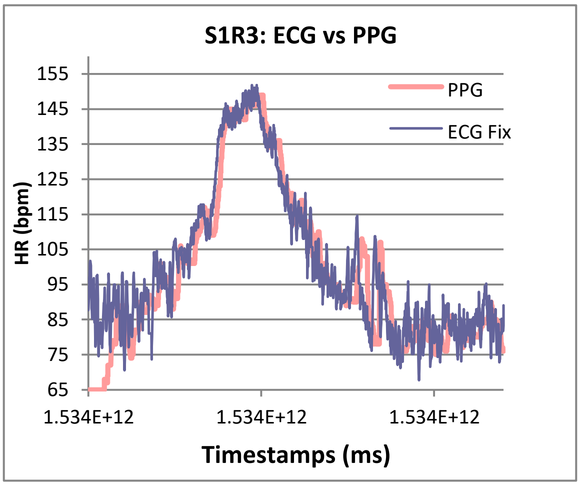

Figure 2. ECG vs. PPG from the second tester

After the correlation analysis, the first finding was the time-lag of heart rate data from PPG wristband compared with the data from ECG tag, that the average time lag of the PPG wristband was 14.8 seconds. In the paper proposed by Sungioo Hwang (2016), the lag time of PPG was 10.43 second. We then used 5 seconds as the window to calculate 2 seconds moving average, as a result 5 data sets were selected to conduct further analysis. They are S1R3, S2R3, S4R1, and S5R3, shown in Table 2, which indicates the Rs (Correlation Coefficient) and MAPEs (Mean Absolute Percentage Error). Our PPG wristband has better performance in high frequency heart rate activities like walking and running, which R is 0.9602 and 0.9802 respectively. In resting period, R is 0.8835, which is still higher compared to the result, R≧0.75, achieved by Wonil Lee, 2017.

Table 2. Accuracy test of the PPG heart rate monitor wristband

Validation Index	Round	Subject 1	Subject 2	Subject 3	Subject 4	Subject 5	Average
Sensor Coverage%	Round 1	95.88%	100.00%	100.00%	100.00%	100.00%	99.18
	Round 2	98.00%	95.75%	92.26%	92.35%	100.00%	95.67
	Round 3	100.00%	100.00%	100.00%	100.00%	100.00%	100
R (R>0.7)	Rest	0.8128	0.8408	0.9029	0.9764	0.8848	0.8835
	Walking	0.9785	0.9857	0.9090	0.9337	0.9942	0.9602
	Running	0.9905	0.9945	0.9461	0.9772	0.9947	0.9806
MAPE% (±5%)	Rest	2.73	-0.51	1.89	0.83	-0.03	+0.98
	Walking	0.68	0.08	-0.55	4.50	0.72	+1.09
	Running	-0.29	-0.12	-0.92	-0.73	-0.10	-0.43
Time lag (seconds)		16	15	15	14	14	14.8

Furthermore, MAPE from our test has better performance compared to the result achieved by Hwang, S., 2016. In running activity, our MAPE= -0.43% and R=0.9806, where MAPE=4.79% and R=0.85 (heart rate >110bpm, R=0.61) achieved by Hwang, S.. We are convinced that our customized PPG heart rate detection wristband achieves high reliability and availability.

2.4 Design of Heart rate Detection and Safety Management System

In the recent years, for the concern of worker's safety issues, there is a strong demand of sensor network for the tunnel construction project. Under the consideration of space constrain and data communications difficulty, we propose a total solution to establish the IoT senor network and application system for the use of tunnel construction sites. We use fiber-optic cable to connect each section of the tunnel construction site, which are office, standby area, material loading area, launching shaft, service area, tunnel front, tunnel middle, and tunnel end (drill control station). Each section is installed with a BLE gateway and is connected to TCP/IP intranet. Heart rate data of each worker can be collected and transmitted instantly to the application system. Table 3 shows the specifications of the PPG heart rate detection wristband and the BLE gateway proposed.

Table 3. Components of the wireless heart rate senor network

Product Name	Specifications	Product Feature
Bluetooth PPG Heart Rate Wristband	1. PPG heart rate detection 2. RFID MiFare M1 3. Support BLE 4.0 4. Up to 24hr power duration 5. IP66	

Bluetooth Gateway	1. Support BLE 4.2 2. Support concurrent 20 BLE clients 3. 100Mpbs Ethernet interface 4. Support Wifi 803.11a/b/n 5. DC5V/2A	

The software application system developed for this research is built on AWS cloud platform. AWS cloud platform supports IoT application which can process bulk data package in second level. Web application is designed to receive, process, and store heart rate data sent from those BLE gateways installed at the tunnel construction site. User interface of the web application are shown in Figure 3 and Figure 4, which explain how worker's heart rate data are received, processed, displayed, and recorded.

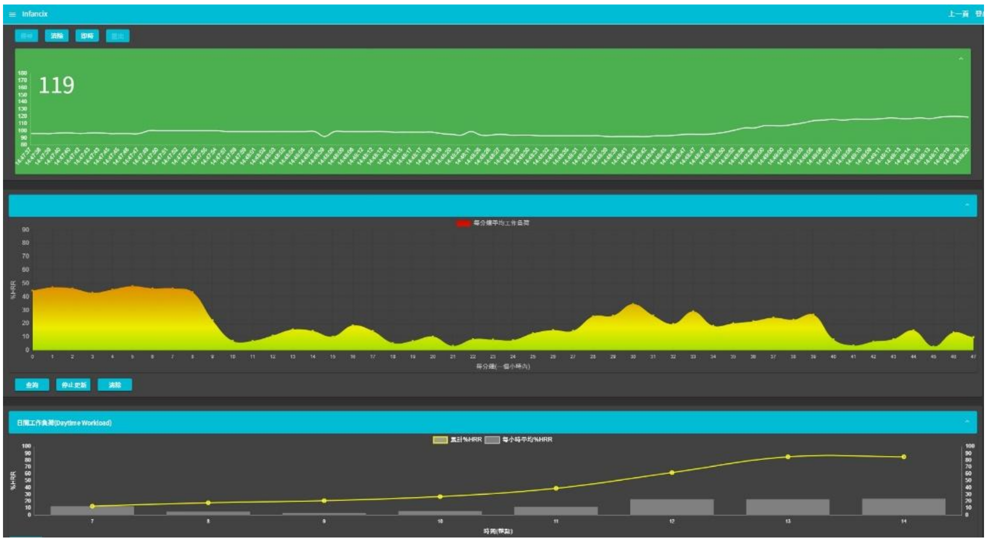

Figure 3. Dashboard of worker's real-time heart rate

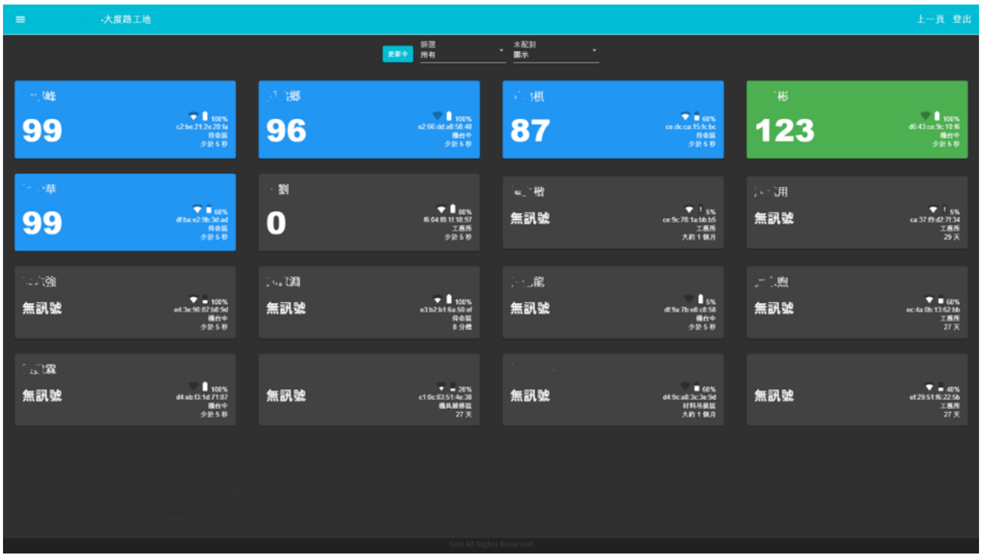

Figure 4. Heart rate monitoring dashboard of the construction worker

2.5 Developing the Management of Worker's Workload.

Based on sporting science research, Karvonen proposed the concept of Heart Rate Reserve (HRR), in which the change of heart rate (△HR) reflects the workload (L%) imposed on workers under different tasks. The equation developed by Karvonen is shown as follows;

$$HRR=MHR-RHR \quad [1]$$

$$\%L=\triangle HR/(MHR-RHR) \quad [2]$$

Resting Heart Rate (RHR) is considered as aerobic fitness index, so the better aerobic fitness, the lower of RHR, and vices versa. L% can be calculated and monitored as to assess worker's physical status, so that overloaded workload can be prevented. Working Heart rate (WHR) can therefore calculate and the equation is shown below;

$$WHR=RHR+\triangle HR$$

$$=RHR+(MHR-RHR)*L\%$$

Thus,

$$L\%=(WHR-RHR)/(MHR-RHR) \quad [3]$$

$$MHR=206.9-(Age*0.67) \quad [4]$$

Resting Heart rate (RHR) is a variable and can be refined by applying big data analysis. Maximum Heart rate (MHR) is adopted from the research result made by Jackson et al. (2007).

According to James F. Evans(1972), human's heart rate may increase by external stimulation, and there is no concern of the Reserve Heart Rate. Furthermore, such an increase of heart rate isn't limited by the ceiling effect. For example, any person's heart rate increases 10 bpm is an independent activity and no matter his or her RHR. Follow this analogy, RHR can be considered as worker's physical heath index, and such an quantitative index can monitored throughout the working hours to safeguard worker from overloaded in the high risk construction sites. Based on construction worker's RHR, this research is to develop an adaptive algorithm of calculating HRmax generated by on-duty, that can be refined to be a management protocol of conducting continuous workload monitoring. A procedure of initiate the monitoring work and data calibration was designed to fit in the regulations of Health and Safety the construction sites. A 10 minutes toolbox meeting was held before starting all work, and each worker put on their PPG wristband during the meeting. Worker's heart rate data were then collected for 10 minutes long and these heart rate data were processed to obtain RHR10 which becomes the baseline of workload assessment for safety concern.

In the clinic practice, patient's RHR is normally recorded using ECG devices and patient is lying down in a quiet room for at least 10 minutes. In the practical situation of the construction site, the collection of RHR must be adjusted to meet the complicated environment and worker's behaviors, so the 10 minutes toolbox meeting becomes the proper period for collecting worker's RHR. Although minor RHR difference may cause, but the refinement of RHR based on daily data collection and analysis can effectively minimize the difference between practical RHR and clinical ones. For safety concern, the heart rate ranging from 60 bpm to 100 pbm was set as the standard RHR_{10}, any heart rate exceeding this range was considered as an unusual case and subject to further review. The calculation procedure of RHR_{10} is shown in Figure 5.

In working hours in the construction site, worker's heart rate may drop to some low value even lower the average heart rate while taking long breaks like launch or short sleep. The minimal heart rate, HRmin, may occur during working breaks, so that If HRmin is lower than RHR_{10}, RHR_{10} is replaced by HRmin to proceed the calculation of working %HRR for the remaining working hours.

This paper proposes a novel method with the algorithm of determining worker's RHR using PPG monitoring system and big data analysis theory. Due to the refinement process automatically conducted by the PPG monitoring system, worker's RHR shall converge to a stable constant.

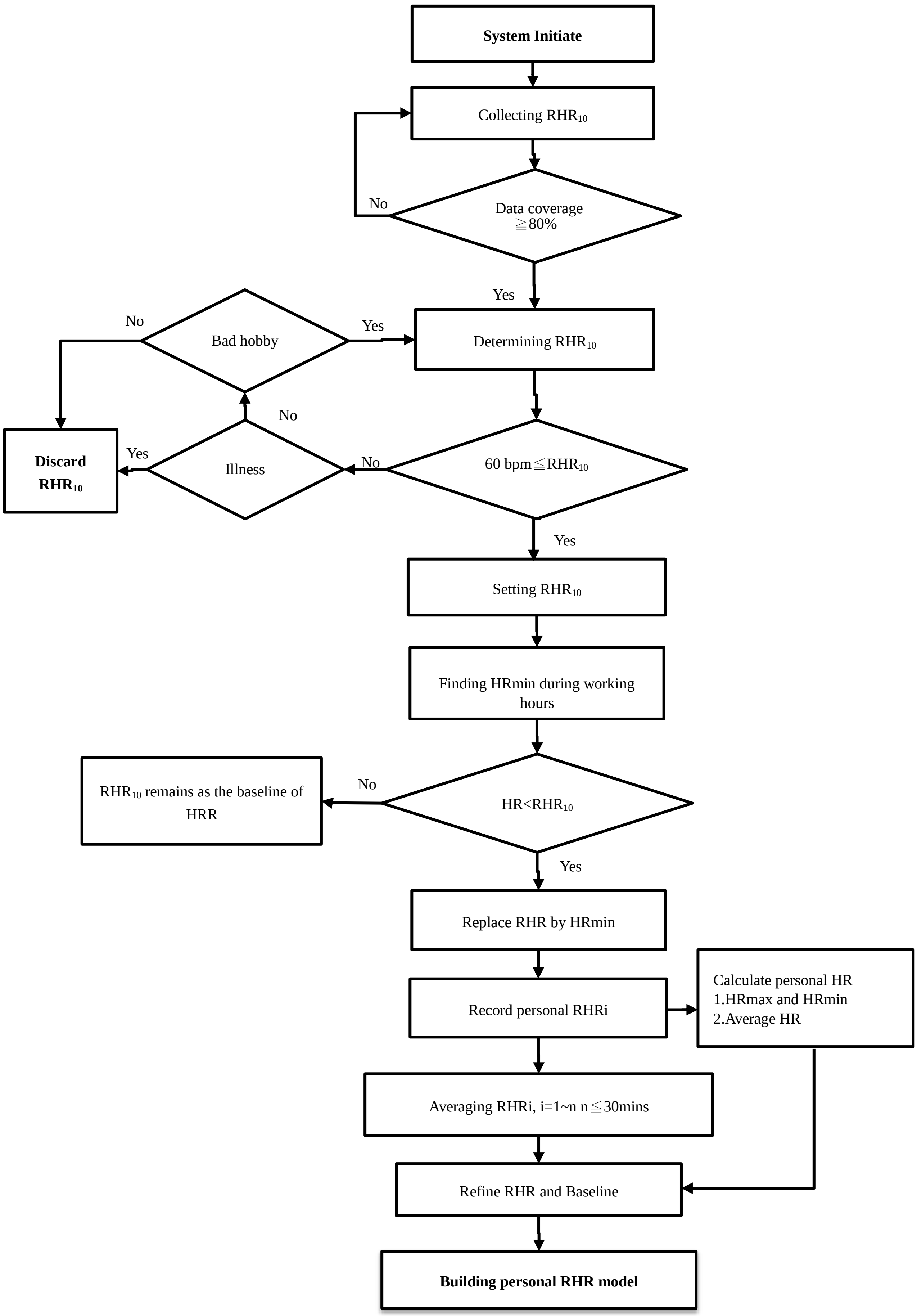

Figure 5: The calculation procedure and algorithm for optimizing working %HRR stated worker's RHR.

3. EXPERIMENT RESULTS AND DISCUSSIONS

The heart rate data sets collected from field construction workers from October 15 to November 14, which are processed in batch to generate workload L% (same as %HRR). In Figure 6., %HRR of the five workers are shown respectively dated November 12, 2018. With different job assignment, %HRR has different characteristic, in which it's apparently P1 is from the manager with less workload, and P8 is form the shield segment installer who has the most workload of all. In Figure 7., it's shown that in Monday and Friday P8 has higher workload than the other weekdays.

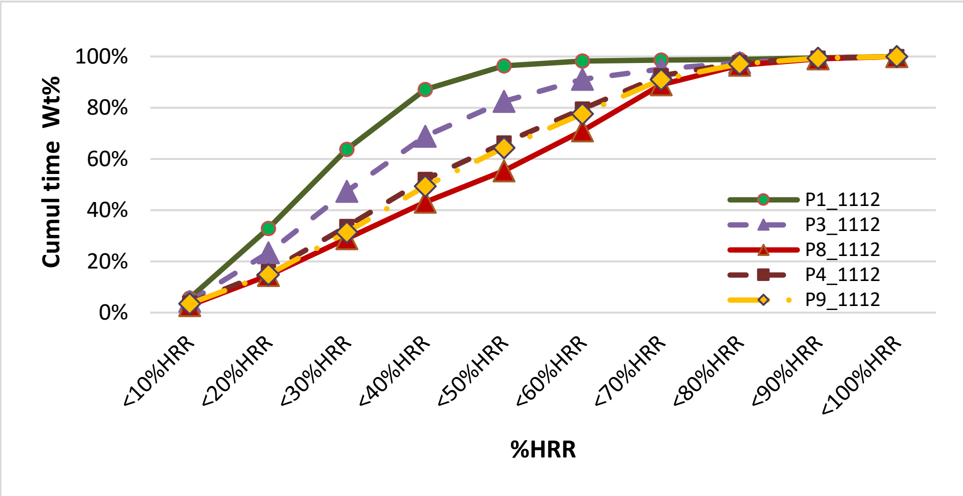

Figure 6. Workload (%HRR) difference between tunnel construction workers

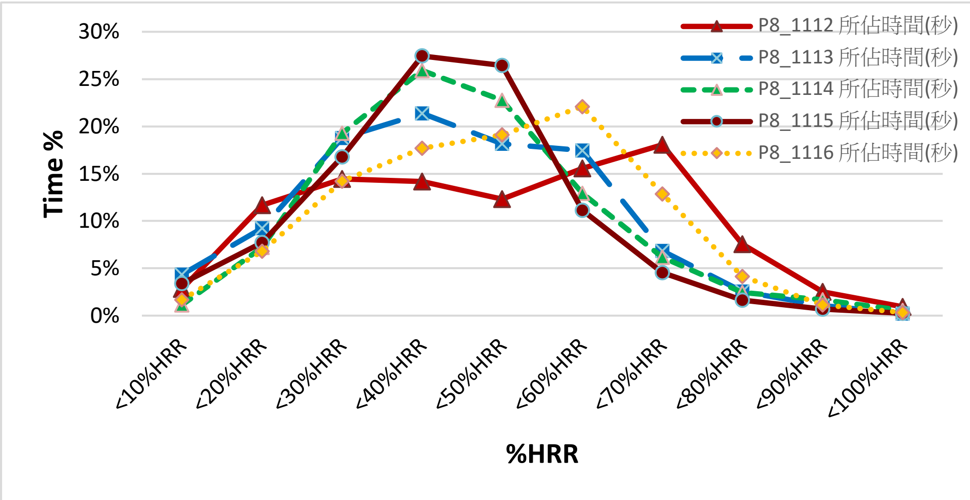

Figure 7. Workload (%HRR) distribution of No. P8 workers in one week

This research can be constantly refined and to develop the workload assessment baseline for the use of tunnel construction projects. In the paper of H. C. Wu et al. (2002), it is safe for workers that any workload of the 40%HHR task imposed on workers can only last for 60 minutes at most. For the 30%HRR tasks, it can last for 8 hours to any worker under the safety consideration. Hwang, S. et al. (2017) have pointed out that tasks of carpenter, builder and transporter may exceed 30%HRR, but tasks of electrician are less than 30%HRR. In Table 4, we proposed the %HRR guideline of different tasks involved in the shield tunnel construction project. This %HRR guideline proposed can be refined by having more data input and analysis generated from other tunnel construction projects.

Table 4. Guideline of workload for different construction sites

Operation Environment	workload	Limit of Duration
Standard Operation Environment	30%HRR	< 150 minutes
	40%HRR	< 60 minutes
	50%HRR	< 30 minutes
Hazardous Operation Environment	60%HRR	< 20 minutes
	70%HRR	< 10 minutes

5. CONCLUSIONS AND FUTURE WORK

In this research, we have achieved three contributions; first is the design of PPG heart rate monitoring devices to be usable and sustainable under the critical environment of tunnel construction sites, which has the outstanding performance of meeting MAPE <5% and R > 85%. Secondly, the integration of different communication methods and come up with an affordable and reliable heart rate senor network with the coverage rate exceeding 80%. Finally, based on the heart rate data and tasks involved, the proposed application system can instantly calculate the heart rate data collected from construction workers, and then generate the workload %HRR seen as the fatigue index. Such an application system can bring great benefits to the safety management of construction projects and as well as to all tunnel construction workers.

Future research work is to enhance data analytical models of HRR and HRV. Worker's psychological status can be analyzed and measured based on more HRV related theories (Hulsegge, G. et al. ,2018)(Madhan Mohan, P., 2016). Besides the assessment of fatigue and workload, worker's psychological factors, like stress and nervousness, are also inferential to worker's fatigue and safety.

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EXPLORING THE USE OF VIRTUAL REALITY TO SUPPORT VALUE ENGINEERING DECISIONS

Lauren Donatelli
Massaro Construction, Pittsburgh, Pennsylvania

Robert Leicht and John Messner
Department of Architectural Engineering, The Pennsylvania State University

ABSTRACT: *The use of virtual reality (VR) has seen rapid growth in construction in recent years, following the rise in popularity and lowering of cost associated with the diverse display systems, notably head-mounted displays. The cost efficiency associated with these new displays, in conjunction with significant increases in building information modeling (BIM) adoption across the construction industry has led to many new and creative applications of the visualization tools. This paper explores the application of VR to support the decision-making associated with the value engineering processes commonly employed in the late design stages of building projects. BIM and VR have been commonly noted for their value to support client visualization and decision-making, however the focus specifically on how to inform value engineering decisions has been minimal. In this exploratory research, industry practitioners are interviewed that have employed VR technology in preconstruction stages of projects, specifically associated with value engineering and value management processes. The interviews were coded and categorized to understand the use cases associated with value engineering. The findings highlight the potential for VR tools and software to play an invaluable role in the support of certain types of value engineering decisions. The discussion will also highlight the challenges associated with the timing and planning for using VR in the late design stages of construction projects.*

KEYWORDS: *Virtual Reality, Value Engineering, Value Management, BIM, Modeling*

1. BACKGROUND

Virtual reality (VR) is an immersive and multi-sensory experience. It takes “real-time interactive graphics with three-dimensional models and a display technology to give the user the immersion in the model world and direct manipulation” (Mazuryk and Gervautz, 1996). The user can watch and manipulate the simulated environment in a similar manner to the way we act in the real world, which holds the benefit of being user friendly and intuitive rather, reducing the need for extensive computer and model knowledge. The AEC industry has primarily adopted it to achieve better communication within their project teams and to their clients (van den Berg et al, 2017).

Bridgewater identifies two ways that VR is employed to support design processes. One of the most common ways is through the design process so that designers can visualize the spaces they create. Traditional forms of visualization used by designers include sketches, architectural drawings, mockups, or photomontages (van den Berg et al, 2017). However, tools such as VR, can create an immersive experience to visualize designs. For designers, this visualization tool provides a means to increase the creativity of the designers.

A second common application for VR during design is to allow owners a new media to review the design and make comments to enhance the design. The design data generated and saved through the use of VR will allow designers and their clients to understand their designs three-dimensionally, which in turn allows them to make changes that they would not have otherwise seen or noticed (Chan, 1997).

VR can impact the construction process as well. The first of these impacts is that VR implementation can reduce rework because with more owner input, the tendencies for changes once the work is in place are significantly lower (Bridgewater, 1994). The elimination of rework is conducive to a more fluid and efficient construction schedule.

Additionally, VR has the ability to limit the number of physical mockups made on the job site. Typically, virtual mockups will suffice for any mockups with a visual intent (Bridgewater, 1994). However, if the mockup is needed from a constructability standpoint, such as ensuring no leaks, they may still be necessary. It is possible to do such mockups in place in order to eliminate the extra work associated with the mockup.

Safety is an important use for VR in the construction realm. It can be utilized to help train workers while engaging them rather than lectures, videos, or demonstrations (Sacks et al, 2013). VR can also be used for simulations of the construction process, constructability, construction logistics, and site activities planning. (Bridgewater, 1994).

However, the industry has also seen uses of VR to add to the value of a construction project, whether that be through value engineering, value management, or general added value. These categories were derived through various industry member interviews whose experience VR pointed toward the topic of value. The following sections provide examples of how VR is being used in the construction field and contributing to value-adding factors of construction projects.

2. METHODS

In order to gather information on VR and how industry members are using it with regard to their value engineering practices, five expert industry professionals were interviewed regarding their value engineering, use of building information modeling (BIM), and VR practices. These were semi-structured interviews that began with a few of the following sample questions:

- What were the goals in using virtual reality on your past projects?
- What benefits did you see when using VR?
- Have you ever used VR for the value engineering process?
- What do you see is the biggest challenge to using VR in the value engineering experience?

The interview participants represent a range of industry experts who were chosen with different backgrounds and experiences with VR, ranging from 8 to 25 years of experience. The focus was to identify different parties that have direct experience with using VR in value related discussions during the preconstruction process. Some of the industry members' positions focus specifically on implementing virtual methods of designing and construction, while others were project managers or preconstruction and procurement specialists that focus on value engineering. Interview responses were analyzed using a mind mapping approach, organizing both based upon the use cases of VR that were discussed, as well as the common barriers and enablers to applying VR.

3. RESULTS

3.1 Value Engineering

The first category that was analyzed is value engineering. It was a common statement among the interviewees that VR is used for value engineering on a project by project basis. The opportunity needed to present itself in order for VR to be considered for the true definition of value engineering of a project. This is because most value engineering applications, as discussed by the industry members, do not always need the application of visualization, but rather equipment or system based applications.

However, there were a few examples that were provided by the interviewees that demonstrated that VR can be applicable and useful in the value engineering process. The first was in the selection of a patient headwall example that was used for a hospital project. The VR model was used to show three different patient headwalls so doctors and nurses could use VR to determine usability. The owner was able to choose a final product based on their criteria of usability and cost.

The next example was provided by the interviewed design representative. Using VR, they were able to engineer a solution to a lighting issue. This took place in an office where the client was concerned about having proper lighting levels in the middle of the room, because of the height of the cubicle walls. Instead of installing more lighting, which would have been an added cost to the owner, they developed a mirror, similar in concept to a light shelf, that was able to reflect enough daylight deeper into the space above the cubicles. The model in VR was able to provide a visual that confirmed the lighting levels and visual impacts were acceptable to the owner. Without this visualization, the owner likely would have spent the money to install additional light fixtures to ensure proper lighting levels.

3.2 Value Management

Next, value management was analyzed as a category of value that VR has the opportunity to enhance. The largest application discussed that fits into this category is the ability of the owner to choose finishes for certain spaces. These included such materials as paint, carpet, tile, casework, exterior facades, ceilings, and accessories. Using the VR software, owners were able to choose between a variety of finishes based on the way they will look in the space and are able to evaluate how important these finishes are in conjunction with their cost. Using the VR software, clients are sometimes able to determine that two products are so similar that it does not make sense to spend the extra money. However, there were varying opinions whether the VR representation of these materials was sufficient to choose materials based on the model alone. The perceptions were varied with the modeler's familiarity with using the modeling and VR tools. The industry members who are project managers had the tendency to say that that the finishes portrayed in the VR program were not of sufficient quality for the owner to choose based on the virtual image alone. However, the virtual design and construction focused experts were more confident in choosing certain finishes using the model. This is more than likely due to their experience using the tools and programs available for VR, as well as their knowledge of the rendering capabilities available. The programs that produce higher quality rendered spaces are typically specialized software tools that are not as well known. The combination of the knowledge of the specialized rendering and visualization tools and having the skill level to use them properly can allow for owners to choose finishes for a space, though the accuracy of the models has not been validated in this study.

A strong example of this was brought up in an interview with one VDC profession, as he stated:

> *It definitely does depend on the tools you're using and the skill level. In certain, smaller offices, for example, they have a VR set up, and it does some pretty cool things, but the software that they use and the expertise they have available limits them to looking at Sketch-Up models. With that, you get accurate spaces, proportions, and sizes and can feel like you're in the space, but you're never going to get away from that 'cartoon-y' look Sketch-Up has. This is in contrast to some of the more advanced tools out there, which require an advanced user.*

However, even the more skilled VR users caution that it is important to get physical samples for the owners to approve. This is because some owners can be particular with the way their spaces look. If they are building an addition or a building that is a part of a network or campus of other buildings, they may want the materials to match exactly.

Additionally, the type of materials has a lot to do with the perception of the material in the virtual model. One of the examples that was brought up by another VDC expert was selecting or matching a particular stone. The colors provided by the quarries are always vary a little, so it is important to work with the quarry and ensure the color is exactly what the owner is looking for, especially if they are trying to match an existing color.

3.3 Project Value

The final, and most broad, category that addresses the ways that VR can add value to a project. This category is identified as general value because these were not instances that directly save the project costs on choosing a certain product, finish, system, or piece of equipment, but instead, the VR model was utilized to save costs that cannot be quantified directly, such as site planning, user group visualization, inspections, and bidders meetings.

One of the most common ways that VR is used in practice is through end-user visualization. This enables early visualization of the space by end users, such as doctors and nurses in a hospital, the future inhabitants of an office space, the engineers of a fabrication plant, or even judges in a courtroom. These individuals, using VR, can see the space before it is constructed to provide feedback and changes that they would like to make. This minimizes the amount of rework that would have needed to be done if they would not have seen the space until it was constructed and wanted to make changes in layout or function after the work was in place.

Although the interviewees provided many examples of how they have used VR for end-user visibility purposes, a few examples are noteworthy: The first example is how a nurse's station was modeled and visualized in VR to allow the nurses who would be using the space to make comments on its layout and use. Some of the comments that the nurses made on this space included the location of the printers, where the standing desks should be located for better view of the patient rooms, and some casework changes to reflect the number of files that they needed. The modeling of this space was especially important for this project because this nurse's station was repeated over thirty times throughout the hospital. If the nurse's stations were built and changes needed to be made, each of the thirty stations would have needed changes. Additionally, the original mock-up of the space made was built out of foam core and cardboard to help the nurses visualize the space; however, many of the nurses still did not feel confident in how the space would look. This led the team to the VR model, which was extremely helpful for feedback, but also to validate the user experience.

Another example of user visualization in VR was provided by the designer that was interviewed as a part of this research, who worked on modeling a courtroom. One of the main reasons that this project was targeted for VR use is the multiple iterations of physical mockups that would have been needed to be built to ensure a number of criteria, such as the judge's bench being high enough to see the entire court room, safety and security, and lighting conditions. Courtrooms are typically built out of plywood as a mockup in an offsite warehouse before the final design is approved. However, VR's visualization capabilities have eliminated this need, saving the cost and time the physical mock-up would have taken (Maldovan et al, 2006).

Another example, provided by an owner's VDC leader, was a pharmacy layout that allowed the end-user to visualize and critique their space. This was especially helpful for them because the project team was also able to model the constraint of the robot that would be placed in the space. Through the VR model, the client was able to visualize how it would move around the space and place it in such a way to maximize efficiency and ensure the room would be big enough to house it. They were able to move certain cabinets to locations where they knew that they would need to be based on the robot's location and movements.

Inspections were an emerging example of how VR can add value to a project. Essentially, this process did not start out as something intentional. It started with the owner's request to be able to visualize and comment on the layout of their future space, similar to that examples cited as a part of the user-group visualization topic. However, as more detail was put into the model by the design team, it became very simple to add in the last few details in order for it to look exactly like the finished product. Once this was realized by a member of the project team, they decided to invite the fire marshal, building inspector, and health inspector to view the space with the VR head-mounted display, identifying anything that would become an issue in the future if the building were to be constructed as shown in the VR model.

After viewing it, the inspectors identified needed changes, such as changing the color of the exit signs, adding strobe lights, altering the height of the hand wash sinks, and moving control panels. These are typical changes for inspectors to flag at the end of construction projects, so they are not entirely unexpected to the project; however, the VR review with the inspectors saved extra time, labor, and materials at the end of the project. The VDC manager confirmed that spending the extra time and effort to detail out the model in VR was absolutely worth it. He estimated that it took about 80 hours of an engineer's time to create the model, totaling only a few thousand dollars. This is significantly less money than what it would have cost the project to change all of the exit signs that were the wrong color. This example, along with the fact that this process has paid off on other projects, shows that it adds significant value to the project.

Finally, VR has also added value to construction projects during preconstruction bidders' meetings for specialty contractors. Before the specialty contractors have the opportunity to put their bid together for the project, they were invited to a meeting where a general contractor previewed the model to identify the systems, scopes, and relevant construction considerations. It allowed the specialty trade contractors to ask questions about the design, make suggestions, and open the opportunity for discussion of the design. In the long run, with buy-in from the specialty contractors, there may be future potential to identify scope gaps or identify design challenges that may need to be altered before construction. Although this is not something that is used consistently because it requires a design early enough to be created and imported into a VR software, it is something that has proven to be beneficial, adding value to the project. Additionally, this is something that can be accomplished using a 4D BIM model; however, contractors have gained benefits when this occurs in VR by having a better understanding of the building and can put together a more reasonable estimate.

Through the interviews, several useful ways to utilize and incorporate VR on design and construction projects have been uncovered, all of which have provided value to the project through means of value engineering, value management, or just general value-added objectives.

4. DISCUSSION

In addition to how VR adds or enhances value, other information from the interviews was also uncovered, such as the impact of schedule, delivery method, and budget on the ability to use VR for added value. Utilizing VR on a project may have the added benefits to project value, as listed in the sections above; however, the following are constraints that can affect how VR can be used during the construction process.

4.1 Schedule

Schedule and timing are important factors in the way that VR can be leveraged on a project to add value. Timing is important because it addresses when team members engaged in the process to give input on the development of the project and when a model can be produced.

First, the timing of value-related decisions is important. It is much more beneficial if value decisions are made as early as possible on a project. This idea is reflected in Figure 1. The chart depicts that as the project and the design progresses, it becomes more and more costly to make changes. If these decisions were to be made as early in the project as possible, through the means of reviewing VR models, for example, the cost to changing the design is significantly lower. This is because the cost of rework or changing systems is marginal in the early stages of the project, but once materials have been ordered and work has been put in place, changing it adds larger materials and labor costs. It would also push back the schedule, especially if the new solutions' materials require an extensive lead time.

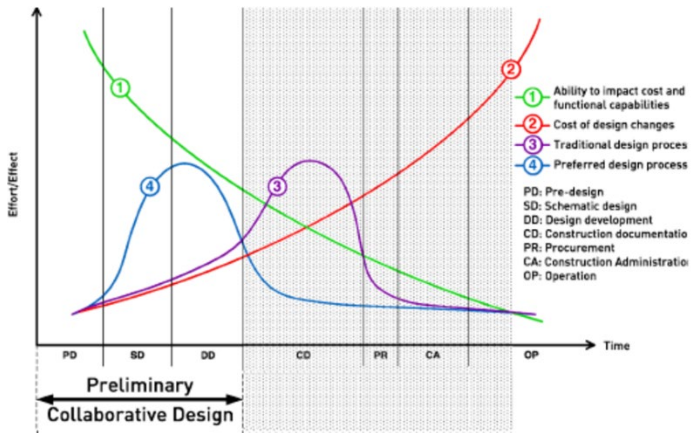

Figure 1: Optimized Plans Cut Down on Costs (Jones et al, 2011)

Ideally, value decisions would be made early, but there are some key factors at the beginning of the project that affect when value decisions can be made. In order to make the best value engineering decisions, it is important to have feedback from more than just the owner and the design team. Depending on the delivery method, which will be discussed in more detail in the following section, the contractor and subcontractors will likely be brought on later than the designer. This may be a missed opportunity for their input on the constructability and function of the systems within the building, which is also a missed opportunity for additional value engineering. Having these parties involved in the design process early on allows them to provide constructive feedback to the design, which is why the timing of the process is so important.

If the contractor or subcontractors see a major concern with an aspect of the design already decided and implemented by the designer, they will likely have the opportunity to value engineer the system on their own; however, to re-engineer the entire system based upon one small value adding aspect may not be worth the time in the long run. If the design is already passed the point of making that particular decision, the owner misses the opportunity of having additional value to their project, or at least having it at low cost.

In order for VR to be utilized early in the design process as a means of adding value, a model is important to get the process started. The issue could be that the model is not developed into enough detail to use because it is too early in the design process. In this situation, if there were to be something that would be beneficial to visualize during the decision-making process, such as the shape of the building or the location of a curtain wall, a model will need to be created before VR can be an option for visualization. A model can be made in a VR software; however, it is typically more beneficial and efficient for the model to begin with the designer, especially when it comes to the first steps of the building, such as its exterior shape and appearance. When considering the ability that a project team has to utilize VR to add value to their project and their decision-making process, timing is a big factor.

4.2 Delivery Method

Because timing is so influential on the value engineering process, it is ideal for contractors to be on board as early as possible. For this to be possible, the selection of a delivery method is very important. Figure 1 in the previous section, shows that the preferred design process, i.e. an integrated project delivery (IPD) delivery method, allows more of the decisions to be made between the schematic design and the design development stages, rather than the traditional (design-bid-build) delivery method where more effort is needed by the team in the construction documentation phase. Making value engineering decisions early, whether VR is being used or not, is best for the success of the value of the building. However, if VR is a tool that the owner knows that they want to implement, the following information should be considered when a delivery method is chosen for their project.

One of the main differences between IPD and design-bid-build is the level of integration and collaboration associated with them (Franz et al, 2017). In an IPD, the members of the team help to choose other members to ensure that they are able to work together well for the duration of the project. These teams, because of their high level of collaboration, are more likely to produce better value engineering solutions for the project. In addition, if VR is a method that they choose to incorporate into their value engineering process, the team will be better equipped to make this happen. Having an IPD delivery method means that whatever party is better equipped to do something takes on that risk, so the most skilled VR users would be in charge of this; it does not have to be put in the hands of the general contractor or designer to run this process. Overall, an IPD delivery method would produce more collaboration for value and better quality models, visuals, and information to make it an easy process for the owner and other parties involved.

In the design-bid-build delivery method, the designer is the only party making design decisions. Because these decisions are made without the input of the contractors or subcontractors, there are limited considerations made for value engineering options in the beginning stages of design. In contrast, the IPD delivery method allows group collaboration for better value designs and keeps potential options for value open. The IPD team are able to employ decision-making tools as a group in order to achieve this.

For these reasons, IPD, or at least a more integrated and collaborative delivery methods, are recommended for high quality value engineering and use of VR. The owner will be able to be involved from the very beginning as a part of the team and help make these value engineering decisions, depending on the information that the team provides them with. In regard to the VR aspect of value, this can easily be utilized when visualization is a necessary component of the value decision.

4.3 Budget

The owner’s budget preferences have the ability to affect the way that value engineering is approached. Based on the owner’s funding needs, contracts and budget may not allow the opportunity to use VR to help value engineer the building. This is something the owner may want to consider before the project begins, depending on their project goals.

First, different contract types have different levels of design flexibility, under a contract like a GMP, for example, the cost of the project will be capped at a maximum price that the owner will pay. However, it is encouraged to save costs where possible. Typically, these contracts include a shared savings clause to encourage the contractor to reduce costs as well as provide value engineering services throughout the design and construction process. On the other hand, a contract such as a lump sum provides a fixed price for the work shown in the contract documents. This type of contract does not incentivize contractors to work towards a better value project. For this reason, VR as a means of adding value to a project may be less likely.

Additionally, each contractor has different policies on how they charge for value engineering services. If an owner wants to use VR for a specific value engineering application, it should be written into the contract to ensure that the owner will not incur additional charges for this. Some contractors will mention during the interview and proposal process and include the VR model as a part of their service because they understand how beneficial it is in the long run. However, if a contractor is not experienced using VR, or it is not initially procured with the contract, they may charge the owner additional costs in order to use it. This cost is likely to discourage the owner away from using VR in the value engineering process.

The price per subcontract work scope may also affect how if VR is used for value engineering. Often times, when the owner receives an estimate that is over budget, they will review the scope of work individually to see where they are spending more than anticipated. If they are spending more money on something that is more "behind the scenes" such as environmental systems, then VR may not be used in the value engineering decisions to change the systems or cut costs. However, if excess money is being spent on interiors or finishes that includes a visual concern, the project team may utilize VR for in order to make decisions on what changes to make to the space.

A project owner is not typically using these considerations to decide on a project scope or contract. However, they should be aware of how their decisions may affect their value engineering experience.

5. CHALLENGES OF VIRTUAL REALITY

Across the interviews with the industry members, there were many challenges associated with the utilization of VR and how it is used on projects, whether that be for value engineering, value management, or just general value adding activities.

The first challenge that contractors identified is model accuracy, or lack of a design model. Typically, for this process, the designer is responsible for providing an accurate and detailed design model. However, depending on the architect's contract with the owner, the designer may not have a model or the architect may not be required to share the model. Although this changing in many markets, this situation seems to still occur quite often according to the interview responses. This provides a challenge to the contractor if they want to use VR because they would then have to re-model the building on their own. Depending on the size of the building, this may take more time than what it is worth, depending on the goals for the future uses of the model.

Additionally, another challenge that the industry faces when it comes to implementing VR in their practice is the labor investment necessary for it. VR programs require technically savvy employees who are passionate enough about doing it to keep learning programs and testing out new ideas. Typically, a high skill level is necessary in order to use some of the more advanced software programs that will produce better quality models. This issue links to the hardware and software investments. These infrastructure elements of VR are not typically expensive as long as they are continuing to add value to the company projects. However, if they are not managed and used properly, they could be an inefficient and ineffective use of time. Skilled VR users are necessary to find the right VR solutions that meet the projects' and the company's goals and second, ensure that there is a return on investment.

One of the biggest challenges that the interviewees faced is getting the owners interested and supportive of using VR. Every client is different and has different opinions: while some are very interested in using VR, others are more skeptical. First, some owners are not usually well informed about VR, and thus do not understand what benefits it can provide. Lack of knowledge or experience generally decreases their likelihood of using it on their projects. Additionally, some owners do not like change or trying new things. They are traditional and do not see the value adding components to new technology. Third, some owners believe it would be too expensive and do not believe in the return on the costs. Finally, some owners are afraid to extend the schedule or increase cost to allow their end users to make too many significant changes, despite the potential that if engaged earlier enough, these aspects of the project should not cost more, and if they do there is still time to adjust how costs are allocated to address the added expense. Overall, the goal interviewees commonly cited with owners is to get to them to ask to use it because they understand the value that it adds. Many of the contractors have a goal to educate owners on the positive effects of using VR on their projects.

The comfort level of people using the VR headsets has also presented itself as an issue for owners. First, some people do get queasy depending on the flickering and the refresh rate of the model, which bothers some people more than others. Occasionally, people are embarrassed or feel they understand enough to watch on the screen without the immersive experience that VR provides. If the owner does not want to use it, it is not something that can be forced on them; however, it is not productive to make a model that the owner does not use.

A final challenge that some contractors struggle with is when exactly VR should be used, i.e., what can be communicated with an immersive VR model that cannot be communicated through a 3D model review. Because of this, it is important for the project team to go into a project with a plan in mind of how they want to utilize VR.

These challenges are faced by contractors as they use VR method, especially to improve value on a project. None of these challenges are severe enough to stop the research and implementation of VR. Additionally, with more and more emerging technology, these challenges will not be difficult to resolve.

6. VIRTUAL REALITY IN RELATION TO BIM

In talking to the industry members, they identified several use cases for adding value to the projects on which they were working; however, they were not specific software solutions or methods that always incorporated VR. This speaks to one of the challenges that is faced in the industry, the specific value-add or differentiation of virtual reality above and beyond 3D visualization. One industry member in particular used the terms “VR” and “augmented reality” interchangeably when, as noted in the literature review, they are different. Others took the term VR to mean anything having to do with BIM or BIM implementation, however, VR is just one tool to implement BIM on a project.

Nonetheless, the interviewees provided valuable feedback regarding how they are using other tools, not just VR, to add value to their projects. These range from laser scanning to drones to renderings. With a well-executed plan, the project team can easily incorporate VR as a BIM use for the duration of the project.

7. CONCLUSIONS

In conclusion, VR has the potential to expand and add value to construction project, whether that be for uses in value engineering, value management, or other ways to add value more broadly. However, it is important for the owner and the project team to realize that the timing for which value decisions are made, the delivery method used, and the anticipated budget of the project can affect and potentially limit the available performance of VR. If VR is being used on a project, the project team should anticipate the challenges before putting additional work into a high-quality VR model because the challenges may diminish the time and effort already put into it. Finally, the project team should evaluate how the VR model can interact with other BIM uses. VR is an up and coming tool that will revitalize the future of the construction industry.

Further research was identified related to the rendering and accuracy of materials in VR platforms, as well as the differentiated value of VR over and above 3D model visualizations.

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CREATION AND QUALITY EVALUATION OF THREE-DIMENSIONAL ROAD SPACE DATA USING CAMERA FOOTAGE

Satoshi Kubota, Kokichiro Horishita, Chiyuan Ho & Kotaro Nishi
Kansai University, Japan

ABSTRACT: *In road maintenance, it is necessary to construct an environment that manages three-dimensional data and maintenance information for its effectivity and efficiency. Three-dimensional data of road space are often constructed using mobile mapping system (MMS) and terrestrial laser scanner. When acquiring three-dimensional point cloud data with a laser scanner, the laser hits the feature in front, data cannot be acquired for the features behind the sidewalk. Therefore, it is necessary to measure it several times. On the other hand, as one of the methods for constructing three-dimensional data, there is the Structure from Motion (SfM) technique. In this research, a method to generate three-dimensional data of road space based on SfM technique from camera footage taken with a commercially available video camera was studied for road maintenance. This research was defined road space composed of roadway, sidewalk, directional arrow, bar, street lamp, boulevard trees, and building. For acquiring video animation or photographs, Go Pro Here6 of video camera that takes 4K video animation and photographs was used. In this process, there are parameters of direction and height of camera. A video animation is separated one second interval images using animation edited software. The images are input data for SfM software 'Photo Scan.' Then, a three-dimensional data of road space is created using SfM technique. In this research, quality evaluation method of three-dimensional road space made by point cloud data was proposed. The quality elements are location accuracy and completeness of road features. Location accuracy is evaluated by standard deviation and root mean squared error based on location reference point. Completeness is evaluated by overmuch and lack numbers of features. This research was considered the characteristics of acquiring method using video camera, creation using SfM, and quality evaluation method.*

KEYWORDS: *Road space, Maintenance, Structure from Motion, Three-dimensional data, Point cloud data, Quality evaluation.*

1. INTRODUCTION

Much of infrastructure that was built during the period of rapid economic growth is now beginning to approach the time at which it must be rebuilt. It is said that 67% of all roads will deteriorate by 2033. Appropriate maintenance and management is a necessary step. The Ministry of Land, Infrastructure, Transportation and Tourism is promoting a policy named i-Construction, in which information and communications technology is used to increase productivity at construction sites. i-Construction involves the generation and use of three-dimensional data in planning, design, and construction stages as well as during maintenance and management stages in order to achieve a more efficient and advanced construction process.

When performing maintenance and management, it is important to make repairs based on data that has been accumulated during inspections. However, information generated during the design, construction, and maintenance stages, such as tables and diagrams, are managed separately. A system for managing this crucial information in an integrated manner and visualizing the information is lacking. Furthermore, many of the diagrams that are used during maintenance and management do not consider three-dimensional environments and positions, and are managed in two dimensions only. Therefore, representing the target road space in three-dimensional would make it possible to add information to arbitrary locations in the three-dimensional environment and to visualize the shapes of buildings from a variety of viewpoints.

In order to perform maintenance and management in three-dimension, it is necessary to construct a set of three-dimensional data to serve as the foundation. three-dimensional data of road space is commonly generated using mobile mapping systems (MMS) or terrestrial laser scanners (Imamura, 2015; Emori, 2015). The Ministry of Land, Infrastructure, Transportation and Tourism conducted an experiment for collecting road infrastructure map data by using vehicle-mounted sensing technology (Ministry of Land, Infrastructure, Transportation and Tourism, 2017). However, the list price of the device is approximately 15 million yen. In order for local governments to be able to use this technology, it is desirable to develop a lower-cost device. Furthermore, when collecting three-dimensional point cloud data using a terrestrial laser scanner, the laser may hit features in front of the target object, making it difficult to collect data on features behind it, such as sidewalks. This makes it necessary to move the terrestrial laser scanner several times while collecting data. Another method for constructing a point cloud data involves capturing multiple images of the target by photographing the target with multiple cameras or by moving the camera while photographing the target. The correspondences between the feature points in the multiple images are identified, and the three-dimensional structure is reconstructed while the poses of the viewpoints are estimated simultaneously. This technology is referred to as 'structure from motion' (SfM).

In this research, a method for generating three-dimensional data of road space based on video data captured using a commercially-available video camera that employs SfM technology, for the purpose of constructing fundamental data for three-dimensional maintenance and management of roads is constructed. We also propose a method for evaluating the quality of such three-dimensional data. The features that compose the road space studied in this paper are presented in Fig. 1.

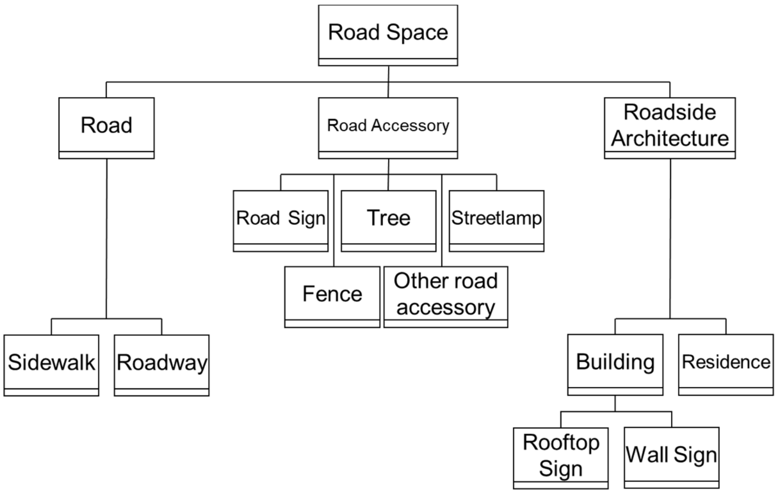

Fig. 1: Features of road space.

2. METHOD FOR 3D DATA AND EVALUATING QUALITY

Two GoPro Hero6 cameras, which can record 4K video, were used for the measurement. Images were extracted from footage captured by the cameras at intervals of 1 s and were used to generate point cloud data in PhotoScan (Agisoft), a software package built on SfM technology. Finally, we displayed the point cloud data using CloudCompare, a three-dimensional data editing software package.

Based on information reported in the reference (Kubota, 2018), the PhotoScan processing was set to "maximum" in order to increase the accuracy of the generated point cloud data (Table 1). To construct the video capture apparatus, we mounted a ladder on a dolly and attached the GoPro cameras on either side of the top of the ladder to allow for sufficient filming height (Fig. 2).

Fig. 2: Video capture apparatus and measurement site.

Table 1: Parameters affecting data generation.

Parameter	Measurement conditions and software settings
Selection of camera model based on resolution	GoPro Hero 6 (12 megapixels)
Camera direction	Installed to the left and right (50 degrees)
Location at which to install camera	Height of 1 m
PhotoScan processing settings	Maximum

To evaluate quality, the completeness and positional accuracy of captured features was used, in accordance with "Quality Demands and Regulations Regarding Evaluation and Reporting" described in the Japan Profile for Geographic Information Standards published by the Geospatial Information Authority of Japan. Completeness was evaluated based on the number of errors of addition and the omission of features in the point cloud data. For positional accuracy, coordinates were assigned to the point cloud data of the road space such that the origin was defined to be the reference point from the Fundamental Survey of City Blocks for Urban Renaissance or the value from Global Navigation Satellite System (GNSS). Positional accuracy was evaluated according to the difference between the verification point and the GNSS point or the Fundamental Survey of City Block for Urban Renaissance reference point. Furthermore, because a feature may have some parts for which point cloud data can be generated by SfM and others that cannot, the feature coverage of the point cloud must be evaluated. The images of the target feature from within the point cloud data and created a mesh for the extracted feature were extracted. Its shape to that of the target feature was compared and calculated the proportion of the feature that was able to be generated, using the mesh count as a reference.

3. GENERATION OF 3D DATA AND QUALITY EVALUATION

3.1 Site measurement and 3D data generation

Based on the chosen parameter settings, a rad space was measured in Suita City, Osaka Prefecture that was approximately 3 km long. As an example, we captured an approximately 2-minute-long video of the site (Fig. 3) and generated a three-dimensional point cloud data (Fig. 4) using the method described in Section 2. The point cloud data shown in Fig. 4 required 117 photographs to generate and the processing time was 210 minutes.

Fig. 3: Example section of the measurement site.

Fig. 4: Generated three-dimensional point cloud data.

3.2 Site measurement and 3D data generation

To evaluate completeness, errors of addition and omission for each feature in the constructed road space were compared with the actual site. The results are shown in Table 2. Overall completeness was approximately 53%. Failure to generate certain point cloud data resulted in feature omissions. The system was not able to generate point cloud data for traffic signals due to the thinness of the poles they were attached to, the complexity of their shape, and because of the cameras' limited field of view. Similarly, the system was able to generate the point cloud data for only the trunks of trees, omitting the upper parts. In the future, it will be necessary to define evaluation criteria for additions and omissions for all target features, and to validate the completeness of all defined features. It will also be necessary to define the evaluation criteria for additions and omissions in relation to the coverage of the target features.

To evaluate coverage, the images of the target feature were extracted from the point cloud data and were created a mesh for the extracted feature. The proportion of the feature was calculated that was able to be generated by comparing its mesh size the shape of the target feature. The results for the sign shown in Fig. 5 revealed that the coverage was approximately 98% with high-density cloud processing, and was approximately 77% when a mesh was constructed on the aligned image. To evaluate positional accuracy, GNSS or Fundamental Survey of City Block for Urban Renaissance coordinates were assigned to multiple feature points within the three-dimensional road space data. Accuracy according to the difference between the coordinates of the verification point and the GNSS or the Fundamental Survey of City Block for Urban Renaissance reference point coordinates was evaluated. However, after defining verification points and performing the processing, we were unable to generate the point cloud data because the assigned coordinates were unable to be identified as feature points.

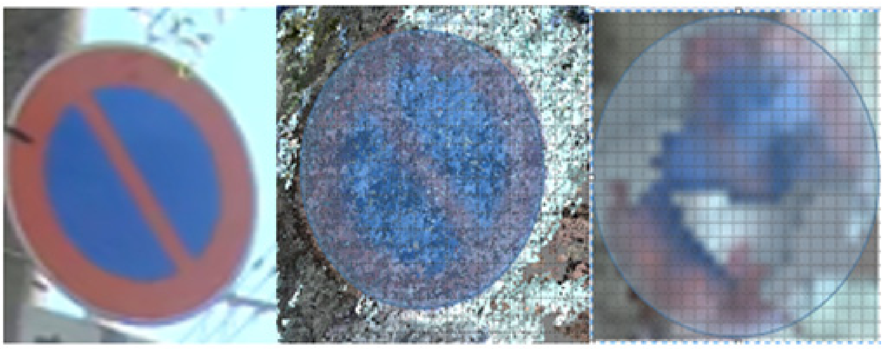

Fig. 5: Evaluation of feature coverage ((a) target image, (b) point cloud data, (c) coverage).

Table 2: Evaluation of feature completeness.

	Telephone poles	Stop lights	Road signs	Signs	Trees
Actual Site	75	6	21	4	61
3D point cloud data	51	2	19	3	30
Omissions	24	4	3	1	31

One characteristic of SfM is that it is able to generate accurate point cloud data if successive images of the target contain objects that can be used as features. Generation of point cloud data is affected by the environment at the site, including factors such as the angle of sunlight and the height and number of buildings. In addition, if a vehicle passes by during the measurement, the continuity of the processed images is broken. In this case, the system is unable to align the images, and it may not be possible to generate dense point cloud data.

4. CONCLUSION

In this study, SfM technique was used to generate a three-dimensional point cloud data of a road space based on images extracted from footage captured by cameras attached to the top of a dolly for the purpose of constructing a fundamental data for three-dimensional maintenance and management of roads, and evaluated its quality.

This study showed that it is possible to construct a three-dimensional point cloud data of the side of a road or a sidewalk with unique features by walking along the road using the measurement device. New evaluation criteria consisting of completeness and coverage was proposed. By increasing the accuracy of these criteria, it may be possible to develop new methods for evaluating the point cloud data of a given feature by sight. In order to create dense three-dimensional data, sunlight and other environmental conditions at the measurement site must be considered. The method proposed in this study enables the construction of point cloud data of pedestrian environments, which may be difficult to measure using vehicle-mounted instruments. Therefore, it is possible to use this method to understand the structure of a pedestrian environment and to perform maintenance and management.

5. ACKNOWLEDGMENT

This work was supported by Japan Society for Promotion of Science (JSPS) Grants-in-Aid for Scientific Research (17K06521).

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A DEEP NEURAL NETWORK-BASED METHOD FOR THE DETECTION AND ACCURATE THERMOGRAPHY STATISTICS ESTIMATION OF AERIALLY SURVEYED STRUCTURES

Giorgos Sfikas
Centre for Research & Technology, Information Technologies Institute, Thessaloniki, Greece and Computer Science & Engineering Dpt., University of Ioannina, Ioannina, Greece

João Patacas and Charalampos Psarros
School of Science, Engineering and Design, Teesside University, Middlesbrough, UK

Antigoni Noula, Dimosthenis Ioannidis and Dimitrios Tzovaras
Centre for Research & Technology, Information Technologies Institute, Thessaloniki, Greece

ABSTRACT: *Building thermal output determination is fundamental for the development of energy use optimisation strategies, and can provide important inputs for the estimation of flexibility in demand response strategies. Current building energy assessment procedures are based on design values, not taking into account the uncertainties introduced during the construction and installation processes. The analysis of thermal images of buildings provide the opportunity to carry out the estimation of energy demand based on the actual building performance.*

This research presents a deep neural network-based method for the accurate estimation of thermography statistics from pairs of RGB and thermal images. The proposed method identifies a region of interest (ROI), which is assumed to be a building found approximately at the centre of the image field of view ('target building'). The visible spectrum/RGB input is used to determine the position and outline of the target building in the field of view, and create a pixel-level binary mask with non-zero mask elements corresponding to the target. The binary mask is used to produce an intensity matrix containing only the values that correspond to the building / ROI, and applied to its corresponding thermal image pair. This enables the consideration of the thermal output of the region of interest, as opposed to the whole image, improving the accuracy of the estimation of the ROI's thermography statistics.

KEYWORDS: *digital image processing, automatic structure detection, infrared image processing, deep neural network features, thermal statistics, unmanned aerial vehicle, demand response potential estimation*

1. INTRODUCTION

There is an increasing need for accurate building thermal output determination methods that can be used to assess the actual energy performance of buildings. Currently, the determination of the thermal output of a building presents a series of challenges, due to the difficulty in accounting for the differences between the building design values that are considered in the estimation of energy demand, and the actual performance of buildings. This is largely due to the uncertainties associated with the accuracy of building project documentation, the quality of building materials, and the quality of the construction and installation process.

The estimation of thermography statistics and their usage as a basis for the estimation of energy demand in buildings has been considered as an alternative to current energy assessment methods, which are based on design values (Fokaides et al. 2011; González-Aguilera et al. 2013; Ham & Golparvar-Fard 2012), such as SAP in the UK (BEIS 2014). Accurate methods for the estimation of energy demand in buildings are a key input for the optimization of building energy use, including effective demand response (DR) programs.

Demand response programs are mechanisms developed to ensure that the electricity grid remains stable during times of peak demand (Rodriguez-Trejo et al. 2018). DR programs prompt actions that alleviate the load on the electricity grid by leveraging the flexibility that users have in their electricity consumption at specific times of the day (Crosbie et al. 2017). Flexibility is established in contracts between companies acting as aggregators and the Transmission Network Operator (TNO) or Distribution Network Operator (DNO). Aggregators acquire flexibility from users (mainly industry and large energy consumers) managing the available assets in response to the grid's requests to increase or reduce electricity consumption or generation (Rodriguez-Trejo et al. 2018; Sisinni et al. 2017). The potential impact of smaller energy consumers on DR flexibility is increasingly being recognized, and challenges such as the lack of integrated tools for optimization, planning and control/management of supply side equipment have been the focus of research efforts such as the Demand Response in Blocks of Buildings (DR-BOB) project (Rodriguez-Trejo et al. 2018).

This research investigates the use of pairs of thermal/infrared (IR) and visible-spectrum (RGB) digital images captured using an UAV to produce features that could aid in identifying the demand response potential of building assets. One such feature that could be correlated to DR potential, is an image of the thermographic characteristics of a building. In the current paper, a novel deep neural network-based method is proposed for the localization and estimation of the thermal output of a region of interest given a pair of thermal (IR) and visible-spectrum (RGB) images. The need to consider pairs of thermal (IR) and visible-spectrum (RGB) images, as opposed to the use of IR images solely, stems from the fact that while IR images already contain temperature data that is used to determine areas of low or high thermal output, they are not appropriate to be used to semantically differentiate objects.

The proposed image processing pipeline has been successfully applied to RGB/thermal image pairs of an existing building captured using a UAV. Preliminary results obtained from the application of the proposed method are expected to contribute to more accurate estimation of baseline and DR flexibility in order to increase the exploitation potential of building assets in DR programs. In addition, the obtained thermal statistics can in perspective be analysed to provide detailed insights in users/customers behaviour. Our proposed method can be leveraged by both smaller energy consumers and energy providers in order to increase the amount of flexibility in DR programs.

The remainder of this paper is structured as follows. In section 2, we present the proposed method, that involves using a pre-trained neural network and unsupervised machine learning methods to localize the structure of interest. In section 3, we discuss the details of image acquisition as well as the test site used for this work, and present qualitative and numerical experiments. We close the paper with conclusions and a discussion of future work in section 4.

2. PROPOSED METHOD

The proposed method involves processing an input of optical and thermal images that depict a building, with an aim to obtain a measurement of thermal characteristics; we shall further assume that this statistic is desirable to be obtained in the form of a thermal intensity histogram (Klette 2014). In order to achieve this aim, as an initial step we use the optical input in order to localize the structure of interest position, and subsequently we use the calculated mask over the thermal input to produce the desired thermal intensity histogram. An overview of the proposed pipeline is provided in Fig. 1.

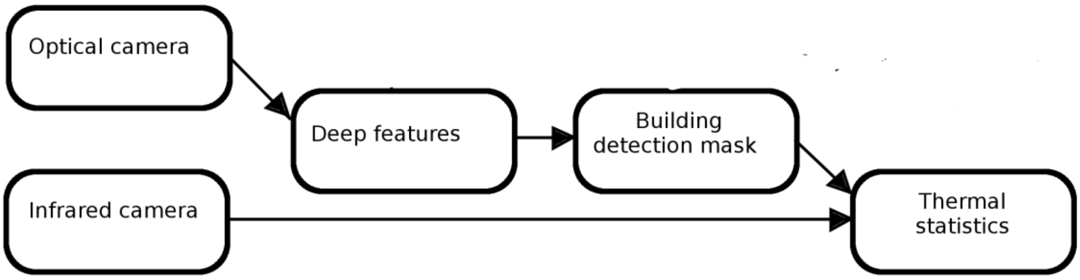

Fig. 1: Proposed image processing pipeline.

2.1 Deep features

The first step of the proposed algorithm involves processing the optical input in order to extract deep features (Sfikas et al. 2016, Retsinas et al. 2019). Deep features are defined as pixel-level cues that are obtained by feeding a pretrained neural network with a particular input – in our case, the input optical image – and calculating the activations of an *intermediate* network layer by performing a standard feed-forward pass (Strang, 2019). The neural network involved is thus used as a tool for feature extraction, instead of the goal it has originally been trained for.

Fig. 2: Typical architecture of feed-forward neural network. Information flows from the input (left) towards the output (right). Intermediate layers correspond to feature maps, each produced by some linear combination of the previous layer or layers (e.g. a convolution). Deep features extraction amounts to simply computing any one of the intermediate feature maps instead of the final network output.

The rationale behind using intermediate layer activations of neural networks as features comes is that we can see a neural network as a representation learning machine (Goodfellow 2016). For example, considering a neural net classifier we can express its output as a linear combination of the penultimate layer activations (composed with a softmax function to produce probability vector). Other, non-neural network classifiers such as the Support Vector Machine (SVM) are based on the same principle, that is perform a linear combination over some set of features and determine whether the output falls in this or the other part of some hyperplane. The difference is that while neural networks follow the same principles as other learning machines, the representation is *learned* during training instead of being hard-coded in the form of 'hand-crafted' features. In the current work, while there is no proper 'training' phase for our method, we assume that the employed networks use weights that have been produced as the optimum of a previous training process, on a third-party dataset, unrelated to the current task (hence the term "pre-training").

In the current application, we have used the Deeplab v3+ neural network, a network that has been proposed for semantic segmentation (Chen et al. 2016). Deeplab comprises a series of convolutional layers, topped by non-linear activations, which eventually lead to a pixel-level set of *K+1* softmax outputs. The number of *K* possible outputs is the number of object classes that the network is trained with, plus one reserved for background. The deep feature cues are returned as a matrix of resolution *H x W*, with each of the cues comprising in general *D* channels; in other words, on each pixel of the feature map grid, a vector in R^D is produced.

2.2 Calculating the building detection mask

Deep features are processed in order to produce structure of interest segmentations. We perform clustering over the computed deep features, reduced with Principal Component Analysis (PCA) to 8 dimensions. *k-means* is used to cluster the 8-dimensional features, and k is heuristically set to 3, initialized with the k-means++ scheme. Between the computed clusters, we have in practice observed that one of the clusters will correspond to the structure of interest, provided of course that the structure of interest covers a significant part of the field of view. We tag the cluster that is situated the closest to the center of the field of view to be the structure of interest cluster. Formally, we use the cluster *j* that minimizes the heuristic:

$$\sum_{n=1}^{N_j} ||x_{jn} - c||$$

where x_{jn} is the position of the n^{th} datum of the j^{th} cluster, and *c* is the position of the field of view center on the image.

2.3 Calculating thermal statistics

After having computed the building segmentation in the previous step, we proceed to calculate thermal statistics over the structure of interest. As the two inputs (optical, thermal) are products of two cameras with different characteristics, both intrinsic (lens, field of view) and extrinsic (different position and pose), the mask cannot be directly applied on the thermal input. The deep feature map, and subsequently the building segmentation map is obtained as a product of the optical cue, hence a step of registration must be applied on the thermal cue. In this work, we register the images manually, by applying an affine transform on one of the inputs so that the two modalities visually match. While this approach will lead to small errors due to misalignment, we must note that alignment of images of different modalities can be a non-trivial task, as different modalities are related to different gradient information, leading to difficulties in feature-based matching that typically uses gradient information to work (Klette 2014).

After applying the segmentation mask over the thermal input, we obtain the set of thermal intensities that correspond to the structure of interest surface. These can be in turn used to compute thermal intensity statistics. We have computed histograms of thermal intensities, as well as computed thermal intensities means, though in practice any other, possibly more complex, statistic can be computed over the features. The advantage that stems from the proposed scheme, is that *only the actually relevant* thermal intensity values are obtained, thus any statistic over thermal values will objectively be more accurate. In the numerical results section, we show that indeed in practice a great disparity on the thermal estimate using our method versus not using it can exist, validating the usefulness of the method.

3. EXPERIMENTAL RESULTS

3.1 Experiment site

The site used for the aerial image acquisition is the Smart Home building, located at CERTH's facilities in Thessaloniki, Greece. It is a rapid prototyping & novel technologies demonstration infrastructure resembling a real domestic building where occupants can experience actual living scenarios. It was chosen because it is equipped with features found at a typical modern domestic building (PV array, solar water heating, heat pump units) and is located within adequate distance from other structures, making it convenient to safely fly a drone for aerial surveys.

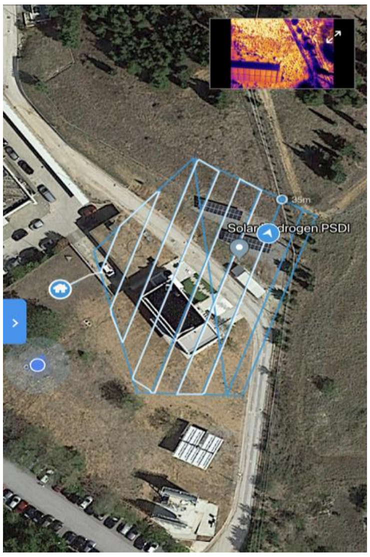

Fig. 3: UAV typical flight plan used for our experiment over the test site.

3.2 Image acquisition

The UAV used was a DJI Matrice M200, equipped with a DJI Zenmuse XT2 Visual+Thermal Imaging camera. The visual camera uses a 4K (Ultra HD) sensor with a resolution of 3840x2160 pixels while the thermal camera uses a Vanadium Oxide Microbolometer with an output resolution of 640x512 pixels. Video capture of the cameras were at 29.97 frames per second for the visual imager and 30Hz for the thermal imager. A flight plan (Fig. 3) was programmed for the drone to perform an aerial survey as an autonomous mission, followed by a manual flight around the building for video acquisition. In Fig. 4 an example of an input IR/RGB image pair is provided.

Fig. 4: Example input pair. An optical camera frame (left) and corresponding thermal input frame (right). Images were captured with cameras mounted on an Unmanned Aerial Vehicle (UAV), surveying the structure of interest.

3.3 Results

Let us note that the proposed pipeline is completely unsupervised, in the sense that it requires no annotated data or a training phase to run. We have run tests using either ADE20k or the Pascal VOC pretrained weights[1]. These have been trained on the respective homonymous datasets, which comprise 150 and 20 classes respectively. We have found that either of the two weight sets produces useful results, segmenting the target structure correctly; this is certainly a useful feature, especially for the Pascal VOC weights, as training in this dataset has been done in a set that does not contain buildings or structures as a separate class.

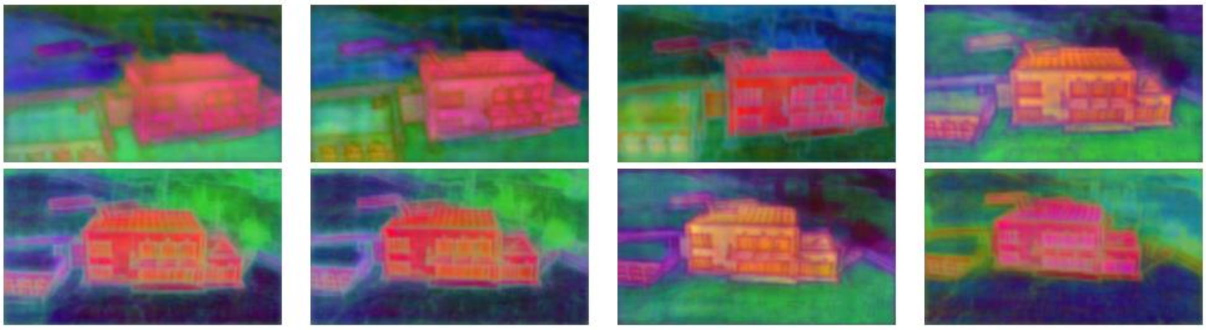

Fig. 5: Visualization of deep features for input images. High-dimensional, pixel-wise deep features were reduced to 3 dimensions with PCA and shown here as pseudo-colorized images. Note that on each frame semantically similar objects correspond to similar colors.

Furthermore, with preliminary tests on buildings other than the location and structure discussed in subsection 3.1, we have noted that the proposed structure estimation algorithm runs quite well in a wide range of structure types. Regarding computation of deep features, we have used the ReLU activation (Strang, 2019) of the last feature map before the network output (“*decoder/decoder_conv1_pointwise”*). Deep features originally are of dimension equal to 256, i.e. each pixel-level cue is a vector in the R^{256} space. These vectors are reduced to the R^3 space using Principal Component Analysis (PCA) (Strang, 2019), solely for the purposes of visualization. Each of the three obtained channels is then assigned to one of the optical Red, Green or Blue channels, and after scaling values to an 8-bit range (0..255) the visualizations shown in Fig. 5 are produced. Note that the visualized features do indeed carry semantic information, as areas of similar color correspond to *semantically* same or similar areas. For example, the whole are of the building is marked with a similar reddish color, even though its image in either the optical or thermal domain is visibly diverse, in the sense that it comprises areas with different colors and/or different thermal intensities (see Fig. 5).

Qualitative results can be examined in the subsequent Figures 6 and 7, where the building detection mask step is shown for the test frames (Fig. 6), and the final thermal statistic calculation step is performed (Fig. 7).

1 Publicly available under https://github.com/tensorflow/models .

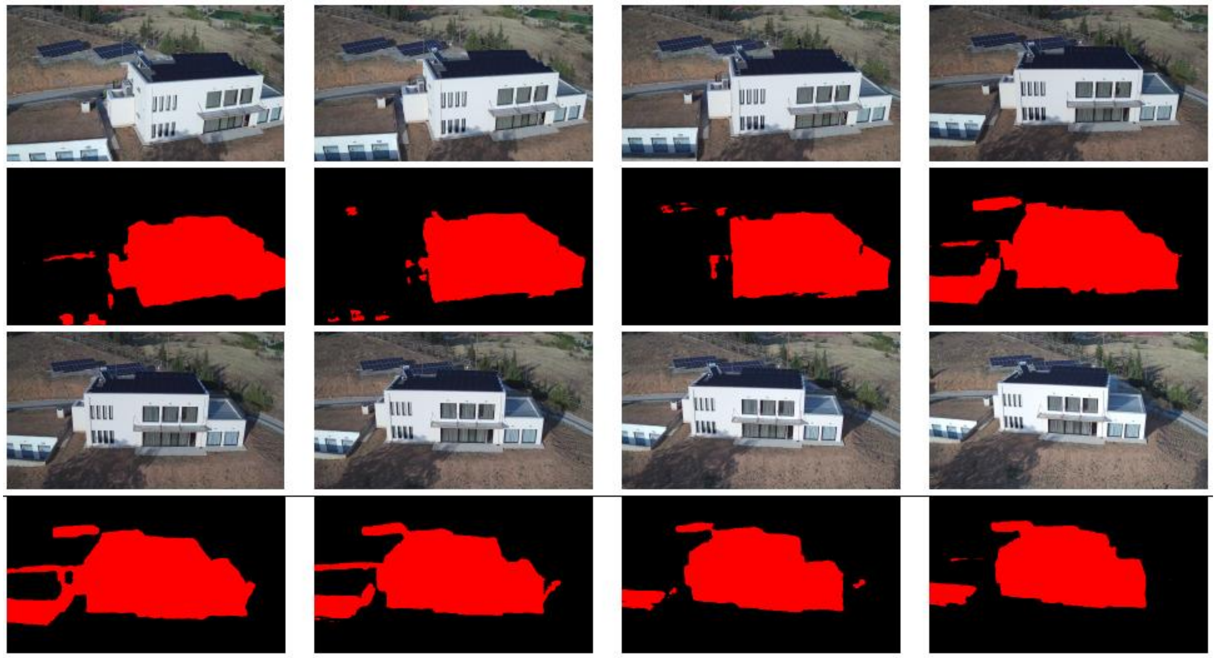

Fig. 6: Detection of main structure in each frame (2nd and 4th row) juxtaposed to original optical input frames (1st and 3rd rows). The areas marked in red correspond to the automatically detected structure.

We report numerical results on Table 1. The reported figures are disparity metrics computed over a number of frames of the captured footage, and they serve to measure the divergence between the statistics of the infrared / thermal image as computed when taking into account the proposed structure localization scheme versus to not taking it into account and just computing statistics over the whole infrared frame each time. In particular, we compute disparity using the following formula:

$$disparity = \frac{|\mu(IR_{full}) - \mu(IR_{proposed})|}{\mu(IR_{full})}$$

where μ(.) denotes mean values over either the while infrared input frame (IR_{full}) or the infrared frame masked using the localization result with the proposed scheme ($IR_{proposed}$). The reported figures show that the disparity between the two cases is certainly not at all negligible, with figures ranging around the 15% mark. In practice, this means that a 'naïve' estimate of the structure thermal signature, i.e. without localizing it correctly first, will lead to a significant error in estimating the correct temperature of the region of interest. Note also from the shown infrared intensity histograms (Fig. 7), that not only the means and peaks of the two infrared intensity distributions differ significantly, but also the whole distributions as a whole. The structure thermal distribution is characterized by a second, low intensity peak, which corresponds to the photovoltaic units found on the structure roof (shown in histogram figures in blue color). This is completely missed by the naïve thermal estimate (shown in histogram figures in green color), which erroneously shows a roughly unimodal thermal distribution. Aside from being an important aspect in the context of computing a thermography statistic estimate *per se*, using the bimodal nature of the histogram could have implications in further digital image processing steps, as for example performing a simple intensity histogram-based algorithm to localize the low-intensity cluster that corresponds to the photovoltaic units.

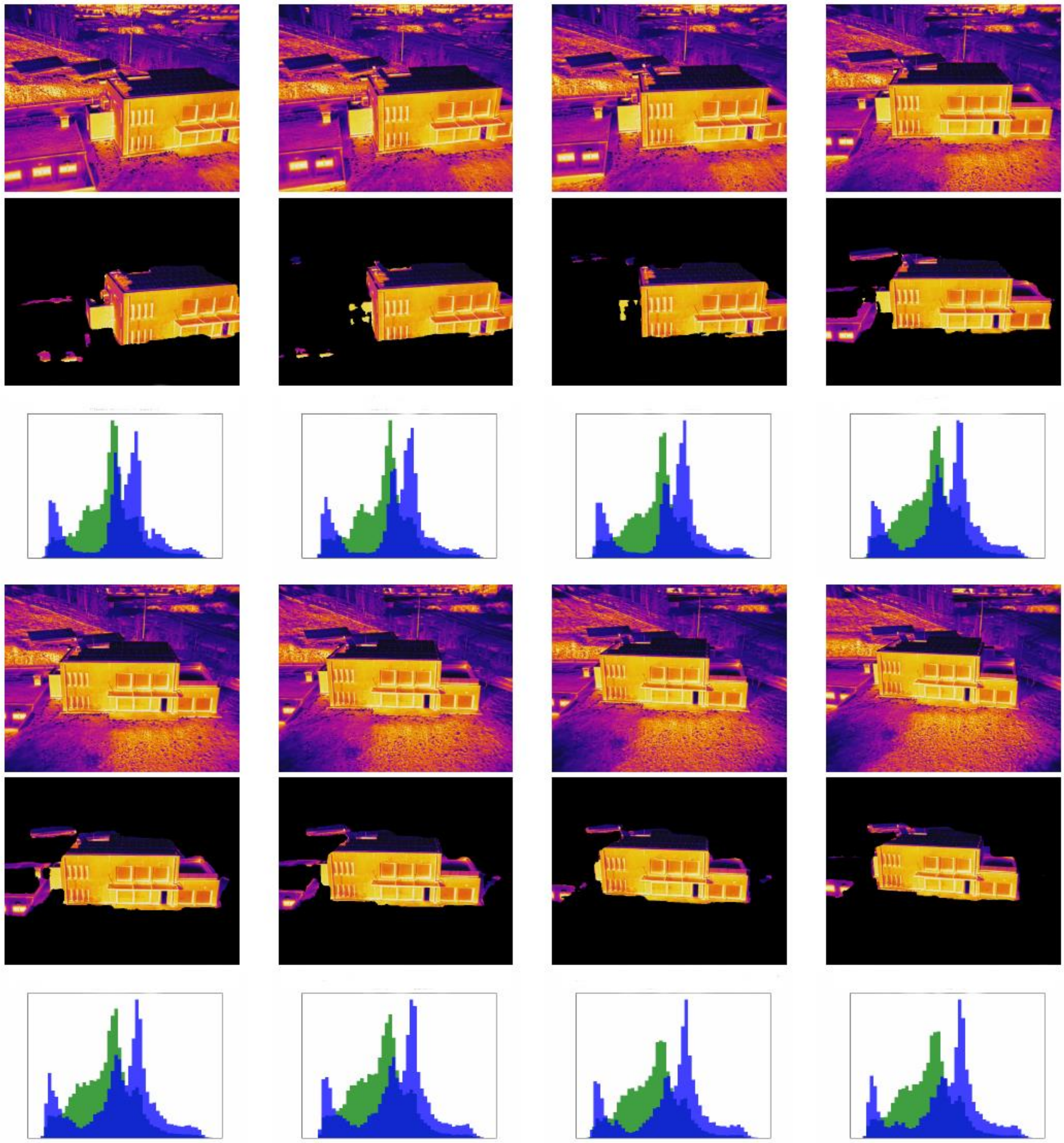

Fig. 7: Segmentation of thermal imaging intensities that correspond to the structure of interest (2nd and 4th rows), juxtaposed to full thermography scans (1st and 3rd rows). Thermography statistics using our method versus using all thermography intensities, for each frame are shown (3rd and 6th row). In all cases there is a clear disparity between thermal statistics versus only the structure intensities, justifying the use of our detection method. In the histograms, the horizontal axis comprises bins from minimum to maximum thermal intensity, and the vertical axis corresponds to the number of pixels with the given thermal intensity.

Table 1: Disparity between thermal statistics computed using the proposed method versus computing whole thermal image frames. Figures are computed over the 8 test images shown in figures 2-4. In all cases, disparity is far from being negligible; hence, using the proposed method is necessary to produce accurate thermal statistics.

Percentage offset								
Image 1	Image 2	Image 3	Image 4	Image 5	Image 6	Image 7	Image 8	Mean +- St.dev.
12.9%	12.8%	12.5%	14.6%	14.9%	15.8%	18.2%	17.6%	14.9% +- 2%

4. CONCLUSION AND FUTURE WORK

In this paper we have presented a method that uses a dual input of optical (RGB) and thermal inputs in order to localize a structure of interest and simultaneously obtain an accurate reading of its thermal characteristics. The proposed method is completely unsupervised, with no training or manual annotation of the structure of interest required. A neural network is used to produce deep features, that are processed to produce the required outputs. The pretraining of the network is not even required to have 'seen' a building class, and we have checked that valid outputs are obtained with two different sets of network pretrained weights. In perspective, the method can be extended to perform detection of other assets, like photovoltaic units. Also as future work, we plan to use multispectral image processing methods (Sfikas et al. 2011) to align and process the optical and thermal pairs more accurately, or integrate the proposed method with an Internet-of-Things (IoT)-based scheme (Sfikas et al. 2016). Furthermore, we look forward to applying thermography-based image processing to other tasks related to construction and materials (for example, relation of temperature and concrete cracking risk) (Kanavaris et al. 2017, Kanavaris et al. 2019) and exploring other uses of UAV-obtained thermal statistics of surveyed structures.

ACKNOWLEDGEMENTS

The work presented was carried out as part of the eDREAM project which is co-funded by the EU's Horizon 2020 framework programme for research and innovation under grant agreement No 774478. The authors wish to acknowledge the European Commission for their support, the efforts of the project partners, and the contributions of all those involved in eDREAM.

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Augmenting building energy usage models with data segmentation

A. William Mounter [1], B. Nashwan Dawood [2], C. Huda Dawood[3]
[123]Teesside University, Stephenson St, Tees Valley, Middlesbrough TS1 3BA, United Kingdom

ABSTRACT: *Energy is the lifeblood of modern civilisation, with buildings and building construction contributing to roughly 40% of the global energy usage and CO2 pollution. Predicting building energy consumption is essential for energy management and conservation; data driven models offer a practical approach to predicting building energy usage. The aim of this paper is to improve the data driven models available to aid facility managers in planning building energy consumption.*

In this case study the 'Clarendon building' of Teesside University was selected for use in using it's BMS data (Building Management System) to predict the building's energy usage. With a particular focus on how data segmentation impacts a model's accuracy and computational time, in predicting temperature related building energy use. Specifically, the effect of segmenting data to accommodate seasonality, as well as building activity and dormancy periods. With each data segment to be used to train an ANN model (Artificial Neural Network),to address the different patterns and trends present in each period/segment, using ensemble models where data segmentation overlapped.

The potential of these models were compared on the grounds of accuracy to each other, then discussed to identify the various impacts of segmenting the data. This study was performed as part of a larger study, in improving building energy use predictions during the operational period, by incorporating predicted user behaviors.

KEYWORDS: *Buildings, Neural networks, Data segmentation, Energy, Prediction.*

1. Introduction

The aim of this paper is to investigate the effect of data segmentation on the accuracy of prediction building HVAC energy usage. Data segmentation being the process of dividing and grouping data based on chosen parameters, in this case timeframes, so that it can be used more effectively.

To use an analogy, in cars, winter and summer tyres tend to perform better in their respective seasons than each other and all-season tyres, but poorer than each other and all-season tyres outside of their respective seasons. It is hypothesised that a model trained with only a season's recorded building data is likely to be more accurate at predicting the season's building energy use, than a model trained with the variety of data from multiple seasons.

To investigate this aim, the Clarendon Building, which is part of Teesside University Campus, was selected for use in this study due to the data rich environment its BMS (Building Management system) provided. Previous studies into this building utilising square regression analysis reported a "5% Mean Absolute Prediction Error (MAPE)" for the demands of each assets in one day ahead forecasts (Boisson et al.2019).

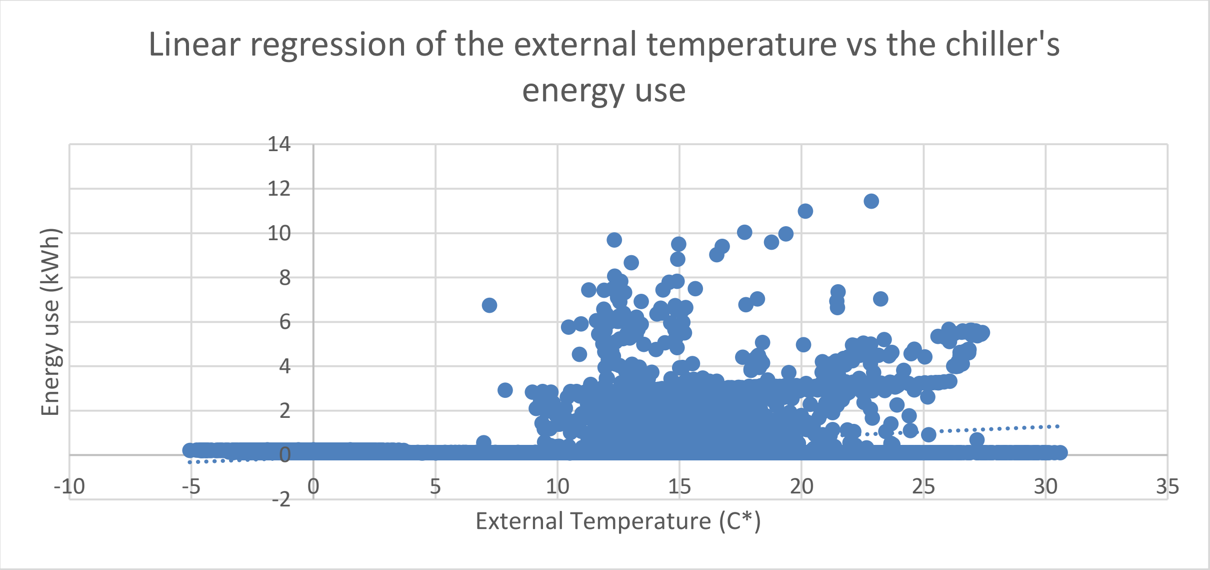
Figure 1: The Clarendon Building, Teesside University (Preston, 2019)

2. Modelling building energy usage

Predicting building energy usage is often complicated by the human element involvement. An empty building is less erratic in it's energy use than a populated one. This issue made worse by the lack of a practical method to capture the building information regarding energy use of each user in the workplace; 'since the conventional methods use plug-in power meters that are extremely expensive and difficult to maintain over long period of time' (Rafsanjani H, Ghahramani A. 2017).

One would expect there to be a positively correlated relationship between the energy used by the building's chiller systems and the external temperature, as the weather gets hotter, the chiller uses more energy to achieve the desired internal temperature. However as Figure 2 demonstrates, this is not the case in an active university building. When linearly regressed, predictions of the chiller's energy use from the external temperature would on average have 114% MAPE error.

Figure 2: A comparison of the Clarendon's chiller's energy use relative to the external temperature



This is due to the multiple other factors that impact the building's HVAC usage, than just the external environmental conditions it is trying to shift away from. The internal temperature can be impacted by many sources other than the external temperature, from the number of people in the building, number of active computers to number of open windows, each effected how much work the chiller system has to do. The difference between the internal temperature and what HVAC system is expected to meet would seem like a reasonable trend that could be correlated to predict the HVAC usage. But once the build reaches the appropriate temperature, the HVAC system will still be expending energy.

Relying upon building's previous average energy usage is a simplistic approach to accommodate for these influential factors, but incorporating them produces more accurate predictions (Wang Z, Srinivasan R. 2017). Two of the main limiting factors in developing building energy use models is integrating occupant behavior into consumption models as well as extending those energy consumption predictions into the long term (Amasyali k, Nora M.2018). The further into the future, the increasingly likely the factors that impact the building energy usage will be different from the ones used to train the model.

By using data segmentation, it may be possible to better accommodate the changing patterns and relationships between the factors that influence the buildings energy usage through creating multiple models, rather than creating a single model can accommodate all of the building different behaviors. Historically data segmentation has been used in marketing to better predict the success of marketing to different groups, developing differing models for potential customers based upon their demographics, lifestyle, behaviors and value (as a customer) (Experian, 2012).

Examples of segmenting building data to improve the accuracy of their prediction models have been met with mixed success. Removing outliers in building energy use data reduced the overall accuracy of its predictions compared to predictions based on unsegmented data in 80% of predictions in one case study (Huyen D, Cetin k, 2018). Whilst in another in the context of energy usage of event venues, found that its models were unable to accommodate both on and off events days, instead requiring separate models to cope with the difference of the behavior of energy usage (Grolinger K, 2016). Depending upon how the data is segmented, their lies the potential to both improve and reduce the accuracy of its predictions.

To test the potential of data segmentation to improve predictions, a method of modeling and predicting building energy use would have to be selected. The most applied machine learning techniques in the field of modelling energy use were: Neural Networks (ANN), Support Vector Machines (SVM), Distribution regression and clustering. (Seyedzadeh, S. 2018). Of these ANN (Artificial Neural Networks) were selected for use for modelling within this study. This was due to ANNs ability to interpret non-liner data compared to other machine learning methods such as multiple linear regression (Which interprets non-linear data poorly) (Zeyu, W & Ravi, S. 2015). Or in the case of Support vector regression, which is also capable of interpreting non-linear data in irregular energy usage environments, due to the size of the datasets available. SVR possessing greater accuracy in smaller datasets than ANN, but being out performed by ANNs in larger datasets (Grolinger, K, Et al, 2016).

ANNs are based upon the concept of establishing a relationship between independent and dependent variables, though the use of training algorithms (Abbas et al, 2019). These relationships are formed in 'hidden layers' in-between the inputs and outputs of the neural networks, where in the equations that assign values to the inputs are systematically randomised dependent on the training algorism used. During the training process the model is fed historical inputs and outputs, of which the training algorithm uses to calibrate the hidden layers continually until its accuracy ceases to increase.

A choice when implementing ANN is whether they are 'feedforward' NN or 'feedback' NN. In Feedforward ANNs, there are no feedback (loops); e.g. the output of any layer does not affect that same or previous layer. In Feedback ANN, networks can have signals travel in both directions by introducing loops in the network (A. Rethinavel Subramanian, 2014). In theory, the predicted weather, and desired internal temperature range would not change depending upon the building's energy use. As such it was decided to employ a feedforward neural network to predict the buildings energy usage, as feedforward neural networks perform better when predicting one way relationships than feedback networks.

3. Research Methodology

To investigate the potential for a neural networks facilitated by data segmentation, from the Clarendon building, datasets were available of BMS data from October 2017 to August 2019. These datasets contained 15-minute averages of building elements energy usage, as well as sensory data of the internal and external environmental temperatures. Of these building elements, the building chiller system was selected for use in modelling due to the impact seasonality would have on the overall usage of the chillers.

The chiller's energy usage was then pre-processed to synchronize with the external temperature and internal building temperature at the time of each event. If any set was missing any data points, the whole set would be removed, due to this causing errors in the reading of the later sets when it came to prediction. The pre- processed data was then copied and split up into years, seasons, months, weeks, days. Of which each was then copied and segmented between a control, week days and weekends, work hours and no work hours, and a four way split of both.

As a baseline comparison, the control data was linearly regressed, producing a 114% mean percent error. Error being calculated through taking an average of the modulated difference between the actual outputs and the predicted outputs, divided by the actual outputs (Absolute percent error).

The first tests were to investigate the optimum training algorithm and number of hidden neurons on the control data. Hidden neurons were tested logarithmically (1, 10, 100 ect…), with Levenberg marquardt, bayseian regularization and scaled conjugate being tested as training algorithms. Each model being trained by taking the inputs (internal temperature and external temperature) to the outputs (Chiller energy use) and randomly selecting 70% for training the model, 15% for validation the model and 15% for testing the model. Ultimately a neural network using ten hidden neurons and a Levenberg marquardt training algorism proved to have the least error and overall processing times.

The segmented data could then be used to predict the building's chiller's energy usage. In that when it is x temperature externally, how much energy would the chiller's use to achieve y internal temperature, with the mean percent error and computational time of each being recorded. Specifically the following points were be tested:

- The impact of size of training data to a set prediction period, e.g. how a year data set compares to a month data set in predicting the following day's energy usage.
- The impact of size of training data to size of predicted data, e.g. how a year data set compares to a month data set in predicting a range of following periods' energy usage.
- The impact of size of the training data in combination with the period between the training data on the predicted event, e.g. to predict a month period, is it better to use the previous month data to train a model, or the that same month in the previous year.
- The impact of segmenting into building active and inactive periods, where in separate models are created for the 8:00am to 18:00pm active period and the 18:15pm to 7:15am period of the data set.
- The impact of segmenting into week days and weekends, where in separate models are created for the Monday to Tuesday period and the Saturday to Sunday period of the data set.

At which point the results of each test could then be compared and reviewed to determine impact of data segmentation on accuracy and computation time

3.1 Method limitations

As the external temperature training data used the temperature at the time of each event, opposed to what the external temperature was predicted to be before the event, this would represent an absolute ideal situation. Where in predicting true future events, the difference between the accuracy of the predicted temperature would impact the overall prediction of the building's energy usage and predicting one year into the future in this manner would be significantly more inaccurate. Though some percentage error could be potentially reduced through greater focus being given to optimise the number of hidden layers of the NN.

4. Results and Discussion

4.1 Computational time

Whilst evaluating the optimum number of hidden layers it was observed that the computation time did not exceed 1 second until the number of hidden neurons exceeded 1000 regardless of size of the dataset used. As changing the size of the dataset did not visibly affect the computational time of the process up until 1000 hidden layers, it can be assumed that the number of times the data is processed has a more significant impact on the computational time than the size of the dataset itself. For all following data 10 hidden neurons were used, due to the comparably less percent error observed.

Table 1: Changes in MAPE and Computation time caused by changing the number of hidden neurons

Number of hidden neurons	10^0	10^1	10^2	10^3	10^4
Percent Error (%)	0.45	0.41	0.42	0.49	28.70
Computation time (Hour, Min, sec)	0.00.01	0.00.01	0.00.01	0.03.20	0.23.45

4.2 Segmenting by period

The following is a selection of the percentage errors observed:

Figure 3: A comparison of MAPE caused by changed in the period of the training data

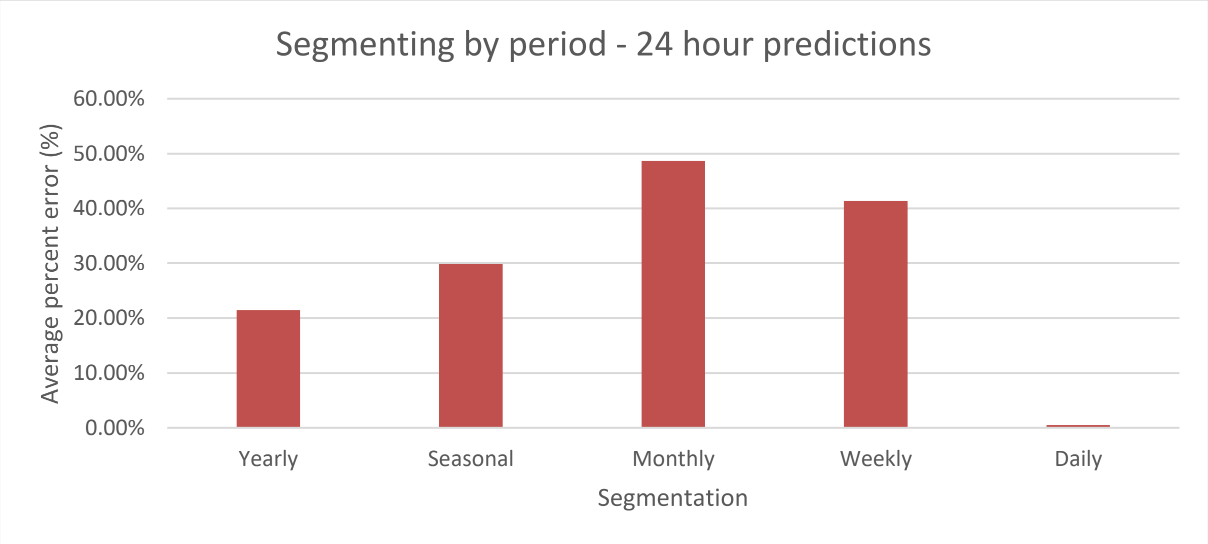


Table 2: Corresponding percentages to figure 3

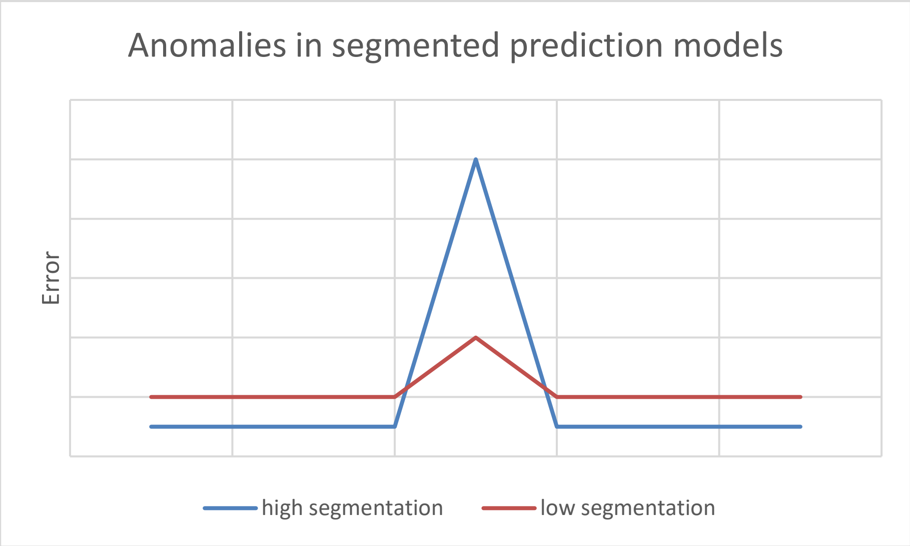
	Yearly	Seasonal	Monthly	Weekly	Daily
Average percent error	21.41%	29.86%	48.62%	41.32%	0.50%

The above is a graphical representation of the average percent error of each segment size after being used to predict the following twenty four hours after the training period. Averages being take of each period over the entire year, e.g the monthly average is of every month. The strange observation was made that the smaller and larger the training datasets, the more accurate on average it's model's predictions would be. Analysis of this trend identified two underling patterns:

- When the training data was highly segmented, that the majority of predictions would increase in accuracy, but the error in predicting 'anomalies' or events which parameters exceeded the training data significantly increased.
- When the training data was lowly segmented, that the majority of predictions would decrease in accuracy relative to highly segmented predictions, but the error in predicting 'anomalies' or events which parameters exceeded the training data would occur less and be less significant.

This these patterns are illustrated and simplified in Figure 4:

Figure 4: Simplified example of the relation between the average error, extreme errors and data segmentation



The assumed cause of this effect, is that whilst segmenting data makes it's easier to isolate and predict the trends of that period, it increases the difficulty in identifying and modelling underlining trends present in the unsegmented data set as a whole. As the smaller datasets are less likely to have the variety of events occur within its parameters, they will be able to better optimise towards the one's it contains, but unable to account for the ones they do not.

It was additionally observed that using segments data of periods smaller than the predicted period, would significantly reduce the accuracy of the prediction, whilst using segment sizes larger than the predicted period produces the previous effect. Furthermore, the greater the period of time between the training data and the predicted period, the greater error caused by segmenting the data. Noting an exception in that once time between the training data and the predicted period approached that periods position in the previous year, the error would decrease. With predicting seasonally and yearly periods having a higher accuracy on average using their own previous year's data, than the period directly previous to them.

4.3 Segmenting by 'Building Activity and Dormancy'

Due to the monthly segments producing the most error off all prediction periods, they were selected to investigate the potential to isolate internal patterns within segmented periods, as they would demonstrate the largest potential for reduction of in error.

Figure 5: The change in MAPE cause by segmenting monthly data by building activity

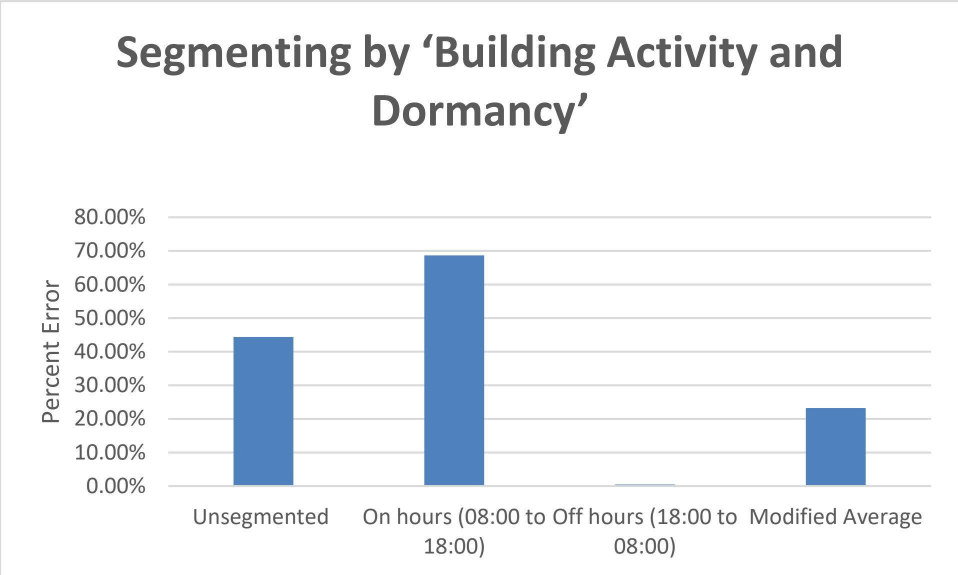


Table 3: Corresponding percentages to figure 5

	Unsegmented	On hours (08:00 to 18:00)	Off hours (18:00 to 08:00)	Modified Average
Percent Error	44.33%	68.70%	0.48%	23.22%

As shown in figure 6, segmenting the monthly predictions by building activity and dormancy periods, reduced the mean percentage error by 21.10%, from 44.33% to 23.22% error. (Within this context 'modified average' refers to taking the average of both periods with consideration to the different durations of both). The building dormancy period follows a pattern of using 0.1 or 0.2 Kwh depended upon if the external temperature is above or below 0*c respectively, allowing significantly more accurate modelling due to its simplicity than when incorporated with the whole day cycle. Conversely the average mean percentage error of the active period's prediction are increased by 24.37% to 68.70%, indicating that either:

- Removing the night cycle increases the error of predicting the day cycle.
- Removing the nigh cycle does not increase the error of the predicting the day cycle, and that period errors were being 'balanced' by the dormancy period's low errors when the mean error was originally calculated.

Investigation of the specific predictions (rather than means) indicated that it is that later rather than former, with segmenting active and dormancy periods reducing the average mean error of the monthly predictions of the chiller system (under ideal circumstances) by roughly half.

4.4 Segmenting by 'Week days and Week ends'

Given the success in reducing predicting error by separating trends in the data set, it was expected that firstly the weekend and weekdays of a university building would have significantly different usage patterns and thus chiller requirements. And secondly that segmenting along these lines could produce reductions in error similar to segmenting building dormancy and activity periods.

Figure 6: The change in MAPE cause by segmenting monthly data by week days and ends

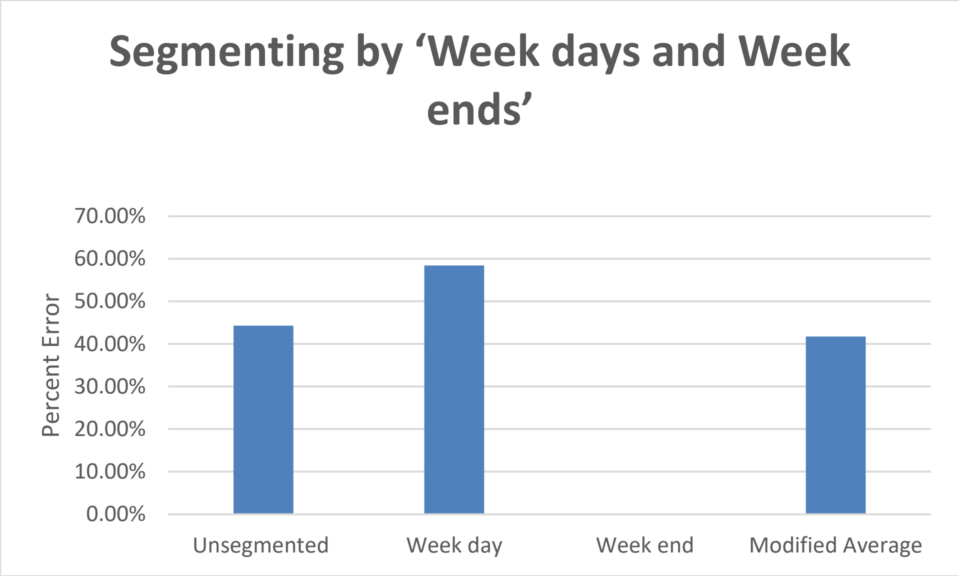


Table 4: Corresponding percentages to figure 6

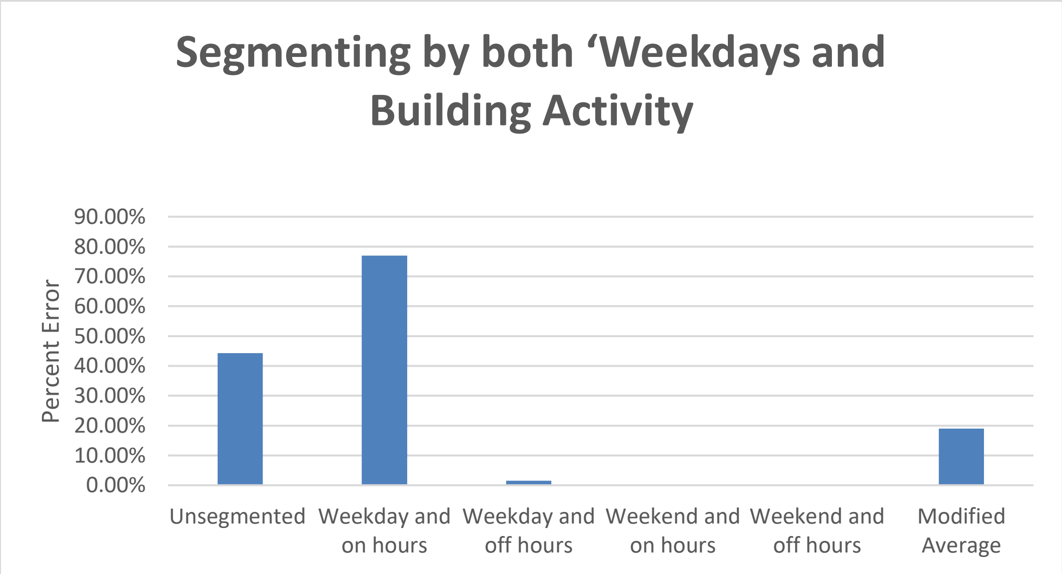
	Unsegmented	Week day	Week end	Modified Average
Percent Error	44.33%	58.43%	0.02%	41.75%

As shown in Figure 6, segmenting by weekend and weekday only produced an average reduction of mean percent error by 2.58%. With the weekend period sharing the behaviors of the dormancy period and the active period (but predominantly the former) during the day, and the dormancy period during the night; when active periods did occur during the day, there was an expectation that energy use to be underestimated during the active periods. Though the reduction of error the weekend period was greater than expected; being only 2/7s of the overall prediction period, was not enough to significantly counter balance the increase in error observed in the means of the remaining 5/7s of the period (relative to active and dormancy periods).

4.5 Segmenting by both 'Weekdays and weekends' and 'Building Activity and Dormancy'

Combining the two processes together, and segmenting monthly data into four parts, produced the average percent errors shown in figure 7:

Figure 7: The change in MAPE cause by segmenting monthly data by building activity, week days and ends



Tables 4 and 5: Corresponding percentages to figure 7

	Unsegmented	Weekday and on hours	Weekday and off hours
Percent Error	44.33%	76.93%	1.48%

	Weekend and on hours	Weekend and off hours	Modified Average
Percent Error	0.01%	0.05%	19.03%

Doing so reduced the average of monthly prediction's percent error from 44.33% to 19.03%, reducing error by 25.29%, a further 4.19% reduction in error relative to segmenting by dormancy and active periods alone. At this stage combining the weekend dormancy period with the weekday dormancy period to simplify the system into three rather than four models, Would likely not significantly impact the overall accuracy of the system, but as there is a higher chance for building activity after 18:00pm during the weekdays compared to the weekend, it is possible that the differences between the two periods could minimally increase the average percent error relative to them being modelled separately.

On average, in situations where the predicted period is expected to be similar to the training data, segmenting appropriately to the patterns present in the data, without reducing the net data used to below the duration of the predicted period produced the least error. Whilst in situations where the predicted period is expected to be dissimilar, or repeatedly/significantly exceed the parameters of the training data, segmenting less with the aim of expanding the training data's parameters to accommodate the outliers produced the least predictions error.

5. Conclusion

The results of data segmentation were mixed, in that it appeared to have both a negative and positive impact upon the accuracy of predicted building energy usage dependent upon: the duration of the predicted period, the time between the training data and the predicted events as well as patterns of the segmented data. In that:

- The greater the segmentation, the greater the accuracy in predicting trending inputs; but the greater the error caused by outlying inputs in each segment.
- The more correlated the relationship between the segments and the inputs, the more likely segmentation will decrease prediction error; but less correlated the relationship between the segments and the inputs, the more likely segmentation will increase average error. E.g segmenting between building active and inactive periods reduced error due to both segment being very different patterns of energy usage.
- The greater the size of the predicted period and time between the predicted event and training data to the size of the training data the more negative the impact of data segmentation will have on prediction accuracy. Due to the larger the period and further away the prediction, the increasing likely there will be events outside of the range of the training data.

Under the ideal conditions of predicting one day into the future, using a one-day segment to train the ANN, with completely accurate temperature data, an average mean percent error of 4% could be achieved. (With a 21.4% error in the control compared to the 114% error of linearly regressing the data). Though it can be expected that this error would increase, in the case of predicting future energy usage based upon predicted weather data for the external temperatures and the building temperate comfort zone for the internal.

Based upon these results, five main areas of future work were identified:

- Investigating the accuracy of smaller data segments such as hours in predicting shorter periods into the future.
- Using predicted weather data to investigate its impact on prediction accuracy, and test the model's robustness, as the actual weather conditions would not be available when predicting the future.
- Investigating the accuracy of other machine learning techniques, such as SVR for use in smaller data segments, or other types of ANN and training algorithms as well as hybridisations of these models.

- Investing the impact of data segmentation using other HVAC systems, as well as predicting the energy usage of the HVAC system as a whole.
- Directly comparing the percent error of this method of predicting energy usage with other methods previously used on the Clarendon building, using the same data to train both models, such as the square regression model used in 'Boisson et al.2019'.

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A Review of Sustainability Assessment and Integrated Modelling for Urban Energy Planning

Bjarnhéðinn Guðlaugsson[1], Huda Dawood[2], Gobind Pillai[3]

[1,2,3] School of Computing, Engineering and Digital Technologies, Teesside University, Stephenson Building, Stephenson Street, Middlesbrough, Tees Valley, TS1 3BA, United Kingdom

ABSTRACT: *Our current energy system is facing increasing pressure for energy transition at all levels of society, as there is a growing concern for climate change brought about by the impact of fossil fuel extraction and greenhouse gas emissions (GHG), in addition to the predicted population growth leading to an increase in energy demand. Future development needs to focus on sustainability, clean and affordable energy, respecting the environment as well as providing prosperity for current and future generation. These factors leave urban energy planning and decision making facing enormous challenges when it comes to figuring out how to enable the transition to a cleaner and decarbonized energy system without jeopardizing the energy security, economic prosperity and neighboring environment of urban populations. During the last few decades we have seen an increasing focus on this kind of research within academia and private and public research institutions. This paper aims to provide a review on the application and use of sustainability assessment method and integrated modelling approach to aid decision-making for urban energy planning. This study applied a systematic literature review approach and identified 31 papers and 16 of those 31 papers, were reviewed and analyzed in more depth. These papers were categorized based on the title, authors, publication year, journal, geographical location, research methods, research domains, model, software and databases. The results identify that sustainability indicators are the most preferred methodological approach used when it comes to sustainability assessment. Life Cycle Thinking (LCT) was the second preferred method. Also, the results identified that 81 per cent of the papers reviewed preferred applying a sustainability assessment model that was constructed out of the integration of two or more methods such as LCT and indicators when conducting sustainability assessment analyses. The results also show that only 13 per cent of the papers reviewed use System Dynamics as the modeling methodology approach, thereby acknowledging that there is space for more research to be conducted around applying system dynamics based sustainability assessment on research regarding urban energy planning and energy transition.*

KEYWORDS: *Systematic Literature Review, Sustainability Assessment, Indicators, Urban Energy Planning, Decision-Making, Energy Transition*

1. Introduction

The United Nations predicts that in 2050 66% of the 9.7 billion global population will be living in urban areas compared to 55% in 2018 (Dominković, D. F. et al., 2018, U.N., 2019) This means that we can expect to see an increase in total urban energy usage, which in 2014 accounted for 67% to 76% of global energy usage. In addition to growing energy usage, it is expected that we will see a growing total greenhouse gas (GHG) emission from urban energy usage, which in 2014 accounted for 71% to 76% of the global GHG emission accounting for more than three-quarters of global GHG emissions (Seto, K.C., et al., 2014, Cajot, S., et al., 2015, Barragán-Escandón, A, et al., 2017). In today's society, we are expected to see a growing population, followed by continued growth in urbanization (U.N., 2019) Additionally, our current energy infrastructure and economic development is highly dependent on fossil fuels which is facing a growing depletion. Accompanied by increasing concerns of the climate crisis cause by human pressure on the environment and natural resources. The points described above are few leading factors, which call for an energy transition towards a decarbonized energy system (Creutzig, F. et al., 2015, Cajot, S., et al., 2017, Santagata, R. et al., 2019).

The factors mentioned along with elements like the current global political landscape, leave current and even future urban planning and energy planning facing an enormous, multifaceted challenge on how to enable the transition from a highly fossil fuel dependent energy system to a cleaner and decarbonized energy system. This transition needs moving away from fossil fuels towards a system built around the utilization of renewable and alternative energy sources (Cajot, S., et al., 2015, Creutzig, F. et al., 2015), without jeopardizing the energy security, economic prosperity and neighboring environment of urban populations (Creutzig, F. et al., 2015). Decision-makers today need to start designing and developing realistic action plans aimed at enabling this transition. Consequently, focusing on decreasing GHG emission through the increased share of renewables in energy systems, and the protection of environmental ecosystems (Creutzig, F. et al., 2015, Cajot, S., et al., 2017).

The focus of urban energy planning in recent decades has begun moving towards strategic planning in regard to how we can account for the changes that future urban areas and cities are expected to face in the coming years along with how to overcome the challenges our current global society is facing (Barragán-Escandón, A, et al., 2017, Cajot, S., et al., 2017, Ibrahim, M. et al., 2018, Ferrari, S. et al., 2019). At the same time, our decision-makers and other stakeholders have often set forward and accepted ambitious goals in the form of global agreements such as the Kyoto agreement in 1997 and Paris agreement in 2015. Those goals and agreements often tend to overlook systematic considerations of associated impact and neglect any dynamic correlation within the involved sectors (Tziogas, Charalampos et al. 2019). Hence, there is a need for designing a robust decision-support tool that manages to account for the systematic factors and capture these dynamic interrelations between different sectors related to urban energy planning and energy transition. The sustainability aspect of the decision is often arduous since urban energy planning and energy transition requires examination from multiple perspectives (Tziogas, Charalampos et al. 2019). Some studies have acknowledged the use of the tools Sustainability Assessment and/or Sustainable Indicators in combination with comprehensive modelling methods such as Life-Cycle Assessment and System Dynamics. These tools can be advantageous approaches to measure, analyse and understand the proposed policies and decisions in regard to complex energy relation topics (Musango, J. K., et al. 2012, Tziogas, Charalampos et al. 2019).

Since urban energy planning and energy transition are complex issues with multiple dynamic correlations between different sectors, stakeholders require a decision-support tool that accounts for those dynamic interrelations and multiple perspectives. It is highly relevant to explore the application of a combination of the Sustainability Assessment and System Dynamics tools in relation to urban energy planning and development in the literature. Therefore, the objective of this work is to conduct a systematic literature review of articles published over the last 50 years focusing on urban or city energy planning and development using select keywords such as System Dynamics, Sustainability Assessment and Decision-Making. The aim is to gain an understanding of the level of published research using sustainability assessment as the core method and identify the preferred methodological approaches when it comes to applying sustainability assessments.

Conducting a literature review is one of the cornerstones behind academic writing and research. Systematic literature review, has the ability to thoroughly assess, capture, and locate research publication within a specific research area, with the aim of enhancing the current knowledge body of the researcher, which is the main reason for selecting systematic literature review as the foundation approach for this study (Tranfield et al. 2003, Littell et al. 2008, Trindade E.P., et al. 2017).

This manuscript is structured as follows: Section one focuses on introducing the basis behind the research, methods and objectives; Section two describes the methodological approach and the research questions; Section three describes and discusses the main results of the analysis, Section four discusses the limitations of the study and the further work planned; and lastly, the Conclusion section discusses the main outcomes of the study and provides answers to the research questions set forwards.

2. Methodology

We adopted a systematic literature review approach structured around a three-step process as shown in Fig. 1. The first step in the process is an unstructured literature review, where the objective is to familiarize with this specific research area and without being bound by a restriction in regard to research questions. Additionally, the first step is also used to identify the databases used in the systematic literature review and the keywords, which are the foundation of the Systematic Literature Review. The second step is the systematic literature review, which focus on applying Boolean search approach and two sets of screening steps to identify relevant papers related to application of ´sustainability assessment´ tool and complex modeling regarding research in the field of urban energy planning and energy transition. The third step in the process, is the analysis which focus on analyzing the identified papers, with the objective of providing answers to research questions set forwards in addition to enhancing the body of knowledge of the researcher.

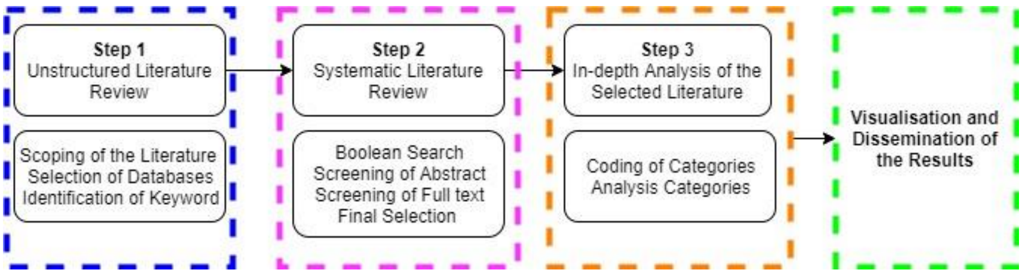

Figure 1 - Simplified Methodology of the Literature Review Process

2.1 Planning the review

This step outlines the research questions that are to be addressed in the systematic review, along with the defining the review approach. The three-step process ensures the robustness of the approach and increases the ability to identify the relevant trends in publication outputs, as well as potential research gaps in the research domain.

The research questions are as follows;

a) What have been the trends in research published related to sustainability assessments, during the last few decades?

b) Which are the preferred methodological approaches for sustainability assessments?

The systematic literature process is centered on a five-step process and applies the Boolean search approach as shown in Fig. 2.

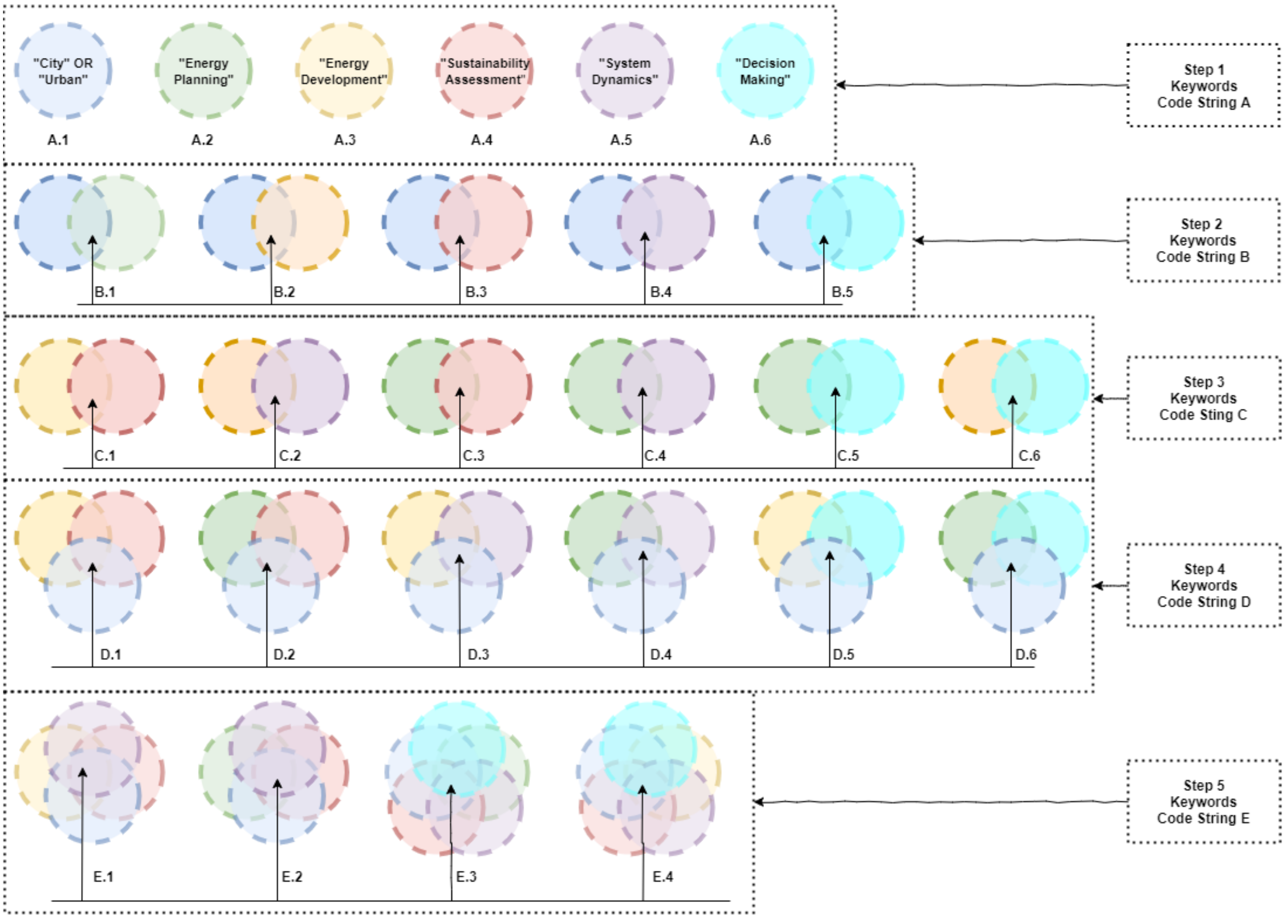

Figure 2 - Systematic Literature Review Process showing Steps and Boolean Search Strings

2.2 Conducting the Review

The databases selected for conducting the review were Sciences Direct, Web of Sciences, and Scopus. Each step of the systematic literature review process focused on running the keywords in different combinations, as shown in fig.2 through the selected academic journal databases. The objective is of the review process was to capture any literature within areas where the keywords overlap in each steps, the overlaps are pointed out in fig. 2. The process also considered the boundaries of the research criteria in the first part and then exclusion criteria in the second part, when narrowing down the scope of the relevant articles. The boundaries are as follows:

- Research Criteria - Article Title, Abstract, Keywords
- Exclusion Criteria – Language, Document Type, Sources Type
    - Web of Sciences - [language: English, and document type: Articles]
    - Scopus - [language: English, document type: Articles, and source type: Journal]
    - Science Direct - [document type: Research Articles]

The first three steps of the review consisted on running each keyword in step A and simple combination built around the keywords "City" OR "Urban" and each of the other keywords in Step B, and then in Step C a combination built using "Energy Development" or "Energy Planning" together with "Decision-Making", "Sustainability Assessment" and "System Dynamics". These three initial steps contribute to getting a comprehensive insight into the plethora of publication in these research areas over the recent decades.
The last two steps in the process focus on narrowing down the literature search towards the aim of the research. The main focus is to look into the degree of publication and research conducted within the field of urban energy planning and development that use a combination method that applies sustainability assessment with system dynamics modelling method.
Finally, the literature review identifies relevant articles. The selection of the articles is based on the research criteria and exclusion criteria, seen above, along with removing any articles 'duplicates. Subsequently, after finishing all the steps in the literature review, the selected literature is analyzed further to identify relevant information and insights that can answer the research questions and strengthen the knowledge of the researcher in this specific area of research.

3. Results and Discussion.

Step 1 provided a the unstructured literature review with the aim of scoping the literature, and helped the researcher gain insight into the type of research has been conducted in these areas of sustainability assessment and to identify the keywords, which are the foundation of Step 2 – Systematic Literature Review. The systematic approach applied managed to capture the publication outputs levels over the period from 1960 to 2019, for all search strings.
Each step of the systematic approach and the associated research criteria set forward by the research boundaries helped narrow down the number of papers identified. The reason for keep constructing new search string combinations was continue defining the search scope until it would capture research papers relevant to the main objective of the study. The aim was to capture papers that apply any type of sustainability assessment approach to help solve problems and improve decision-making concerning urban or city energy planning.
Applying this five-step systematic review approach provided the ability to gain insight into the areas of research related to each keyword through identifying the scale of the publication level. For Step A, we identified around 2,358,279 publications after applying the exclusion criteria. By Step D the number of studies identified fall down to 3,457 publication. Finally, Step E narrows it down to 31 publication, which would be subjective to more elements of limitation – delete of duplication and relevance – after that process 16 papers were identified as the relevant papers to the topic of interest. In this regard, see a) Table 2, show detailed results for Step E., and b) fig. 3, shows in detail the number of publications identified in each step
The identified papers were than analyzed further in Step 3 to get across the primary purpose of this review papers which is identifying the main methodological approaches for sustainability assessments and what is current publication trend level for research relevant to sustainability assessment.

Table 1 – Classification Categories for Step 3 in Review Process

Classification Categories									
Title	Authors	Years	Journal	Research Field	Geographical Location	Method	Model	Software	Databases

Table 2 - Detailed Illustration of Results from Step E of the Systematic Literature

	Web of Sciences		Scopus		Sciences Direct	
Review Boundary Terms / Keyword "Code"	**Research Criteria**	**Exclusion Criteria**	**Research Criteria**	**Exclusion Criteria**	**Research Criteria**	**Exclusion Criteria**
E.1 ("City" or "Urban") AND ("Energy Development") AND ("Sustainability Assessment") AND ("System Dynamics")	0	0	0	0	39	7
E.1.5 ("City" OR "Urban") AND ("Energy Planning") AND ("Sustainability Assessment") AND ("System Dynamics") AND (Decision Making")	0	0	0	0	38	7
E.2 ("City" or "Urban") AND ("Energy Planning") AND ("Sustainability Assessment") AND ("System Dynamics")	0	0	0	0	39	8
E.2.5 ("City" or "Urban") AND ("Energy Development") AND ("Sustainability Assessment") AND ("System Dynamics") AND ("Decision Making")	0	0	0	0	38	9
					Total relevant articles after removing duplicates	n = 16

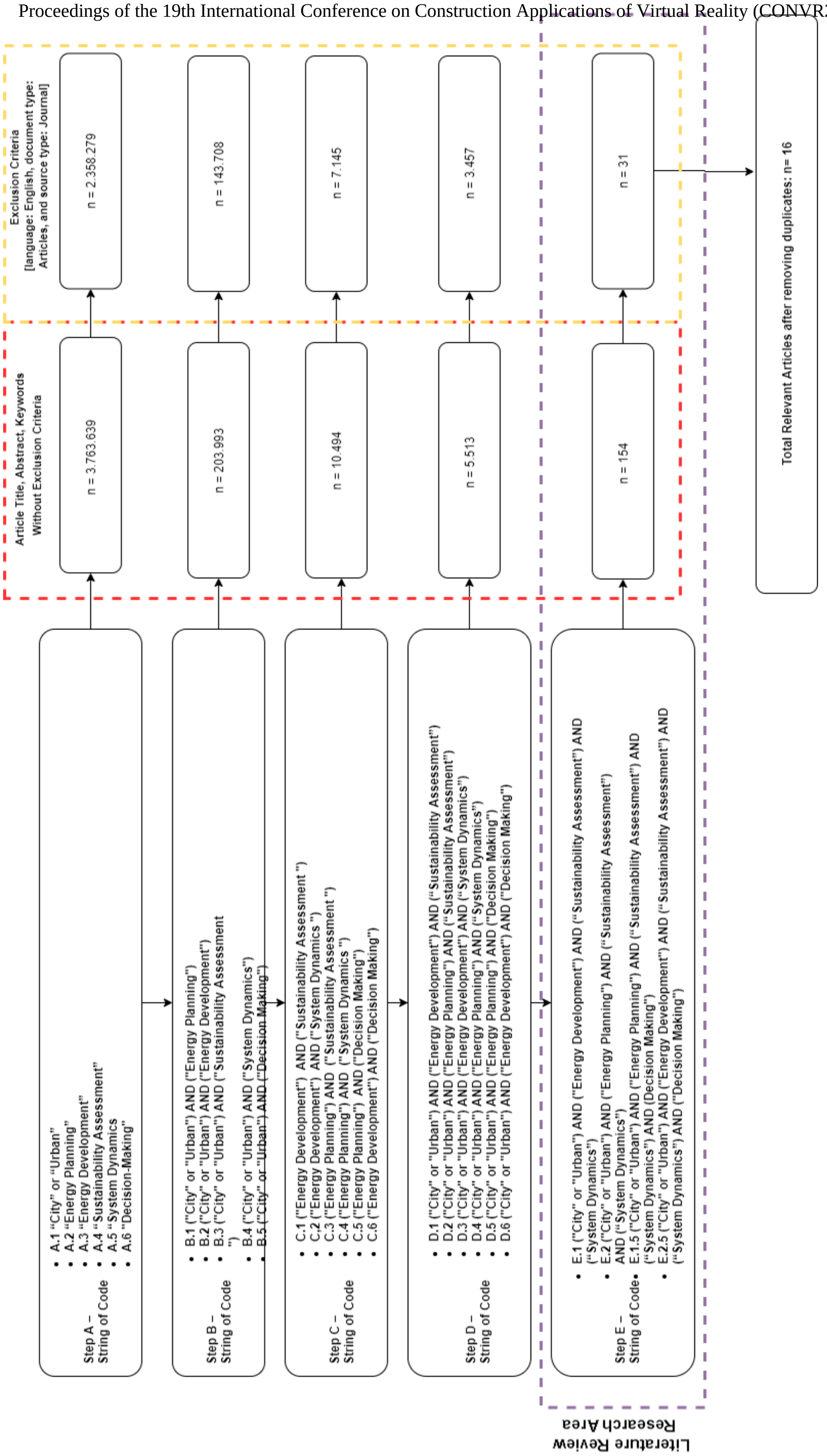

Figure 3 - Detailed Process of the Systematic Literature Review and Results

The literature review, identified 16 papers, which used various multi-disciplinary research application such as stakeholder participation (Krumdieck, S., et al., 2009, Pereverza, K., et al. 2019), system dynamics modelling (Musango, J. K., et al. 2011), combination of business modelling and metadata modelling to improve policy framework (R. Martins et al., 2017) and fuzzy logic Multi-Criteria Decision Analysis (MCDA) (S. Gumusa et al., 2017, H. Karunathilake et al., 2019) to solve problems related to renewable energy development (Gumusa, S., et al., 2017, Karunathilake, H., et al., 2019), feasibility studies of new energy technology (Musango, J. K., et al., 2011), complex decision making to improve energy policy (Martins, R., et al., 2017, Pereverza, K., et al. 2019), and improving energy infrastructure and system in remote communities (Krumdieck, S., et al., 2009). Moreover, 81 per cent of the identified papers are research papers which apply integrate model's application to solving problems related to research areas within energy and sustainability disciplines. Appendix A shows all the papers in, Table A.1.

During the coding of categories and analysis, did this review paper identified multiple research domains and for comprehensive treatment of the multi-disciplinary subject. As a results were paper counted in multiple research domains. In this regard, fig. 4, shows the principal research domains.

The results show that 38 per cent of identified paper are decision-support relevant research, and 31 percentage are bioenergy or renewable energy or Life Cycle Thinking related research. Notable detail from the results is that only 25 per cent of the identified papers are sustainability assessment application research, and only 13 per cent of the papers are working on research that falls under the research domains of system dynamics. Another prominent insight gained from the results is that none of the identified papers are conducting research that falls under the research domain urban or city energy planning, thereby providing indications that there is a need for research focusing on urban and city energy planning structured around using multi-disciplinary application. Lastly, on the other side, 6 per cent of the identified papers are research belonging to the research domains such as applications of Artificial Neural Network (D'Amico, A., et al., 2019), Animal by-product (Santagata, R., et al., 2019) , Waste Management (Santagata, R., et al., 2019), and Remote Communities (Krumdieck, S., et al., 2009).

These are research domains that are considered highly relevant in today's research environment, where the focus is on Artificial Intelligent (AI), improving waste management application, how to bring clean energy to rural and remote communities and lastly, assessment of using animal by-product for electricity generation in meat production facilities (Santagata, R., et al., 2019).

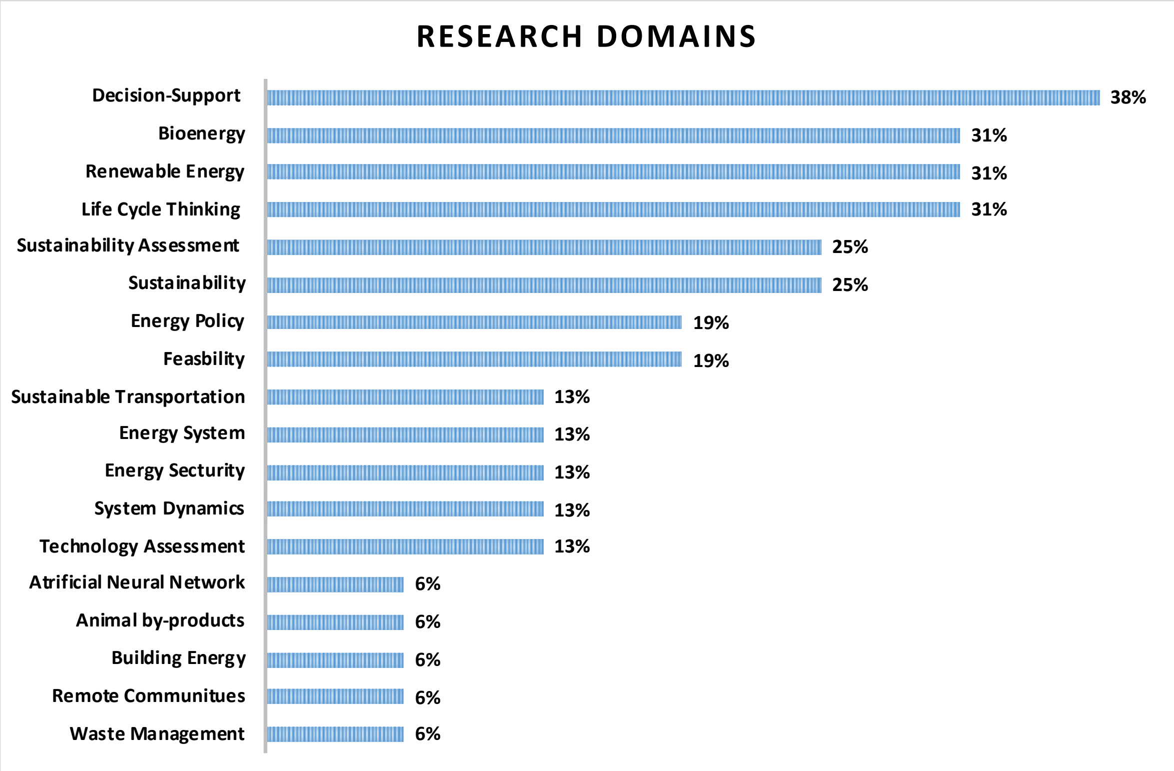

Figure 4 - Research Domains for various multi-disciplinary research application within energy and sustainability research disciplines

The systematic review search resulted in the identification of 16 papers based on search and exclusion criteria. However, for the publication trends analysis is the focus on using untreated data meaning that all identified papers from the four search strings in step E, will used in the analysis. In step E, 154 papers were identified, first papers were published in 2004, and the latest papers are from 2019, as is shown in fig. 5. It is also noticeable in the results that between the years 2004 and 2011, only 20 papers are published across the four search string criteria. However, since 2011 publication level has increased, showing an upward trend since 2011 in publication. Though with the exception in the year 2018 were it seems that publication output dropped down to 2 papers across all four search strings compare to the average publication output of 7.5 papers across the four search strings in 2017. This review research was not able to identify a specific reason for this drop-in publication output in 2018 followed by a sharp increase in publication level in 2019, taking back to similar output as in 2017. The average publication output in 2019 was 7.25 publication across all four search stings.

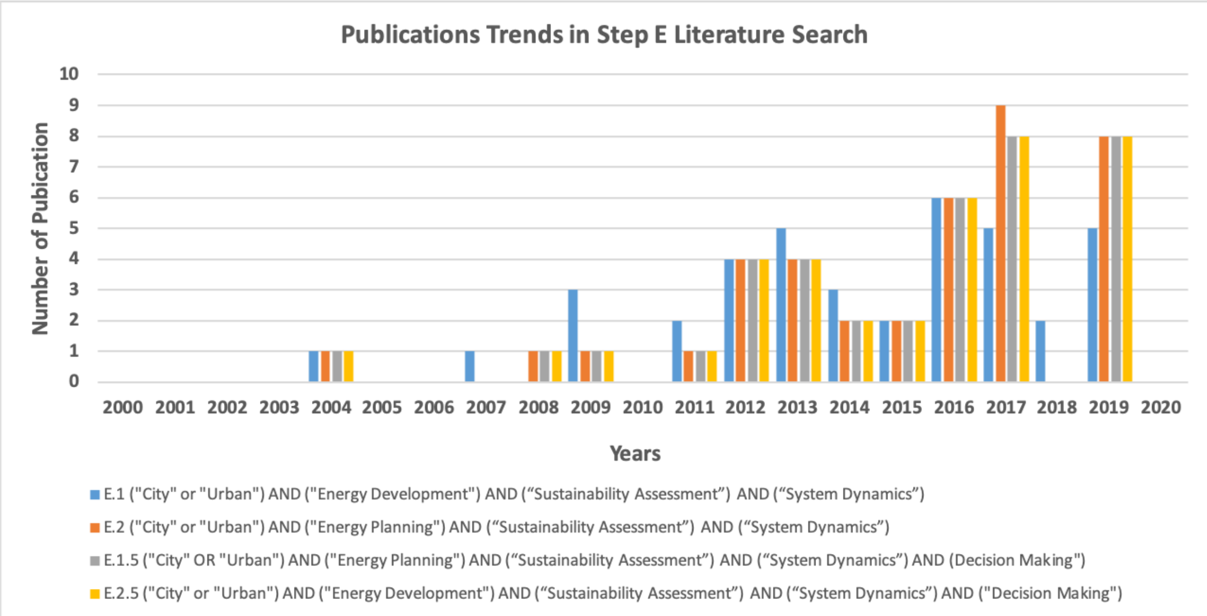

Figure 5 - Number of Publication per year across all Search Strings in Step E

The keywords such as energy planning, energy development, decision-making which are all embodied in the search strings in step E. Have become increasingly crucial within today's society, due to growing environmental, economic and socials concern concerning the climate crisis. This societal change in our society has led to an increased focus on sustainable thinking and improving decision making regarding any development projects, especially energy-related development. This increasing spotlight on topics connected to the keywords, could explain the reason for the upward trend in academic research publication output during recent years.

The results show that 81 per cent of the papers identified apply indicators as one of their research methods to solve the problem, these indicators are in most cases sustainability indicators originate from Triple Bottom Line framework (Jian Liu et al., 2013, Onat, N., et al., 2016). Therefore, providing a strong argument for that indicators are the foundation to any comprehensive sustainability assessment and that well structure and methodologically grounded indicators are essential when designing an integrated model aimed at solving and researching problems within the field of energy and sustainability research. The results also show that Life Cycle Thinking (LCT) methods are the most favoured methods to use as the modelling approach, with 31 per cent of the papers applying an LCT approach. Multi-Criteria Decision-Making (MCDM) approach and fuzzy logic methods seem to be attractive methods either on its own or in combination with other methods to solve and research problems within the field of energy and sustainability (Gumusa, S., et al., 2017, Karunathilake, H., et al., 2019). On the other hand, system dynamics and system thinking methods seems to be the least favoured when it comes to the choice of research method. As can be seen with only 13 per cent of identified papers, are research studies, which apply system dynamics or system thinking in comparison with 31 percentage applying LCT methods and 19 per cent applying MCDM methods and/or fuzzy logic approach when comes to conducting analysis and research within the field of energy and sustainability. The results show that there is a scope for conducting further system dynamics modelling research within the field of energy and sustainability regarding urban and city planning. In this regard, figure 6, shows the major research methods.

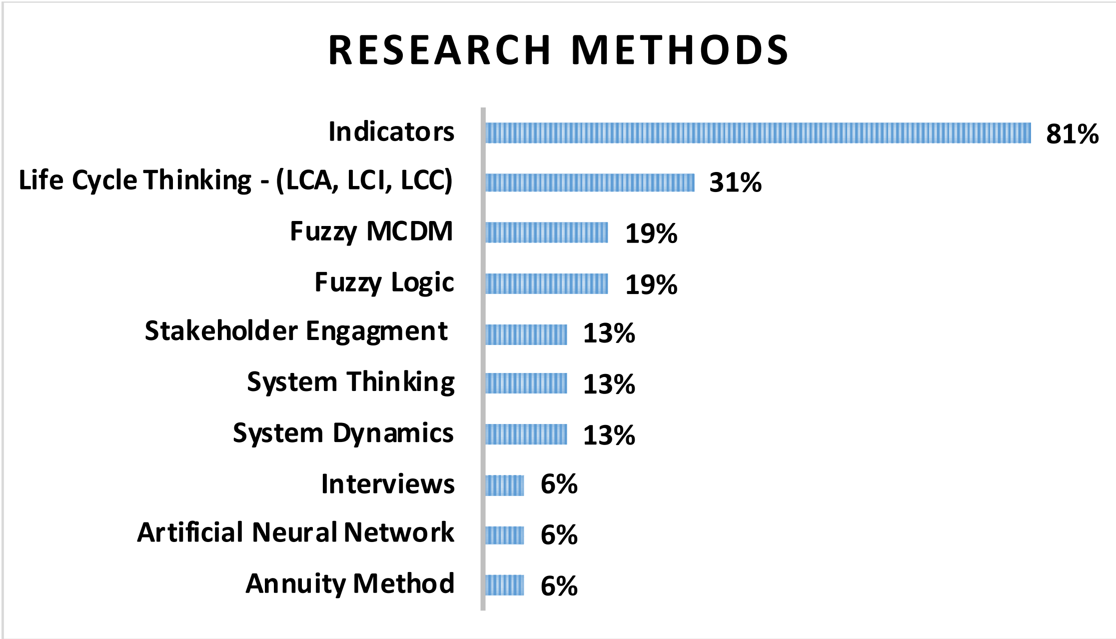

Figure 6 - Major Research Methods of the 16 Identified papers

4. Limitation and Further Work

This review study suffers from limitations. The main challenges are related to two elements of the research. First, the search string combinations were generic in a way that they do not manage to capture the full ability provided by using Boolean Search when conducting a literature search. Second, the selection databases, for this search was based out of knowledge gained from the unstructured literature review. The unstructured literature review identified these three databases to be the most suitable databases to apply for this systematic literature review research. However, as can be noticed in this review paper, Scopus and Web of Science returned 0 results in the literature collection in Step E (See Table 2). Further, these two databases provide insignificant inputs in Step D in comparisons with Science Direct. In that regard see Table B.1, Appendix B.

Nevertheless, it is important to keep in mind that each database gives access to a different quantity of the literature, which can also explain the difference in the literature identification level between those different databases. Hence, for future work, a thorough review of different databases such as Sage Journals Online, GreenFile and Emerald Insight, is needed, in order to ensure that most suitable databases are selected in relation to the research topic.

Further work will be conducted focusing around capturing a better insight into the literature concerning ‘complex modelling’ and ‘sustainability assessment’ application as decision support tools for urban and city energy planning.

5. Conclusion

A detailed structured literature review has been conducted around the keywords ´Sustainability Assessment´, ´Urban or City Energy Planning´ ´System Dynamics´ and ´Decision Making´ to answer two research questions. The first question is the identification of the preferred methodological approaches for sustainability assessments. The second question is focused on looking at the publication trends of academic literature related to sustainability assessment. Results show that there is an upward trend in publication output of academic research which explore the application of sustainability assessment as single approach as well as in combination with other methods and approach to problems such energy transition, technology assessment, and energy policy in the fields of sustainability and energy. For the most preferred methodological approach, sustainability assessment structured around indicators seems to be the overwhelming favoured approach. LCT and MCDM sustainability assessments approach are also seen as suitable methodological approaches in the field of sustainability and energy related research. The findings of this study have provided a useful insight into the application capabilities of an integrated model structured around sustainability assessment using one or more methods to research, analyse and provide solutions to problems within the field of sustainability and energy. The results identified the preferred methods and the trends when it comes to the application of sustainability assessment in the field of sustainability and energy research. In addition to identifying the lack of publications on the application of dynamics and system thinking approach in this research area. Only 13 per cent of papers are identified to be applying system dynamics and system thinking approach. There are opportunities within this research area to develop and conduct research using sustainability assessment model based around system dynamics modelling in combination with one or more methods identified in this review paper. Therefore, this review raises the question, why are we not seeing more research being done using sustainability assessment based on system dynamics approaches concerning the complex issue of urban energy planning.

Further research will be undertaken to clarify and understand, why system dynamics sustainability assessment approach are being used within the area of improving and enhancing urban energy planning and decision-making.

Acknowledgement

The authors thanks the DTA3/COFUND for funding the PhD. I also want to thank my supervisory team at Teesside University (Dr. Huda Dawood, Dr Gobind Pillai, and Dr Michael Short) for all their support and help while working on this review paper.

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7. Appendix

In this appendix are supplementary information to referred into the publication.

7.1 Appendix A

Table A.1 – Information about the 16 papers and their classification categories

Title	An analysis of the legal and market framework for the cogeneration sector in Croatia	2MBio, a novel tool to encourage creative participatory conceptual design of bioenergy systems e The case of wood fuel energy systems in south Mozambique	Biofuels: A sustainable choice for the United States' energy future? Jennifer L. Trumbo a,
Authors	D. Lončar , N. Duić ,Z˘. Bogdan	Ricardo Martins, Judith A. Cherni, Nuno Videira	Jennifer L. Trumbo , Bruce E. Tonn
Year	2009	2017	2015
Journal	Energy	Journal of Cleaner Production	Technological Forecasting & Social Change
Research Field	Policy Work Cogeneration Sector	Bioenergy Energy Systems Conceptional Framework Design	Biofuel Sustainability Energy Policy Future Analysis
Geographical location	Croatia	Mozambique	United States
Method	Annuity Method Economic Analysis	Metamodeling Business modeling Participatory approach	Environmental Scanning w/ Tonn Methodology Sustainability Indicators Three Pillars of Sustainability
Model	Model based Annuity Method for Economic analysis		Indicators based system modeling
Software			Lucid chart Web-based Diagramming Software
Databases			
Title	How sustainable is electric mobility? A comprehensive sustainability assessment approach for the case of Qatar	Sustainable and Integrated Bioenergy Assessment for Latin America, Caribbean and Africa (SIByl-LACAf): The path from feasibility to acceptability	Artificial Neural Networks to assess energy and environmental performance of buildings: An Italian case study

Authors	Nuri Cihat Onata, Murat Kucukvarb, Nour N.M. Aboushaqraha, Rateb Jabbara	Luiz Augusto Horta Nogueiraa, Luiz Gustavo Antonio de Souzaa, Luís Augusto Barbosa Cortezb, Manoel Regis Lima Verde Leal	A. D'Amico, G. Ciulla, M. Traverso, V. Lo Brano, E. Palumbo
Year	2019	2017	2019
Journal	Applied Energy	Renewable and Sustainable Energy Reviews	Journal of Cleaner Production
Research Field	Comprehensive Sustainability Assessment Eclectic Vehicles Life cycle Sustainability Assessment Sustainable Transportation	Bioenergy System Sustainability Decision-Making Feasibility	Building Energy Life Cycle Assessment Decision-Support Artificial Neural Network
Geographical location	Qatar	Brazil	Italy
Method	LCA LCC S-LCA Triple Bottom Line	Integrate Assessment Approach	Artificial Neural Network
Model	A Hyrbid MIRO-LCSA Model	The SIByl-LACAf framework	ANN Model
Software			
Databases	EXIOBASE 3.4		
Title	A system dynamics approach to technology sustainability assessment: The case of biodiesel developments in South Africa	Portfolio analysis of alternative fuel vehicles considering technological advancement, energy security and policy	Strategic analysis methodology for energy systems with remote island case study Susan
Authors	Josephine K. Musango, Alan C. Brent, Bamikole Amigun, Leon Pretorius, Hans Muller	Kamila Romejko, Masaru Nakano	Susan Krumdieck, Andreas Hamm
Year	2012	2016	2009
Journal	Technovation	Journal of Cleaner Production	Energy Policy
Research Field	Sustainability Feasibility Bioenergy Renewable Energy Technology Assessment	Energy Security Alternative Fuel Vehicles Optimization Fossil Fuel Dependency	Stakeholder participations Energy Transition Remote Communities System Dynamics Feasibility
Geographical location	South Africa		Fijian territory

Method	System Dynamics Sustainability Indicators	Optimization Indicators	System Thinking Surveys Stakeholder Engagement Indicators
Model	A bioenergy technology sustainability assessment (BIOTSA) model	Optimization Model	Feedback control model of anthropogenic system dynamics
Software	Vensim		
Databases			
Title	Power generation from slaughterhouse waste materials. An emergy accounting assessment	Intuitionistic fuzzy multi-criteria decision-making framework based on life cycle environmental, economic and social impacts: The case of U.S. wind energy	Combined application of multi-criteria optimization and life-cycle sustainability assessment for optimal distribution of alternative passenger cars in U. S
Authors	Remo Santagata, Silvio Viglia , Gabriella Fiorentino, Gengyuan Liu, Maddalena Ripa	Serkan Gumusa, Murat Kucukvarc,, Omer Tatari	Nuri Cihat Onat, Murat Kucukvar , Omer Tatari , Qipeng Phil Zheng
Year	2019	2016	2015
Journal	Journal of Cleaner Production	Sustainable Production and Consumption	Journal of Cleaner Production
Research Field	Resource Management Waste Management Bio-Refinery Electricity Generation Animal by-products	Wind Energy Multi-Criteria Decision-Making Life-Cycle Sustainability Assessment Fuzzy Logic Decision-Making	Multi-Criteria Decision-Making Life Cycle Sustainability Assessment Sustainable Transportations Sustainability
Geographical location		United States	
Method	The Emergy Accounting Approach System Thinking Indicators	Fuzzy MCDM Indicators TOPSIS Intuitionistic Fuzzy Set theory	Life Cycle Assessment Triple Bottom Line Indicators a Compromise Programming model
Model		Environmentally extended input–output-based life cycle assessment (EE-IO-LCA) model	A multi-objective optimization model integrated with TBL-LCA model
Software			

Databases			
Title	Modular participatory backcasting: A unifying framework for strategic planning in the heating sector	Renewable energy selection for net-zero energy communities: Life cycle-based decision making under uncertainty	Technology sustainability assessment of biodiesel development in South Africa: A system dynamics approach
Authors	Kateryna Pereverza , Oleksii Pasichnyi, Olga Kordas	Hirushie Karunathilake, Kasun Hewage, Walter M?erida, Rehan Sadiq	Josephine K. Musango, Alan C. Brent, Bamikole Amigun, Leon Pretorius, Hans Müller
Year	2019	2019	2011
Journal	Energy Policy	Renewable Energy	Energy
Research Field	Long-Term Planning Energy Security Energy Policy Stakeholder Engagement Heating sector	Community Energy System Planning Renewable Energy Fuzzy Techniques Life Cycle Thinking Multi-Criteria Decision-Making	Biodiesel Renewable Energy Sustainability Technology Assessment Energy System
Geographical location	Ukraine and Serbia		South Africa
Method	Stakeholder Participation Desk Research Modularity Participatory Backcasting	Life Cycle Thinking - (LCA, LCI, LCC) Triple Bottom Line Fuzzy TOPSIS Fuzzy Logic	System Dynamics Sustainability Indicators
Model	modular participatory backcasting (mPB) framework	Life Cycle Thinking based Decision Making Model	Bioenergy Technology Sustainability Assessment (BIOTSA) model
Software			Vensim
Databases			
Title	Sustainability in hydropower development—A case study		
Authors	Jian Liu, Jian Zuo, Zhiyu Sun, George Zillant , Xianming Chen		
Year	2013		
Journal	Renewable and Sustainable Energy Reviews		
Research Field	Sustainability		

	Hydropower Development
Geographical location	China
Method	Indicators Interviews Triple Bottom Line
Model	
Software	
Databases	

7.2 Appendix B

Table B-1 - Detailed Illustration of Results from Step D of the Systematic Literature

	Web of Sciences		Scopus		Sciences Direct	
	Research Criteria	**Exclusion Criteria**	**Research Criteria**	**Exclusion Criteria**	**Research Criteria**	**Exclusion Criteria**

Keyword "Code"	Article Title, Abstract, Keywords	[language: English, and document type: Articles]	Article Title, Abstract, Keywords	[language: English, document type: Articles, and source type: Journal]	Article Title, Abstract, Keywords	[document type: Research Articles]
D.1 ("City" OR "Urban") AND ("Energy Development") AND ("Sustainability Assessment")	0	0	0	0	201	98
D.2 ("City" OR "Urban") AND ("Energy Planning") AND ("Sustainability Assessment")	1	0	1	0	212	96
D.3 ("City" OR "Urban") AND ("Energy Development") AND ("System Dynamics")	2	2	2	0	219	114
D.4 ("City" OR "Urban") AND ("Energy Planning") AND ("System Dynamics")	4	2	6	5	266	139
D.5 ("City" or "Urban") AND ("Energy Planning") AND ("Decision Making")	50	35	104	71	2166	1438
D.6 ("City" OR "Urban") AND ("Energy Development") AND ("Decision Making")	8	6	18	11	2253	1475

A CONCEPTUAL FRAMEWORK FOR INTEGRATING USER EXPERIENCE WITH DESIGN PARAMETERS FOR RESIDENTIAL BUILDINGS

Mian Atif Hafeez, Paul van Schaik, Huda Dawood, Sergio Rodriguez-Trejo, João Patacas, & Nashwan Dawood
Teesside University, UK

ABSTRACT:

The performance gap between as-designed and as-built buildings has been the subject of academic and industry-based research for many years and can be attributed to a variety of reasons. One of the reasons is the lack of consideration of building users' needs in the design process. By systematically integrating user experience (UX) of home use and energy systems with design parameters and building performance, this research aims to address user needs and requirements in social housing design by proposing an approach which puts building occupants at the heart of the design process. A systematic literature review is carried out to identify literature related to user experience, values, value creators and design attributes. Based on the results from the literature review, a framework is proposed to address the inclusion of user experience and values in the design process which was identified as a gap in the literature. Future work will consist of further development of the proposed framework by considering additional data collected from interviews and surveys with several stakeholders involved in housing design process, as well as with occupants. The proposed framework will be validated with designers, manufacturers and occupants on the basis of house design exercises.

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KEYWORDS: *User Experience, Feedback to Design, Design Matrix, Energy System, Social Housing*

1. INTRODUCTION

There is significant evidence to suggest that buildings do not perform as well when they are completed as was anticipated when they were being designed. The difference between anticipated and actual performance is known as the performance gap. For example, studies of the performance of buildings known as Post Occupancy Review of Buildings and their Engineering (PROBE) analysed buildings in terms of energy use and other performance indicators (CIBSE 2019). This and other work have established that energy consumption during building use can be multiples of estimated use during building design (Designing Buildings Ltd. 2019). Studies such as these suggest that various factors, including the following, contribute to the performance gap:

- fundamentally, design assumptions are not always realistic; therefore, estimated building performance does not match actual building performance;
- during operation of buildings, monitoring and feedback to design is often missing; therefore, adjustments to building designs are not made and new designs do not benefit from the outcomes of building use; consequently, the performance gap is perpetuated;
- regulations do not cover all important performance indicators; therefore, some may not be explicitly addressed in design;
- another gap occurs when the actual building is not constructed according to the design specification; therefore, the building has a built-in performance gap;
- designers and other stakeholders are not accountable for the performance gap; therefore, the gap will not necessarily influence the designs they produce, thereby perpetuating the performance gap;
- there is a limited integration among the facilities management and design professions, a problem mainly caused by the nature of project delivery processes in the AEC/FM industry that prevent external input into the design;
- there is a potential lack of practice and awareness of the need to work with occupants (for example, participatory design); because occupants' needs are always not systematically taken into account, there is a gap between these needs and the performance of a building.

It is essential that the **performance gap between design and actual performance** is addressed in order to realize energy savings and deliver high-quality homes (CCC, 2018). In order to close the information loop, briefs need to explicitly state targets for energy use, sustainability, management expectations, control requirements and promote feedback itself (Andreu & Oreszczyn, 2004). From a user's perspective, it is also important to address the gap between actual performance and occupants' needs. The gap between the operation and the design of built assets can be addressed from two perspectives: **asset performance** and **user experience** (here, the extent to which user needs are fulfilled). These are not mutually exclusive, so both of these perspectives can be considered. One approach to combine the two has been proposed in Moghimi et al.'s (2017) framework that is discussed next.

Moghimi et al. (2016; 2017; 2018) provide a useful framework that links building design with building performance and user experience. The authors organise design-related factors in three dimensions: **design parameters** (aspects of the actual building design or building design requirements), **value creators** (theoretical or actual building performance) and **values** (user experience or user needs) (Moghimi et al., 2016, 2017, 2018). These dimensions are not independent (Andargie, Touchie, & O'Brien, 2019). Therefore, the choices that are made for design parameters (e.g. the materials used for interior finishings) influence building performance (e.g. the health of the indoor environmental climate, the energy efficiency of the building and its aesthetics from the choice of interior-finishing materials). In turn, the value creators influence user experience (e.g. pleasure from aesthetics, feeling of achievement from energy efficiency and family security from environmental health) (Moghimi et al., 2018). Based on means-end chain analysis, Moghimi et al. (2018) identified specific linkages from design parameters to value creators to values. The collective analysis results were presented in a hierarchical value map (HVM). This is a frequency cross-tabulation of factors for each of the dimensions to show the strength of connections between factors. These connections can be direct (e.g. from design parameters to value creators or from value creators to values) or indirect (e.g. from design parameters through value creators to values). There are two main ways to read and use an HVM: from design parameters to value creators to values or from values to value creators to design parameters. In the first mode use (bottom up), building performance and user experience (need fulfilment) can be predicted from design parameters. In the second model of use (top down), value creators (directly) and design requirements (indirectly through value creators) can be derived from user needs. In this research, we use literature review, and empirical data collection and analysis to create a three-dimensional design matrix to guide future social housing design and manufacture, with an emphasis on user experience.

The **aim** of our research project is to systematically integrate UX (user experience) of energy systems and design parameters in the design of social housing. The **overall research question** is: how can user needs be systematically incorporated in house design? In this paper, the **specific objective** is to identify to what extent and how design parameters, value creators and values have been addressed in the literature.

2. METHODOLOGY

In order to achieve the aim, **a systematic literature review** was conducted to identify and organise relevant literature addressing different design parameters, users/occupants' needs and values, and building performance.

2.1 Search strategy and search results

Table 1 shows the search queries used in three major databases of scientific literature. Title screening was conducted to select relevant articles. In order to test the idea, social housing was selected as a case and more relevant literature was added in relation to social housing (query # 4) to facilitate future work. A collection of 216 papers was obtained.

2.2 Screening and selection of corpus

Following the removal of duplicates, the titles and abstracts were analysed by the authors and based on relevance to the study aim and objectives, the remaining publications were included in the literature corpus for further analysis in terms of coverage of different design parameters, value creators and values. These included 173 papers which were investigated for their coverage of the design parameters / attributes, value creators and values.

2.3 Framework development

While the literature review and framework are presented linear fashion, several iterations were carried out to modify and adapt the selected framework to its presented state in the paper based on the results of the literature review. The first draft framework was developed from three key papers including Moghimi et al. (2016; 2017; 2018). Further modifications were made following evaluation of papers and presented in Figure 1 and additional iterations will be carried out in future work.

Table 1: Systematic Literature Review search queries and results

Query #	Search query	Science Direct		Scopus		Web of Science.	
		Results #	Selected #	Results #	Selected #	Results #	Selected #
1	"construction" AND "hous*" AND "performance" AND "design" AND "parameter".	31	13	79	33	12	4
2	"construction" AND "hous*" AND "performance" AND "design" AND ("occupants" OR "inhabitants").	32	19	63	39	40	31
3	"hous*" AND "design" AND ("user experience" OR "user value").	11	8	53	15	14	2
4	"social housing" AND "architecture" AND "user need*"	-	-	78	30	53	22
	Sub total	74	40	273	117	119	59
		Results			Selected		
	Total	**466**			**216**		

3. RESULTS AND DISCUSSION

To demonstrate the concept, the following high-level framework is presented below in Figure 1. There are two-way relationships between each level. Design parameters can link with value creators which in turn can link with values for users. This flow can be used for prediction of asset performance and user experience. On the other hand, particular values may lead to requirements for specific value creators, which in turn are translated to requirements and specification of particular design parameters. This flow can lead to design solutions. Wall thickness provides an example to elaborate this flow. From a user's perspective, the main utility and value of the wall may be to provide privacy and separation of space. If the design intent is targeted at what the user values or needs, perhaps an innovative solution which provides these values at minimal thickness can be specified as a design solution without compromising performance and user experience.

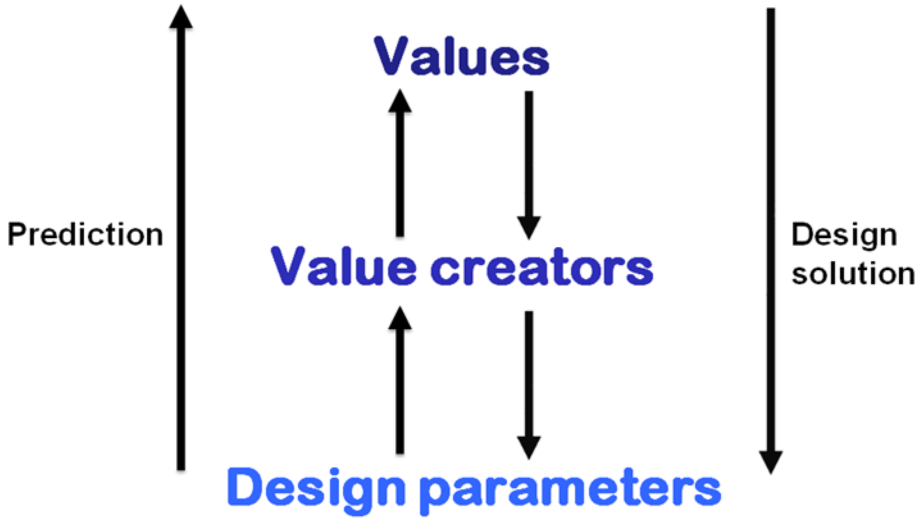

Figure 1: Proposed high-level design framework

This high-level framework was developed in more detail and this provisional framework is presented in Figure 2 based on the relevant literature as described in Section 2.

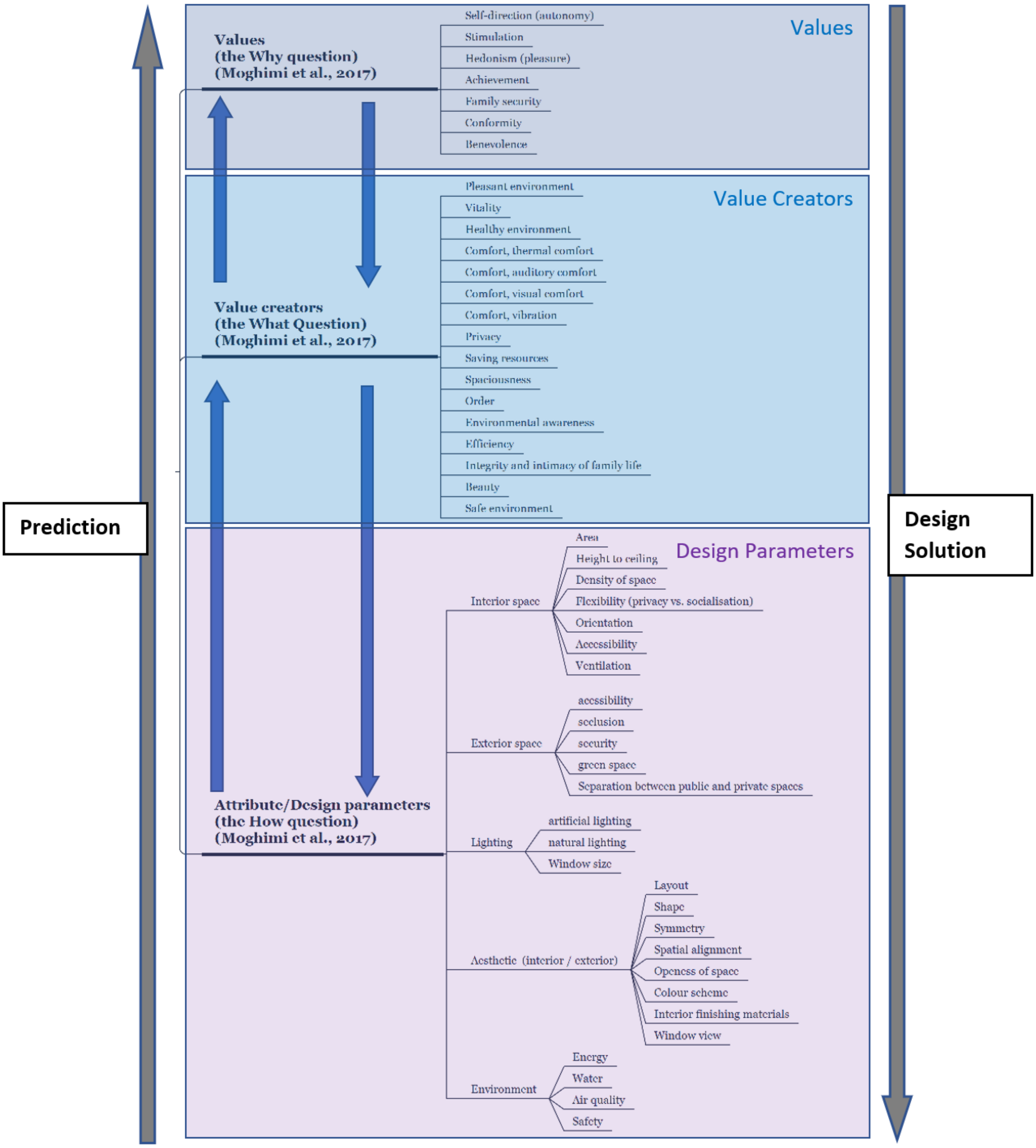

Figure 2: Proposed framework (adapted from Moghimi et al., 2017) to investigate the coverage of literature and further expand/adapt in future work.

Literature analysis was then conducted on the selected corpus of literature to understand the coverage of various design parameters/attributes, value creators and values. Frequency analysis of topics covered in the corpus is presented below in Figure 3, Figure 4 and Figure 5.

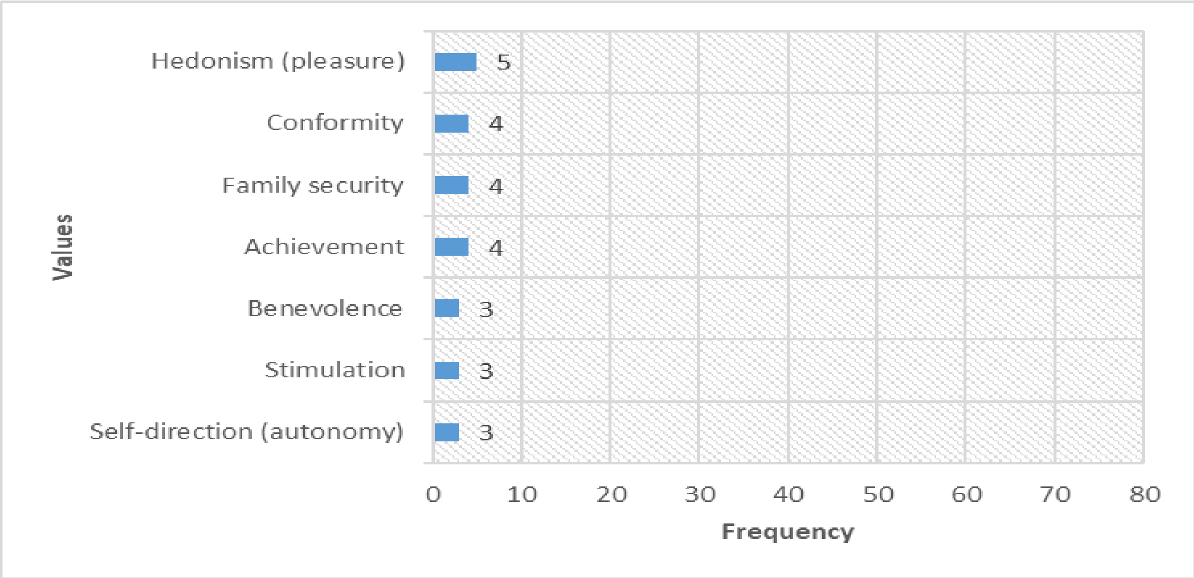

Figure 3 Frequency distribution of values

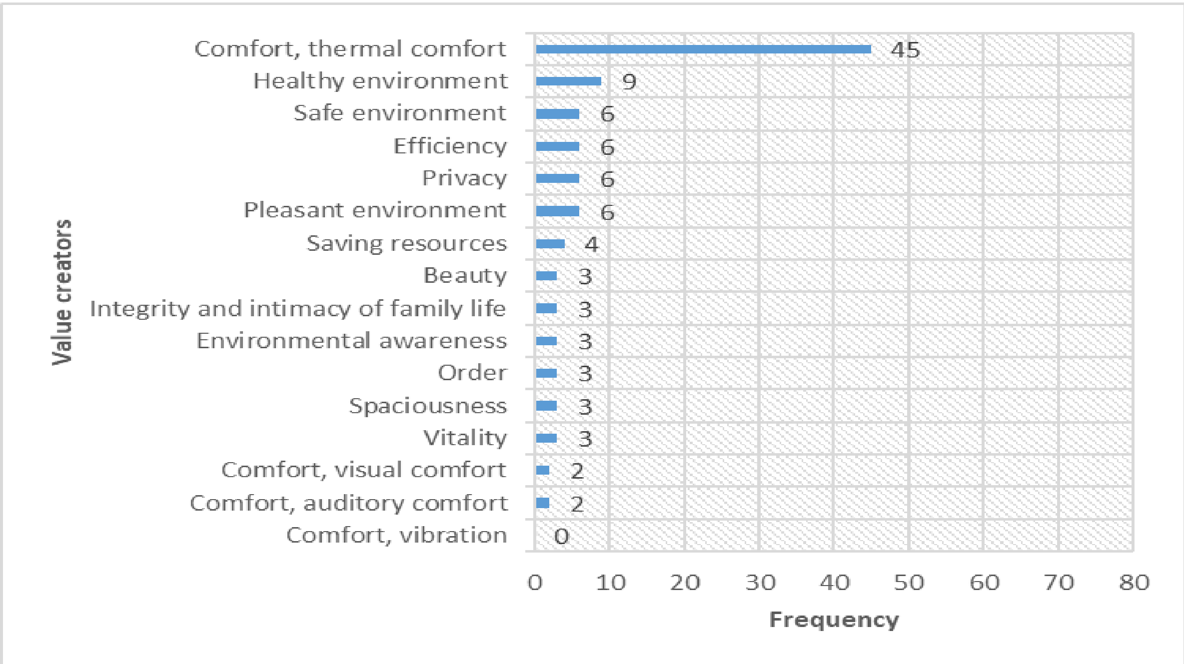

Figure 4 Frequency distribution of value creators

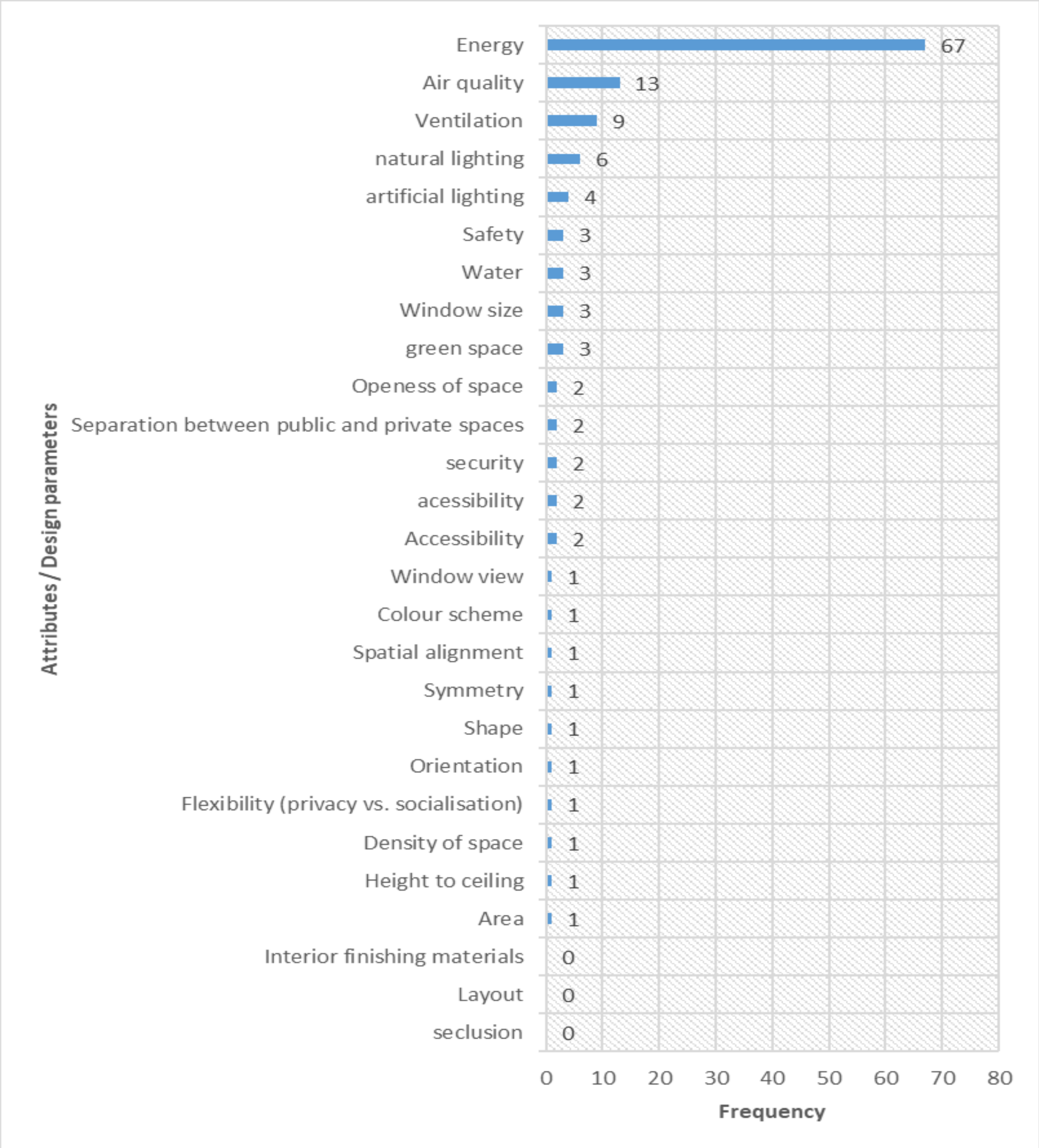

Figure 5 Frequency distribution of design attributes/design parameters

It can be seen in Figures 3, 4 and 5 that most frequently the literature points to energy in design parameters, thermal comfort in value creators while in terms of values, which are closely related to user experience and user needs, the coverage is minimal. Therefore, there is a gap in the knowledge linking user needs and values into the design parameters and value creators. It has been observed in the literature that studies which do focus on users, do so in the context of post occupancy evaluation (POE). Users' satisfaction is measured with psychometric scales in user surveys. There is limited evidence that the results are fed back to the current design or fed forward into future design.

In alignment with these findings, the discussion on performance gap in buildings is also focused mainly on energy. However, there are several other building performance aspects (Wilde, 2018) which need to be considered holistically and in relation to the proposed framework, which is part of the future work.

In addition to literature review and proposed framework, other approaches to reduce performance gap and the gap between operation and design of built assets include participatory design, which intends to reduce the gap between designer and the user. This approach, which is not unique to the built environment and has applications in product design and software design, is also known as co-operative design or co-design. The main idea is to create an environment which is more liveable and economical by providing a contribution of users besides the architect or designer. With the participation of users, comfort requirements in the building can be met in a healthier way (Turkyilmaz & Kizilkan, 2019).

4. CONCLUSION

Based on the result of the literature review this research has highlighted the lack of systematically incorporating user experience, values and input in the design process. A framework is proposed to link design attributes with user values at a high level (conceptual). A detailed version is used to analyse coverage of the framework in the literature. It has been found that most literature obtained systematically to investigate the link between attributes, value creators (consequences) and values, is focussed on energy in terms of design attributes and thermal comfort in terms of value creators; values – which are closely related with user experience are – are not adequately covered. The proposed framework once further developed and validated, has potential significant benefits for helping designers in decision making and helping housing providers with useful insights to help match house design with user needs.

5. LIMITATIONS

The methodology used in the systematic literature review is limited by the defined search queries as well as the selected databases. In order to address these limitations additional quantitative and qualitative data will be gathered in the form of interviews and surveys with several stakeholders involved in housing design process, as well as with occupants.

6. FUTURE WORK

This paper has established that there is a gap in systematically incorporating user experience and values in the design process. To improve the framework and its applicability and generalisability, semi-structured interviews will be conducted with architects, social housing providers and occupants to collect and draw on qualitative rich information based on participants' views and experiences. A design matrix will be proposed and validated on the basis of house design exercises.

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EXPLORING MODEL TECHNIQUES OF MEASURING THE CARBON FOOTPRINT OF RAIL SYSTEMS: A SYSTEMATIC REVIEW

Akponeware A[1], Dawood N[1], Rodriguez S[1] & Dawood H[1]
[1]Teesside University, School of Computing, Engineering & Design, United Kingdom

ABSTRACT: *Over 50% of UK greenhouse gas emissions have been attributed to the construction industry; this is in addition to the more serious damage to health which has prompted the institution of limits from international regulatory agencies such as the Environmental Protection Agency and the United Nations Framework Convention on Climate Change. Whilst some industry focus has been provided in the current PAS 2080 carbon management document, no studies have been found which conduct a systematic assessment of the status quo to promote the adoption of BIM-based approaches. This exploratory study systematically analysed and synthesised literature on current techniques for assessing carbon footprints of rail transport infrastructure by addressing three research questions. The study makes three contributions to knowledge; first it identified current approaches as mainly top-down life cycle analysis (LCA), second, it identified three main clusters of problems with contemporary techniques, finally, it proposed a BIM-compliant conceptual framework for storing and managing carbon emissions in an integrated format. The findings will provide rail industry leaders and academia with the key system and techniques that can support it in assessing and potentially reducing its carbon footprint.*

KEYWORDS: *carbon emissions, rail, greenhouse gas, CO_2, low carbon, energy efficiency, LCA*

1. INTRODUCTION AND BACKGROUND

Over 50% of UK greenhouse gas emissions has been attributed to the construction industry (BSI, 2016); this is in addition to the more serious damage to health which has prompted the institution of limits from international regulatory agencies such as the *Environmental Protection Agency* and the *United Nations Framework Convention on Climate Change* (Barati and Shen, 2016). Typically, the issue of carbon emissions reduction has received considerable attention among practitioners and researchers triggering a huge amount of innovative scientific inquiry. Considering recent extreme events associated with climate change, it is becoming extremely difficult to ignore the threats caused by carbon emissions in the built environment. Crucial policy changes are thus needed to decouple CO2 emissions to achieve the 1.5^0C and 2.0^0C pathways (Pan *et al*., 2018); hence the UK government's infrastructure agenda is achieving an 80% GHG emissions reduction targets by 2050 (BSI, 2016) through decarbonisation of constructed assets. It has been suggested that estimating carbon-related emissions directly promotes emissions reduction in rail projects (Saxe *et al*., 2016). This therefore necessitates a systematic emissions assessment method for the rail industry where several approaches have already been adopted in quantifying the amounts of CO_2 emissions associated with rail systems. Duan *et al*. (2015) highlight that the use of top-down approaches such as national or country emission factors are ineffective. By implication, they promoted the use of scaled-up estimates or bottom up or streamlined LCA. They further posit that this approach is beneficial because it disaggregates the CO_2 emission calculation since it depends on data measured directly.

Crucially, one of the key twenty-first century infrastructure challenge is lowering cost and carbon over the infrastructure's whole lifecycle; it was suggested in the Digital Built Britain (DBB) strategy launched in 2016 that the key to achieving this is the migration to Building Information modelling (BIM) level 3. Findings in HM Treasury (2013) identified the UK government as a key carbon champion and strategic 'push' agent focused on incentivising carbon emissions reduction in the infrastructure industry through promoting efficiencies in cost and carbon performance; exemplified by the PAS 2080 asset and programme carbon management specification. Central to this strategy and specifications is the facilitation of collaborative working across the construction value chain as a tool for efficient carbon management. Albeit, there remains uncertainty as to the amount of carbon reduction targets set for the infrastructure industry to meet climate goals, and yet no clear identification of the role that BIM plays in supporting low carbon solutions via advanced analytics and sharing of integrated carbon data over an infrastructure's lifecycle.

While the debates surrounding the inconsistencies in carbon assessment methodologies have been acknowledged (Ortega *et al*., 2018), the integration of BIM with carbon emissions quantification has yet to be explored fully in the rail industry besides some studies in the building industry (e.g. Mousa *et. al*, 2016). There is also a notable paucity of scientific literature focusing specifically on implementing the capital carbon (CapCarbon) and operational carbon (OpCarbon) methodology. Whilst some industry focus has been provided in the current PAS

2080 carbon management document, no studies have been found which conduct an evidence-based research identifying the requirements of implementing a BIM-based digital and systematic carbon assessment technique for a typical rail infrastructure. The lack of academic-led and industry-focused inquiries into on how the rail industry can achieve low carbon footprints through collection, analysis and use of BIM-integrated carbon data could have negative implications for the rail industry. Such an absence of a data-based carbon quantification tool which can support improved decision-making could potentially derail the focus towards achieving the 2050 carbon targets for the UK transportation industry. In their paper, Akponeware and Adamu (2017) found that the use of openBIM could promote design clash avoidance and facilitate multidisciplinary coordination if adopted by construction professionals. By extension, the use of BIM-enabled carbon management methodology could be adopted to address life cycle carbon emissions assessment for the rail industry.

This exploratory study will systematically analyse and synthesise literature on current techniques for assessing energy efficiency for rail transport infrastructure. The results of the study will support the conceptualization of a BIM-based carbon management strategy. Future studies will validate the conceptual framework using case studies of UK based infrastructure projects which have been identified by the authors. The findings will provide rail industry leaders and academia with the key tools, system and techniques that can support the rail transport infrastructure industry in assessing and potentially reducing its carbon footprint.

1.1 Aim and objectives

The study outlines the following aim and objectives:

The main aim of the study is to synthesize current literature and systematically present current approaches for measuring energy efficiency and or reducing the impact of greenhouse emissions in a rail infrastructure. The main aim will be achieved with the following stated objectives:

i) To explore current approaches of measuring the carbon footprint of rail systems
ii) To investigate problems with current approaches of assessing greenhouse gas emissions of rail systems
iii) To explore the use of BIM in greenhouse gas emissions reduction in rail systems

2. METHODOLOGY AND METHODS

An extensive systematic literature review was conducted using the following steps: review planning and evidence searching, data evaluation and reporting findings. Thematic and cluster analysis were employed in identifying the niches and research gaps. The PRISMA approach which was adopted in this study for locating relevant papers was combined with thematic and cluster analysis methods and are described in the sub-sections that follow.

2.1 Step 1: review planning and database searching

The PRISMA search strategy was created to enable a comprehensive systematic methodology for literature searching, screening, eligibility and inclusion. Once the search strategy planning was concluded, databases were identified for the search. The authors identified three databases: Web of Science, Science Direct and Scopus for the purpose of locating relevant literature for the current study. The databases were selected based on their large availability of papers on carbon footprinting. Multiple databases were also used so that all relevant papers were located. Thereafter, three search strings were applied to each database based on initial keyword identification from a preliminary literature search. Meticulous effort was made in including relevant specific keywords and synonyms to minimize the chances of excluding important papers; thus, three search strings were utilized in locating previous studies. The search strings applied were:

String 1: *(CO_2 OR "low carbon") AND ("ghg emission") AND ("energy efficiency" OR "carbon quantification") AND (rail OR train OR transport) AND (IoT OR "internet of things" OR digital OR GIS OR "smart systems")*

String 2: *("greenhouse gas" OR "carbon measurement" OR "carbon footprint" OR "carbon management") AND ("rail transport") AND (real time OR real-time OR BIM) AND ("life cycle" OR lifecycle OR LCA)*

String 3: *("carbon management" OR "carbon footprint") AND ("life cycle" OR lifecycle OR LCA) AND ("building information model*") AND rail*

Search pre-criteria were applied to the initial literature search results to eliminate irrelevant papers located in the databases. This eliminated about 50% of the papers from 227 to 116. The pre-criteria used for excluding irrelevant studies included *year of publication* (2015 – 2019), *document type* (research articles and review articles) and *language* (English only). The decision to limit the search to the last five years was done to include papers that focused on the use of up-to-date carbon assessment techniques. Following the PRISMA approach, the identified papers (227) were screened for title and abstract after checking for duplicates. This further eliminated 87 papers leaving 41 papers to be assessed for full text eligibility after the inclusion of additional 12 references through the *snowballing* technique. The PRISMA search strategy adopted for this study as explained in this section is shown in figure 1.

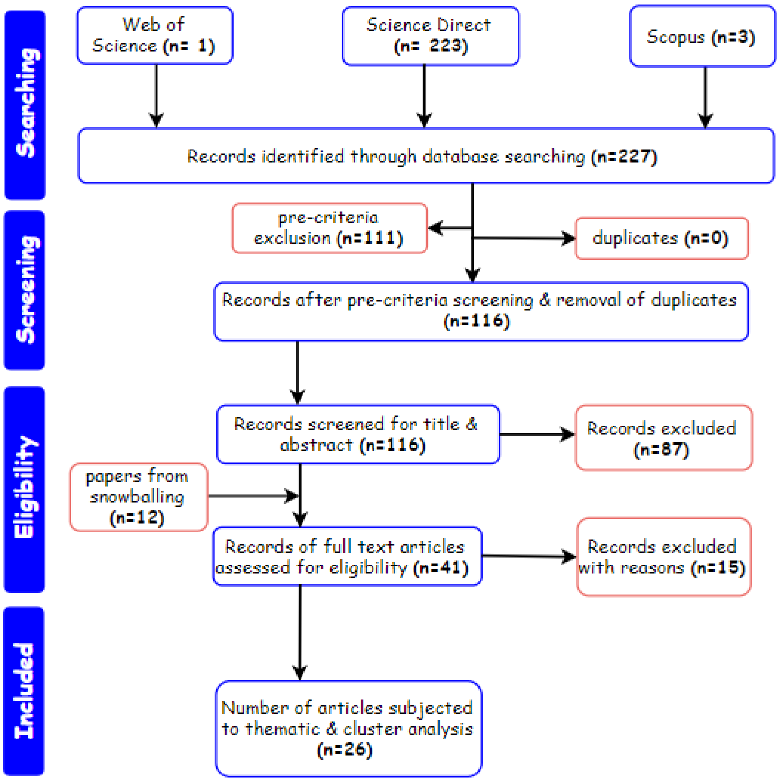

Fig. 1: PRISMA search strategy adopted for the study

2.2 Step 2: thematic analysis for literature synthesis

Thematic analysis and data mining of the located papers was done to further identify papers which had a high ranking for important and relevant keywords. The VOSviewer tool which is suitable for bibliometric analysis was adopted for this purpose. The procedure involved exporting the 227 records which were to be screened for title and abstract to an XML file format. This file was subsequently imported into VOSviewer where a map based on bibliographic data of keywords was then created. The result of the analysis which is shown in figure 2.1 enabled the authors to identify 16 clusters (represented by the 16 different colours of the bubbles in figure 2.1). The authors thoroughly inspected all the clusters and their sub-themes to eliminate irrelevant clusters. Ten clusters were eliminated based on their non-alignment with the research objectives of this study. This led to the exclusion of clusters such as bioenergy, energy security, electric vehicles, climate change and policies. The selected clusters informed the selection of papers which were assessed for full text eligibility and further analysis in NVivo software.

Overall, the thematic analysis and data mining technique for the literature synthesis facilitated by the VOSviewer tool helped the authors identify which sub-themes have received adequate attention by exploring keyword frequencies in the pre-selected papers. By implication, it facilitated easy identification of themes that aligned with the research objectives of this paper, but which have been ignored. This automated title and abstract screening of keywords using the VOSviewer tool was combined with the manual process of screening in the selected databases (Web of Science, Scopus and Science Direct) to exclude 87 papers (as shown in figure 1). The final 26 papers were then exported from RefWorks database and imported into NVivo software to permit a detailed analysis of the selected papers.

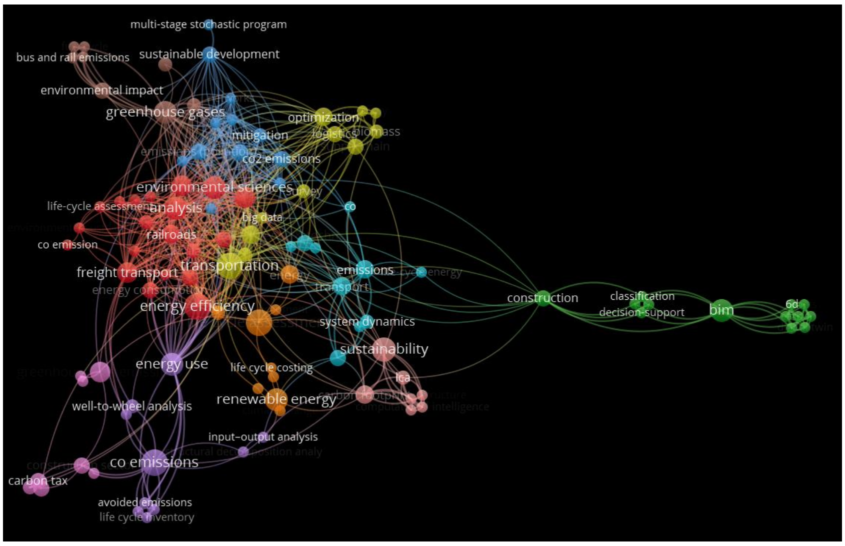

Fig. 2.1: Bibliometric analysis of keywords to identify relevant clusters

2.3 Step 3: cluster analysis for identification of potential themes

The authors conducted a rigorous systematic analysis of the selected papers in the NVivo 12 software. The decision to use the software was to enable a systematic analysis and synthesis of themes and sub-themes in the selected papers. This will further facilitate the identification of current approaches used in conducting carbon footprinting in the rail industry, besides finding the niches and gaps. The analysis of the literature in NVivo began with a keyword analysis of the selected papers. The dominance of the different themes in literature are represented by font sizes. This preliminary keyword analysis was thus used to group the different themes according to how they addressed each research question set forth in the study. Figure 2.2 below shows the result of the preliminary keyword analysis on NVivo.

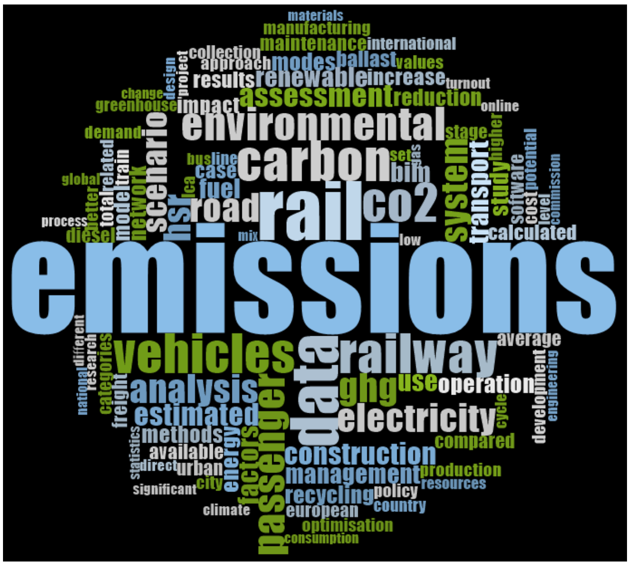

Fig. 2.2: Keyword preliminary analysis to identify relevant themes

A further cluster analysis was done using Pearson correlation coefficient on the NVivo tool to visualize the level of similarity of the papers in the systematic literature review. The tool groups themes from least similar (-1) to most similar (+1) based on word similarity. All the papers were found to have a positive correlation. However, some themes were less positively correlated than others as can be found in the case of two papers outside the cluster shown in figure 2.3. Poulikakos *et al*. (2016) was broader in scope and included other modes of road transport in their study and Martínez Fernández *et al*. (2019) focused on statistics-based optimization techniques of analyzing energy efficiency in rail energy consumption.

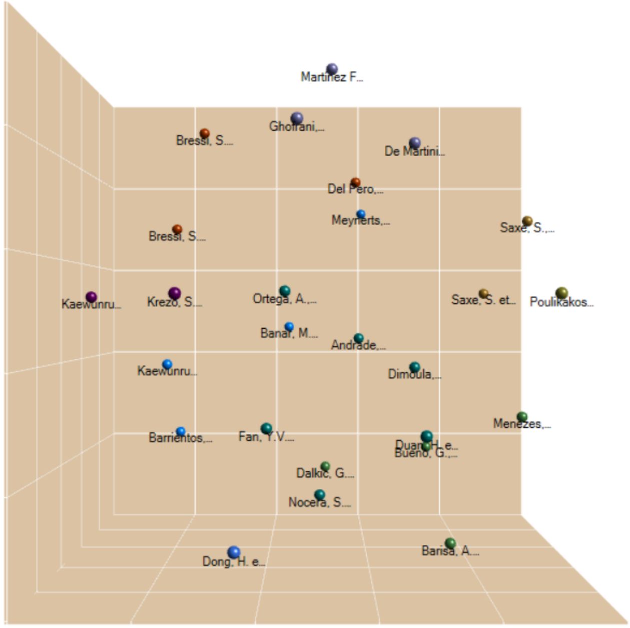

Fig. 2.3: 3D Cluster Map representing the similarity of studies in the systematic review

3. RESULTS AND DISCUSSION

The selected papers were used to address the main study objectives. Figure 3.1 below shows how the papers addressed the main research questions of the study.

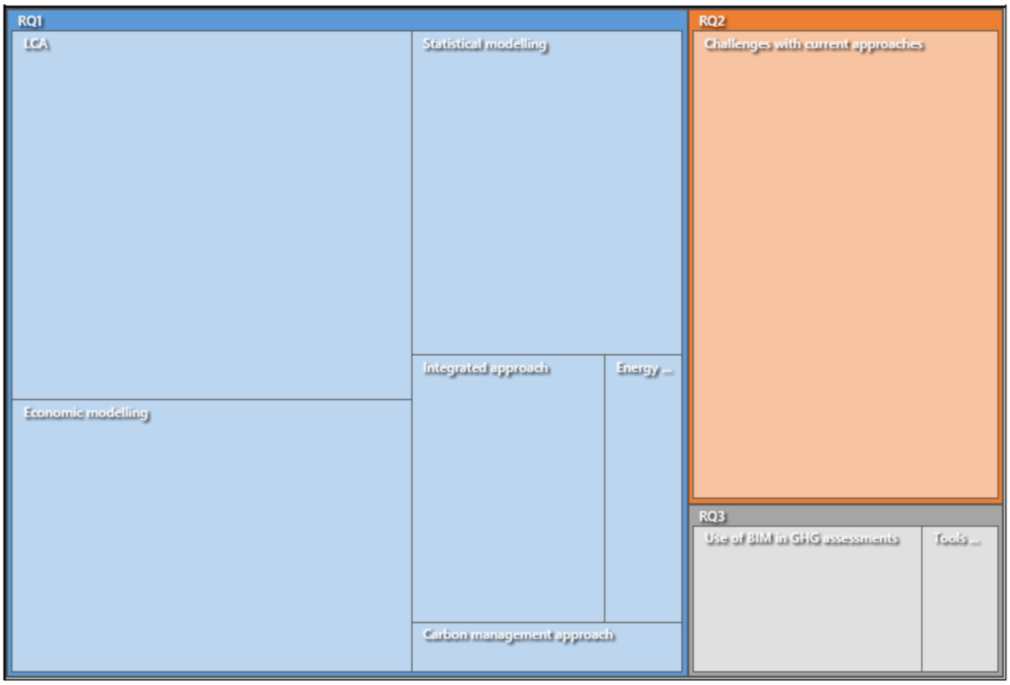

Fig. 3.1: Hierarchy Map of how the papers addressed the main research questions

From figure 3.1, as seen from the size of the hierarchy charts, most of the papers fully addressed the first research question of the study stated in section 1.1. A significant amount of the papers also addressed the second research question whereas there is a paucity of papers addressing the third research question.

3.1 current approaches for measuring environmental footprint in rail systems

The first research question of the systematic review was addressed by reviewing the current approaches for assessing and managing the carbon footprint of a rail system. The authors found the use of multiple methods adopted by practitioners and researchers. There is no consensus by researchers on a straightforward method for quantifying and managing carbon emissions of rail systems. As seen from figure 3.2, six main approaches have been identified from the systematic review which have been used by researchers in assessing the environmental footprint of rail systems, namely: lifecycle analysis (LCA), economic modelling, statistical modelling, integrated approaches, energy system technique and carbon management approaches. The most popular approach is the LCA-based technique. From the systematic review analysis of the studies adopting the LCA technique, it emerged that the main debate related to whether national emission values (country factors) which are mainly top-down should be used or whether this should be built from the bottom-up by measuring actual emissions. The argument against the former in the literature concerned the absence of trustworthy data. A further analysis of the main approaches with time revealed that the use of statistical modelling is gaining popularity among researchers as is the use of economic modelling. Rather than use stand-alone approaches, integrated techniques which combine two or more of these main techniques have also been advocated and employed in recent studies.

	A : Carbon management...	B : Economic modelling	C : Energy System tech...	D : Integrated approach	E : LCA	F : Statistical modelling
1 : Andrade, C.E.S.d. and D'Agosto, M.d.A. (2016)	0	0	0	0	5	0
2 : Banar, M. and Özdemir, A. (2015)	0	5	0	6	3	0
3 : Barisa, A. and Rosa, M. (2018)	0	6	0	0	0	0
4 : Barrientos, F. et al. (2016)	0	0	0	0	0	9
5 : Bressi, S. et al. (2018)	0	0	0	0	5	0
6 : Bressi, S. et al. (2018a)	0	0	1	0	10	0
7 : Bueno, G., Hoyos, D. and Capellán-Pérez, I. (2017)	0	0	0	1	1	0
8 : Dalkic, G. et al. (2017)	2	4	0	0	6	0
9 : De Martinis, V. and Corman, F. (2018)	0	0	0	0	0	14
10 : Del Pero, F. et al. (2015)	0	0	0	0	2	0
11 : Dimoula, V., Kehagia, F. and Tsakalidis, A. (2016)	1	0	0	0	8	0
12 : Dong, H. et al. (2017)	0	7	0	0	0	0
13 : Duan, H. et al. (2015)	0	0	0	0	2	3
14 : Fan, Y.V. et al. (2018)	0	0	1	0	3	0
15 : Ghofrani, F. et al. (2018)	0	0	0	0	0	6
16 : Kaewunruen, S. and Lian, Q. (2019)	0	0	0	0	0	0
17 : Kaewunruen, S., Rungskunroch, P. and Jennings, D. (2019)	1	0	0	0	3	0
18 : Krezo, S. et al. (2018)	0	0	0	0	1	0
19 : Martínez Fernández, P. et al. (2019)	0	1	6	0	0	2
20 : Menezes, E., Maia, A. and de Carvalho, C. (2017)	0	7	0	0	0	0
21 : Meynerts, L. et al. (2017)	0	0	0	3	0	0
22 : Nocera, S. and Cavallaro, F. (2016)	0	8	0	0	0	0
23 : Ortega, A., Blainey, S. and Preston, J. (2018)	0	0	0	0	7	0
24 : Poulikakos, L.D. et al. (2016)	0	4	0	0	0	0
25 : Saxe, S. et al. (2016)	1	0	0	3	0	0
26 : Saxe, S., Miller, E. and Guthrie, P. (2017)	0	0	0	7	1	0

Fig. 3.2: Matrix coding of the main approaches for assessing carbon emissions of buildings

3.2 main problems with current approaches of assessing carbon emissions of rail

The papers were analysed to identify problems with current approaches of measuring the environmental or carbon footprint of a rail system to fully address the second research question of the current study. The result of the in-depth analysis is presented using a mind map in figure 3.3. Three clusters of problems were identified in the literature and were further grouped into A, B and C. The clusters were then presented in terms of the reporting literature in table 3.1. It can be seen from table 3.1 that the most significant problem mentioned by researchers is the unavailability of data. This is closely followed using excessive assumptions when quantifying carbon emissions or employing techniques aimed at reducing the carbon footprint of a railway system. This has prompted the use of national emission values which are primarily top-down approaches. The lack of an industry standard in assessing and managing carbon emissions has also been noted by researchers as is evident from both figure 3.3 and table 3.1. This has serious implications for achieving rail industry emission reduction targets.

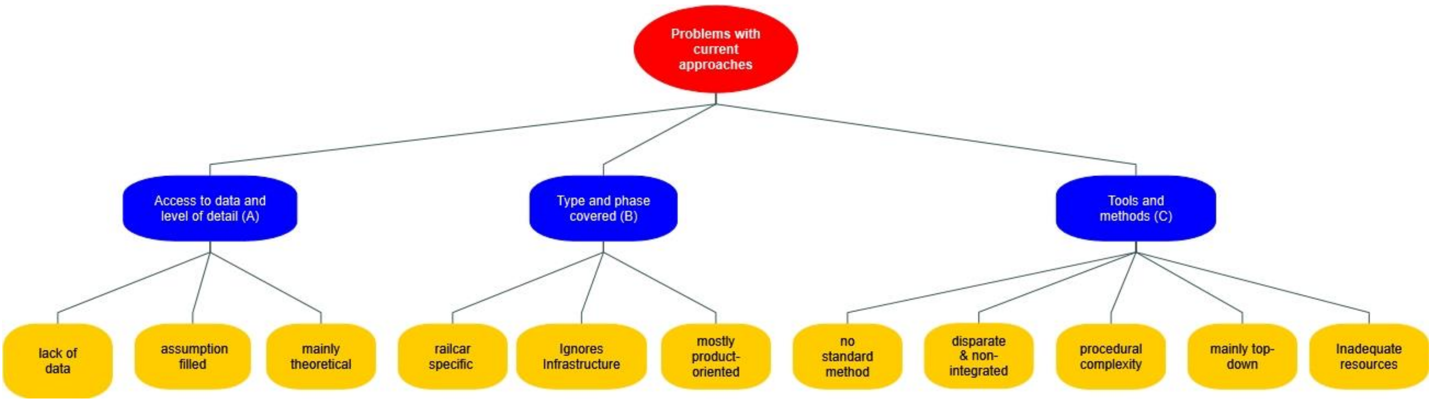

Fig. 3.3: Mind map of main problems with current techniques of carbon footprinting

Clusters	A			B			C				
Probems with current approaches / Authors	Lack of data	Excessive assumptions	Mainly theoretical	Railcar specific	Ignores Infrastructure	Mostly product-oriented	No standard methodology	Disparate non-integrated tools	Procedural complexity	Mainly top-down	Inadequate resources
Andrade and D'Agosto (2016)					x						
Banar and Özdemir (2015)	x		x								
Barrientos *et al.* (2016)	x						x				x
Bressi *et al.* (2018a)	x										
Bueno *et al*. (2017)	x	x									
Dalkic *et al.* (2017)	x										x
De Martinis and Corman (2018)	x							x	x		
Dimoula *et al*. (2016)	x	x									
Duan *et al.* (2015)	x									x	
Fan *et al.* (2018)	x	x									
Ghofrani *et al.* (2018)									x		
Krezo *et al.* (2018)	x	x	x								
Martínez Fernández *et al.* (2019)	x										
Meynerts *et al.* (2017)		x	x				x				
Nocera and Cavallaro (2016)		x				x					
Ortega *et al*. (2018)	x						x		x		

Table. 3.1: Analysis of papers according to the clusters of current problems in carbon footprinting in rail systems

3.3 exploring the use of BIM in greenhouse gas emissions assessments in rail systems

The final research question addressed by this paper is the investigation of the extent of adoption of collaborative and integrative technologies such as BIM in carbon emissions assessment. As mentioned earlier in this paper, BIM has the capacity to reduce the impact of greenhouse gases such as carbon because it provides a platform where stakeholders can collaboratively collect, analyse and manage carbon footprints of a rail system over the whole-of-life of the asset. It was found from the review that BIM-based tools have not been widely adopted in rail infrastructure carbon management. Only Kaewunruen and Lian (2019) reported the use of a BIM tool in sustainability assessment of a rail system. They reported their work as “the world's first 6D BIM for life cycle management of a railway turnout system”. The gains of integrated BIM use in the building industry is well documented in literature. It can thus be hypothesized that BIM-based approaches could potentially address the current challenges of carbon emissions assessment. This hypothesis is explored further in this current study through the discussion of a theoretical framework which is presented in section 3.4.

3.4 exploring a conceptual BIM-based technique for achieving low carbon targets

Based on the PAS 2080 methodology of carbon management (BSI, 2016) and the recent ISO 19650-1 (2018) and ISO 19650-2 (2018) documents on information digitization for civil works and BIM, we propose a conceptual framework for storing and managing carbon emissions in an integrated BIM format. We present our concept in figure 3.4. Our approach is novel and adopts the CapCarbon (capital carbon) and OpCarbon (operational carbon) methodology to enable the management of carbon information using a BIM-enabled life cycle approach.

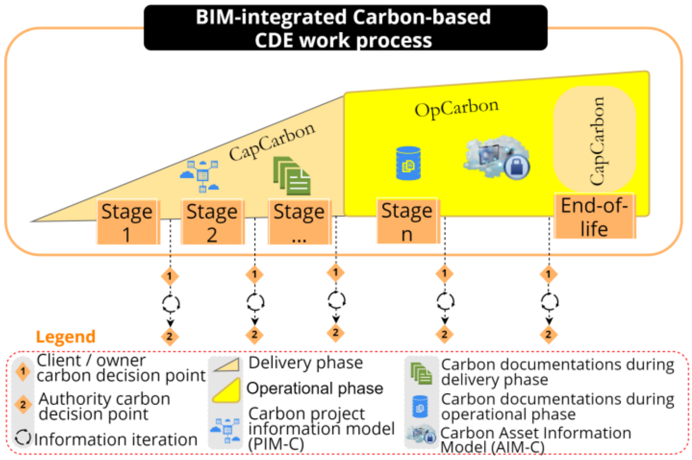

Figure 3.1: A proposed concept for integrating carbon assessment with openBIM

The proposed concept framework will be based on openBIM approach enabling open carbon data information exchange. We also integrate carbon data exchange with stage gates in line with existing BIM management protocols. The level of detail of the information on carbon data is to be agreed collaboratively by *appointing party*, *lead appointed party* and *appointed parties* (ISO 19560-1, 2018). The framework will enable the easy identification of carbon hotspots over the life cycle of the rail system to promote more efficient carbon emissions assessment and management.

4. CONCLUSION

Greenhouse gas emissions assessments in rail systems has been intensively investigated by researchers. The current study emphasizes the importance of assessing and managing carbon emissions in rail systems over the whole of life cycle in a collaborative way. Current limitations in the practice of achieving low carbon targets identified in the literature underlies the need for a paradigm shift. Specifically, current approaches are disparate and non-integrated and do not promote managing the carbon emissions impact of project solutions efficiently. This could derail achieving ambitious carbon targets set for the industry if the status quo is maintained. BIM-based solutions could potentially be a game changer in the rail industry as this could easily be aligned with existing industry standards such as the ISO 19650-1, ISO 19650-2 and the PAS 2080 document on collaborative carbon management.

Future work will focus on identifying the requirements of a BIM-compliant carbon quantification methodology for an improved whole-of-life carbon reduction drive. Also, further work will investigate improving decision-making through the integration of information on carbon emissions data (CapCarbon and OpCarbon) with data drops at stage gates of a case study rail project to facilitate location and managing of carbon hotspots. There is also a need for additional research on developing the Internet of Things (IoTs) capability of BIM-based carbon management solutions to facilitate the capture and management of sensor-based carbon data via data analytics but also to promote the achievement of the UK's Digital Built Britain strategy (DBB) for the industry 4.0 era.

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REVIEWING SEMANTIC WEB TECHNOLOGIES IN THE ARCHITECTURE, ENGINEERING, AND CONSTRUCTION INDUSTRY

Yasir Alani, Nashwan Dawood, Sergio Rodriguez & Huda Dawood
Teesside University, United Kingdom

ABSTRACT: *The complexity of information exchange among different domains in the construction industry is a current problem facing the advancement of Building Information Modelling (BIM), which is coined as the interoperability issue. In this paper we refer to the seamless integration of product/asset information from outline design, and up to decommissioning as the Whole Life Cycle (WLC) of information flow. This needs to be underpinned by digital technologies, well-defined standards, and Linked Data.*

The IFC EXPRESS schema was developed as an attempt to solve or reduce the issue of interoperability. However, this data schema requires extensive mapping, particularly when including attributes of infrastructure domains, making them prone to interoperability inconsistencies.

Semantic Web Technologies (SWT) are expected to form a significant addition to the IFC standards in tackling the issues of interoperability. Also, SWT have the potential of applying rule checking and compliance checking via their logical inferences. All of this is expected to enhance the modelling process.

In this paper, we explore the literature on applying SWT in the Architecture, Engineering, and Construction (AEC) industry through a structured literature review. Further, we present a framework that is being developed to facilitate the WLC of information flow for water utilities assets. Results from the literature review suggest that research on the WLC of data flow is minimal. Moreover, SWT seem to be promising in improving data representation (modelling) across all industries. Nonetheless, as SWT are maturing, they ought to overcome few challenges, mainly the creation and maintenance of links between datasets, and the large generated files.

KEYWORDS: *BIM, Ontology, RDF, SWT, WLC*

1 INTRODUCTION

Semantic Web Technologies (SWT) were introduced in the late 1990s. However, the literature on adopting these technologies in the Architecture, Engineering, and Construction (AEC) industry only started accumulating in the early 2010s (Zhong et al. 2019). The Semantic Web allows connecting different databases on the data level, and hence, allowing a more "linked data". This would in turn allow for smarter querying and data inferencing. For databases to achieve this linkage, they must publish their data in the Resource Description Framework (RDF) format, which is a data modelling framework that forms the basis for the Semantic Web (Allemang & Hendler, 2011). In relational databases, data are represented in tables, which restricts the querying and inferencing capabilities, as establishing relationships between datasets in different cells of different tables is restricted. If we were to represent a relational database in RDF, then each row, column, and cell would receive a global reference (Unique Resource Identifier), resulting in the RDF *triple*, see figure 1. There are few languages that can be used to model data in RDF, such as RDFS-Plus and the Web Ontology Language (OWL), which differ in their complexity and inferencing capabilities. Creating data repositories using RDF languages is known as ontology construction. Gruber (1993) defined an ontology as an "explicit specification of a shared conceptualisation".

Figure 1: The RDF triple

Pauwels et al. (2017) Described interoperability among distinct domains as loading the same content in multiple applications. Therefore, due to the capabilities of SWT, it is possible to connect or *link* data existing in different domains/repositories rather than mapping them. Pauwels et al. (2017) identified two other areas where SWT are expected to make significant improvements, namely linking across domains—which is combining different content existing in multiple applications, and logical inference and proofs. The importance of linked data is a result of the improved interoperability it offers, as datasets in different repositories are linked and continuously being updated. However, this signifies the importance of the links between those datasets. Pauwels et al. (2017) argue that with linked data, the creation and management of links needs human interference, and thus, the interoperability issue now exists on a smaller scale; at the data level. A scientometric analysis was carried out by Zhong et al. (2019) on ontology research in construction between 2007 and 2017, in which they concluded that the initial focus of researchers was on utilising ontologies in several areas of construction management. However, they stated that researchers started focusing on solving the interoperability issue across the building life cycle after 2016. Moreover, the "hot topics" in ontology research that they listed did not include SWT, nor Linked Data, which suggests that the technical aspects of ontology research in AEC are not sufficiently researched. This is further supported by Pauwels et al. (2015), as they encouraged research on the technical issues that are slowing the deployment of SWT in the AEC industry. An example of a technical paper would be that of Niknam and Karshenas (2017), in which they semantically represented building information in an ontology. They argued that there should be a common (top layer) ontology, which can be extended and developed into a specific AEC domain ontology.

In this paper, we conducted a structured literature review to weigh the amount of technical research that has been done on utilising SWT in AEC industry domains. Accordingly, the least researched domain is presented alongside a system architecture for future work.

2 METHODOLOGY

We carried out a structured literature review to identify the gaps in the research on leveraging SWT in AEC industry. Abanda et al. (2013); Pauwels et al. (2017) and Zhong et al. (2019) have reviewed SWT in AEC. However, these papers mainly focused on the general deployment of SWT in AEC. This research identifies only the highly technical journal papers and classifies them into different research domains. We used the search words; "ontology" AND "RDF" AND "OWL" AND "BIM" in ScienceDirect and Scopus databases. The reason for such specific search terms was to obtain technical paper exclusively. There was no time frame for the search, up to the time of writing this paper. A total of 82 articles were obtained, excluding conference articles. Papers were quantitatively categorised into their respective research domain in the AEC industry.

Then, the least researched domain is qualitatively assessed and presented, as it will form the basis for upcoming work. Finally, the "conclusions and future work" section presents a diagram showing the methodology for future work.

3 SEMANTIC WEB TECHNOLOGIES

SWT aim to encapsulate knowledge representation (data modelling). This allows SWT to be utilised across all AEC domains, as it tackles issues at the finite data level. The results from the literature review are depicted in figure 2. Nine categories/domains resulted from reviewing 82 relevant articles. These categories can be further divided into subcategories. However, technical research on ontologies in the AEC industry has not reached such a sufficient level of saturation. Furthermore, different categorisation criteria may result in slightly different categories, as they overlap with each other. For example, overlapping was noticed between the "BIM-FM ontology" and the "Energy ontology", as facility management includes energy management. This overlapping may well be because SWT deals with knowledge representation, and thus, the core principles are the same regardless of the desired ontology. Therefore, harnessing data modelling allows more flexibility in constructing ontologies.

Product Life cycle Management (PLM) is the least researched domain in the literature we explored, see figure 2. On the other hand, one can argue that, in general, all domains require further research efforts, as the technical research on SWT in the AEC industry is far from being intensively saturated.

We have also noticed that most researchers seem to improvise with regards to ontology creation and data management processes. This signifies the lack of standardised guidelines to manage and support the application of SWT in AEC industry. Moreover, most researchers seem to neglect the fact that RDF formats generate large sized files that require good computing power. Barbau et al. (2012) stated that large size ontologies result in poorer performance time, indicating a trade-off between the quality of the ontology (complexity and reasoning) and the performance (computing power required). Consequently, the development of SWT is relatively restrained by computing power.

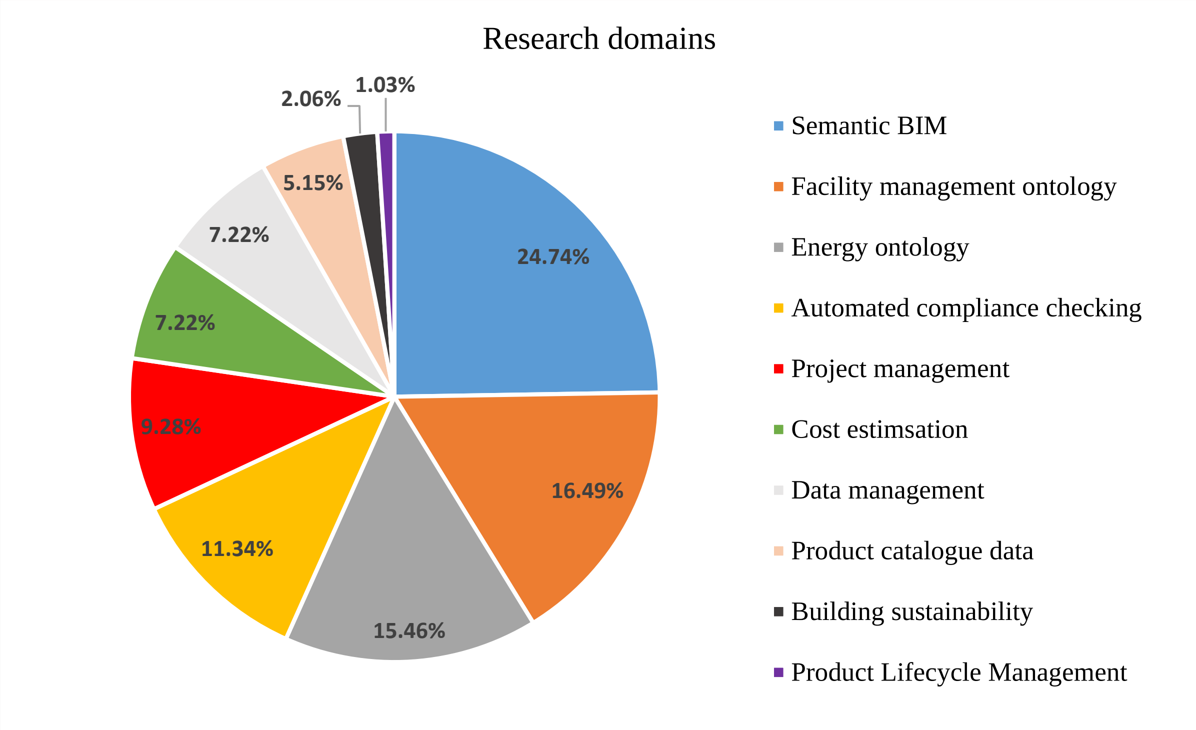

Figure 2: Research domains for applying SWT in AEC

4 WHOLE LIFE CYCLE (WLC) OF INFORMATINO FLOW

Within the boundaries of this study, Fortineau et al. (2019) were the only researchers that investigated some aspects of Product Life cycle Management (PLM) using ontologies. They focused on utilising business rules using the Semantic Web Rule Language (SWRL) in a PLM software. According to Stark (2011) “Product Lifecycle Management (PLM) is the business activity of managing, in the most effective way, a company’s products all the way across their lifecycles; from the very first idea for a product all the way through until it is retired and disposed of”.

Research on the WLC of information flow was not observerd in the literature. WLC of information flow can be defined as a more specific part of PLM that deals with data only. With regards to the AEC industry, Dawood & Vukovic (2015) define WLC as “the steady and continuous evolution and use of BIM information and knowledge from the design stage, through the construction stage, to the facility management stage”. For a valid WLC approach, three important aspects must be fulfilled, namely data creation, data validation, and data maintenance.

4.1 Product manufacturer data

Obtaining the right product data is ought to be the data creation point and the first step in the process. Semantic Web Technologies allow enhanced data querying, and ultimately decision making to allow the user to search and select the most suitable model for the design (Wu et al. 2019). Ideally, product manufacturers/suppliers would publish their data online in the RDF format, which would support a more intelligent querying. Nonetheless, it would take some time into the future for product manufacturers to adopt the RDF format for their websites. An alternative method would be to produce an ontology of classification clusters—this ontology would function like a dictionary including all the related terms for a specific domain. This ontology would then aid the domain expert (e.g. design engineer) to produce meaningful queries when searching product libraries. This approach is further explained by Gao et al. (2015). Moreover, Gao et al. (2017) have used this ontology in annotating BIM documents using algorithms that would determine semantic relationships and provide documents indexing. Once the desired asset model is selected from the library, it would then be imported into the BIM model. However, a problem currently facing such system—in addition to the technological limitations—is how to determine the attributes that are significant for the asset management system or BIM. There is no clear methodology for determining the important attributes of an asset, due to a large number of variables involved. This conveys the fundamental issue of clearly defining the owner’s requirements in the AEC industry (Alani et al., 2019).

In general, it is worth noting that when the user searches for product data by making a query in the BIM model, it exemplifies the "linking across domains" principles as identified by Pauwels et al. (2017). Likewise, the "interoperability" principles are exemplified when select product is imported into the BIM model together with its attributes.

4.2 Regulation compliance checking

The logical data inference is the second step in the WLC approach. Data models re governed by rules, and when these roles are modelled using RDF, then less processing layers are required (Allemang & Hendler, 2011). These rules are used to make logical predictions, which is called *inferencing* in semantic models. SWT are based on an Open World Assumption (OWA) which assumes that the model is never complete and there is always information to be added. Hence, OWA indicates missing information as being simply "unknown" until added into the system. This is in contradiction to current compliance checking and BIM applications that adopt a Closed World Assumption (CWA) logic, and hence, indicate missing information as "false". Researchers usually use the inferencing capabilities of SWT for automated compliance checking, which is the fourth most researched domain in our paper, figure 2.

4.3 Data management

Data management is a broad domain that includes different subcategories such as data archiving, the Internet of Things (IoT) ontologies, and integrating static and dynamic data. For a well-designed data management model, the ontology must be comprehensive, yet precise to accommodate the classifications and standards relevant for the fulfilling requirements. However, as we stated earlier, an OWA system allows modifications and additions to the system, and thus, it can be regularly reviewed and updated. Moreover, Semantic relationships—RDF relationships—are not an explicit solution to the problem of classifying and naming objects. However, they improve the process as they provide the ability to *construct* property relationships between classes in single or multiple ontologies. Therefore, separate ontologies can be used to complement each other.

5 CONCLUSIONS AND FUTURE WORK

We have carried out a structured literature review to identify the current research patterns in applying SWT in AEC industry. Results showed that there is a current trend on applying SWT to different domains of the AEC industry, as semantic BIM, facility management, and energy management make up more than 50% of the research spectrum identified in this paper. On the other hand, research on applying SWT in the AEC industry is generally immature and far from being intensively saturated. Furthermore, as SWT are still immature—at least within AEC industry—they lack the standards and guidelines for their full exploitation. Nonetheless, PLM, and hence, WLC form the least intensively researched domains. A reason for this maybe the fact that they encompass the three main research areas identified by Pauwels et al. (2017), namely linking across domains, interoperability, and logical inferences. Nonetheless, with SWT, the interoperability issue is indeed improved, but not eliminated as it now exists on a finer scale, which is the creation and maintenance of links between datasets. In addition, the standards and guidelines on SWT in AEC are substantially lacking.

This review was to demonstrate the research gaps in applying SWT in the AEC industry, and to provide further justification to the future work that will be based on this review. A case study is currently being developed on facilitating the WLC of information flow for a particular water utility company in the United Kingdom, see figure 3. As depicted in the figure, data will flow from right to left. The process starts by retrieving information from online databases (usually relational databases). These data must be inserted into an ontology editor (e.g. Protégé) in the RDF format. Hence, it is critical to translate the data into RDF format to instantiate the ontology. Conversion from relational data to RDF can be done via a translation language (e.g. D2RQ). Similarly, STEP data (ISO 10303) can be converted into RDF via the Protégé plug-in, OntoSTEP. However, depending on how the data is published online, there may be a need to collect unstructured data from text files (e.g. PDFs), for which, specific ontology construction tools are needed (El Ghosh et al., 2017). Lastly, the created ontology (RDF database) must be connected to BIM/Maximo model to allow the user to make SPARQL queries. This can be done via a plug-in akin to Costa and Madrazo (2015), in which they developed a plug-in for connecting Protégé with BIM.

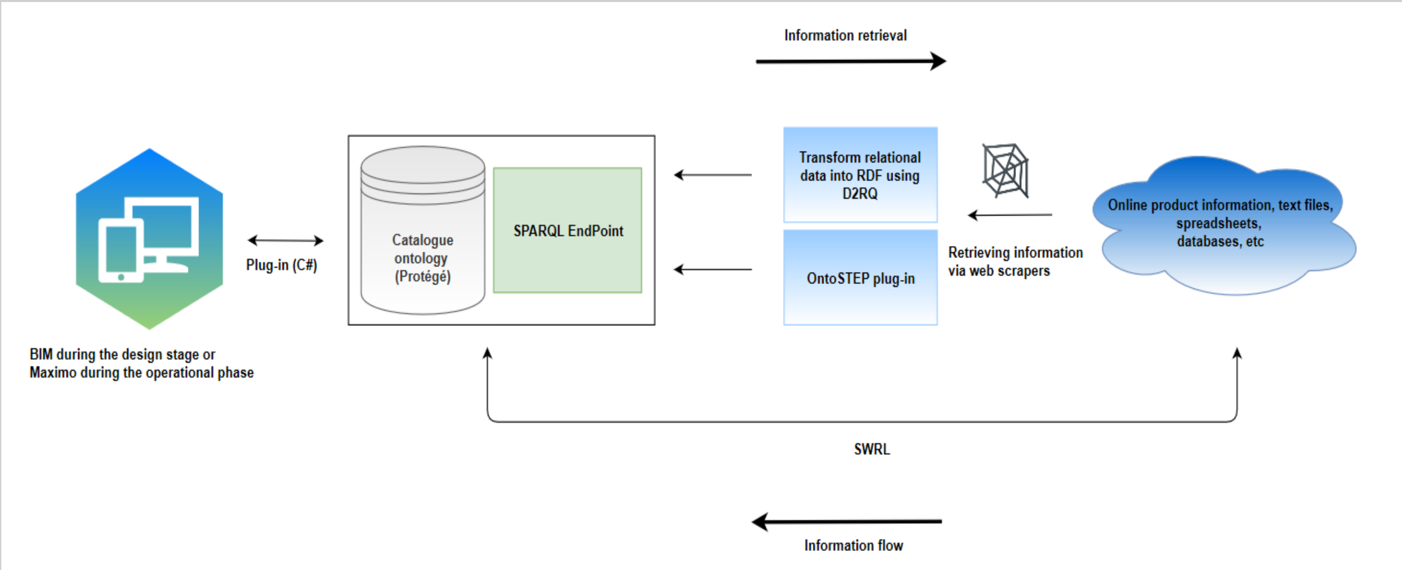

Figure 3: The suggested system architecture

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7 Appendix

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