VISUALIZING REAL-TIME INFORMATION THROUGH A CONSTRUCTION PRODUCTION CONTROL ROOM

Karim Farghaly, Ranjith K. Soman, and Jennifer Whyte
Centre for Systems Engineering and Innovation, Imperial College London, UK

ABSTRACT

Extending current work on visualization in the Architecture, Engineering, and Construction (AEC) sector, this paper describes an industry-led collaborative research and innovation project to develop and use a control room on the construction site. The work is inspired by NASA mission operations, with its large-scale visual display. It addresses the challenges of visualizing real-time construction data. Working with a main contractor, technology companies, and other researchers, we first give an overview of the progress of the overall project to date and discuss our contributions on requirements, real-time simulation of construction data, and visualization. We conclude by discussing the contribution to work on visualizing construction.

INTRODUCTION

The NASA mission operations control room is a well-known example of a large-scale collaborative data display, with multiple streams of real-time data available to engineers. Inspired by this example, a team of industry partners and universities in the UK are developing and piloting a control room on the construction site.

The state-of-the-art in virtual and augmented reality is now beginning to explore the potential to show data in real-time, and advocates work with industry to develop technologies that meet AEC needs (e.g. (Nikolic et al., 2019, Davila Delgado et al., 2020, Zhang et al., 2020)). There is a broader understanding that how the information is displayed affects decision-making (Tufte et al., 1998). Nevertheless, the results are not always media-specific (Leder et al., 2019), with transitions across media also impacting the sense of presence or immersion (Smolentsev et al., 2017). While significant progress has been made in applying advanced visualization methods to construction, as this has mainly through academic work in the laboratory and industry exemplar cases, there is relatively little understanding of visualization complexities at the construction site. There is a small but growing trajectory of work that is beginning to work with practitioners in an engaging way to examine the take-up and use of visualization technologies in the field (e.g., Maftei et al., 2019, Nikolic et al., 2019).

Our work on the AEC production control room project contributes to this emerging trajectory of research, as we engage as part of a wider consortium tasked with developing a control room. Production management in construction is an information-intensive process requiring people at various operational levels in both construction site and office to communicate continuously and seamlessly (Dave and Sacks, 2020). This information includes product and process information (Sacks et al., 2010). The product information is relatively well codified in modern construction in semantically rich information models such as Building Information Modelling (BIM) projects models, whereas process information is codified as precedence relationships (Soman and Whyte, 2020). Current representations of process information such as Gantt charts lack detail, do not show spatial conflicts, resource allocations, and do not reflect the dynamic nature of construction activities, thereby limiting its effectiveness (Dave and Sacks, 2020). ICT and visualization technologies have great potential to improve planning and production management in construction projects; however, current information systems should be extended to achieve it (Chua et al., 2013). Prior research has developed frameworks to enable real-time information flow between the construction site and construction digital twins for effective decision making (Dave et al., 2016, Soman and Whyte, 2017, Sacks et al., 2020). Building on these frameworks, researchers have begun to develop collaborative visualization environments such as control rooms to visualize and interact with real-time construction information for effective production management (McHugh et al., 2019, Ezzeddine et al., 2020).

In the next section, we provide a background for tools and techniques utilized in the construction sector to monitor and control the progress. In the following section, we give an overview of the AEC production control room

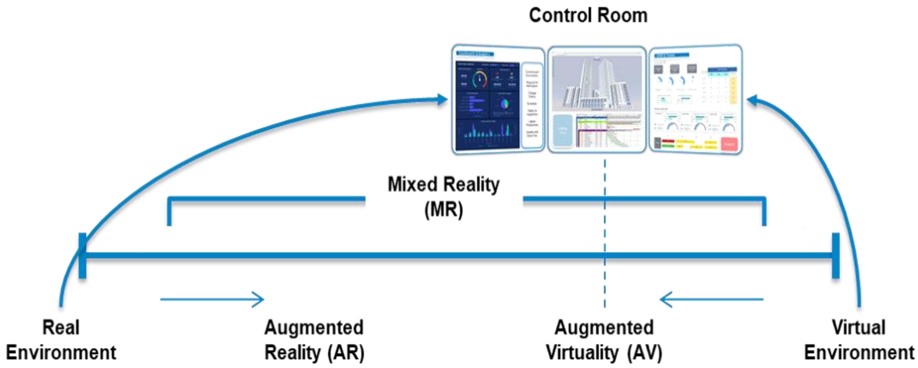

Figure 1: Simplified representation of a Reality-Virtuality Continuum adapted from (Milgram et al., 1995).

project, describing the progress to date and the challenges we have faced due to the global pandemic and changed ways of working through 2020. In the following, particular focus on requirements, real-time simulation, and visualization of construction data. We then discuss the contribution to the broader field of research on visualizing construction and conclude by describing implications for new directions for work on virtual and augmented reality.

BACKGROUND

Reporting on the progress of a construction project is a vital aspect of construction project control. Nowadays, several tools and technologies improve monitoring and control information and progress in construction sites. There are vision-based technologies such as 2D Image processing (Chi & Caldas 2011), Photogrammetry (Kim et al. 2011), Range cameras (Braun et al. 2016), Timelapse (Golparvar-Fard et al. 2007), and Laser scanning (Son et al. 2017). While, there are sensor-based technologies such as RFID (Moon & Yang 2010), GIS (Sonmez & Uysal 2008), distributed sensors (Soman et al. 2017). Other researchers have resorted to earned value analysis, Artificial neural networks, and genetic algorithms (Akanmu & Zhang 2016).

These technologies, tools, and techniques, coupled with mobile computing technology, can provide an environment where users can extract progress information from and input project information into the system. Despite the promises of these tools to provide intangible and comprehensive benefits in communication and labor utilization (Majrouhi Sardroud 2012; Taneja et al. 2011; Demiralp et al. 2012)., researchers argued that without a clear, effective visualization based on user requirements, these tools would not be beneficial (Bouchlaghem et al., 2005, Abualdenien and Borrmann, 2020).

A number of AEC companies are now exploring the control room concept to promote more collaborative uses of their dashboard solutions. The control room concept is not new to construction and has been explored by research groups on several occasions, such as CIFE iROOM (Fischer et al., 2002), the digital obeya room (Nascimento et al., 2018a), Mace lean construction control room (McHugh et al., 2019). These control rooms are media spaces in which very different forms of project information, principally the 3D plan of the structure and Gantt chart schedule, could be drawn together and visualized side by side. Crucially these applications were linked with custom interfaces so that the project's data could be interacted with as an ensemble: filtering the schedule would update the view of the 3D model and vice versa, and both could be visualized according to the functionality provided by an independent time controller to provide integrated 4D views, but different design scenarios and solutions could also be visualized side by side at the same time. This enables human users to explore and identify the relationship between different project data. In our research, we go beyound that by identifiying new visualisng techniques and more datasets to explore.

As Whyte and Nikolic note, Milgram and Kishino (1994) proposed a virtuality continuum categorizing mixed reality environments between the physical world and the virtual world (Figure 1). Within this spectrum is a range of environments that augment reality by adding virtual information to real places and augment virtuality by providing a physical context and setting to interpret primarily digital information. The control room provides a physical place where practitioners can come to a shared understanding of real-time digital data by utilizing a large collaborative data display with interactivity, where their mark-ups go straight into the database.

RESEARCH METHODS

The research is engaged scholarship (Van de Ven, 2007), through which the research team is embedded in the weekly meetings with the main contractor and technology providers. The authors' contributions start with identifying key stakeholders on the three demonstrator projects, capturing and analyzing their data requirements. These are being systematically documented and analyzed, extending systems engineering methods, to guide the

Figure 2: Mockup of AEC production control room

design of the construction Project Control Room, which will integrate the flow of input data from on-site hardware and proprietary software to display real-time data, analyses, and forecasts and enable predictive analytics.

This ongoing work is also seeking to identify priority areas for the deployment of, and work on the development of, a predictive capability for better construction monitoring (building on Soman et al., 2020); and providing research input into the development of the database architecture as a data lake (not relational database) and demonstration of an approach to mapping cost and work breakdown structures that can be standardized.

As a response to the increasingly distributed nature of the research and construction practice, we are also working with a student to extend this work to develop more intuitive methods of engaging remotely with the datasets using augmented reality to manipulate 3D models BIM-assisted construction activity planning.

THE AEC PRODUCTION CONTROL ROOM PROJECT

The Problem

Currently, most construction projects report on out-of-date data that is often days or even weeks behind the live status. This makes it very difficult to take proactive and impactful action as teams report on events that have already occurred and are beyond influence. This research proposes to build a scalable and repeatable 'plug-and-play' Control Room that displays a suite of preconfigured insights using real-time data, facilitating forward planning and collaborative decision making at the team, project, and portfolio levels.

Other sectors such as retail, automotive, process, and industries have all been reliant on data-driven processes to enable supply chain management, lean manufacture, and process control. Users can track real-time changes and take proactive action based on the insights, such as comparing, in real-time, 'what was planned' versus 'what has been delivered', or tracking each element's status.

Overview

The project proposes to build a scalable and repeatable 'plug-and-play' construction management and reporting platform that will be tested on three significant projects in the UK. This digital project management platform will be accessible via physical site-mounted 'AEC Production Control Rooms' that will display a suite of preconfigured performance metrics using real-time data, facilitating planning and collaborative decision-making at the team, project, and portfolio level (Figure 2). A fourth HQ-mounted Master Control Room will enable benchmarking across different projects remotely

The project started in May 2020 with a duration of 24 months. The expert team was bought together to blend the best of academic insight and private sector delivery experience. It includes Mace, who is leading and coordinating the project, academic input, and support from researchers at UCL and Imperial College London, as well as private sector support from 3D Repo, Mission Room, and eviFile. This industry-led innovation project was funded by the UK innovation funder, Innovate UK, and involves partners

Progress to date

At present, the team has established three projects that will act as demonstrators for the general approach, and technology is being installed, with the research team visiting and discussing requirements with project teams. We are currently engaged with two running projects that are using the production control room in their sites.

While the AEC production control room project anticipated the team to be collocated, we have experienced new forms of in-person, hybrid, and remote organizing as a result of the global pandemic. Therefore, progress has been slower than anticipated given the associated challenges of accessing data and site through the various lockdowns, however, the construction sites continued to operate, and we have had the opportunity to

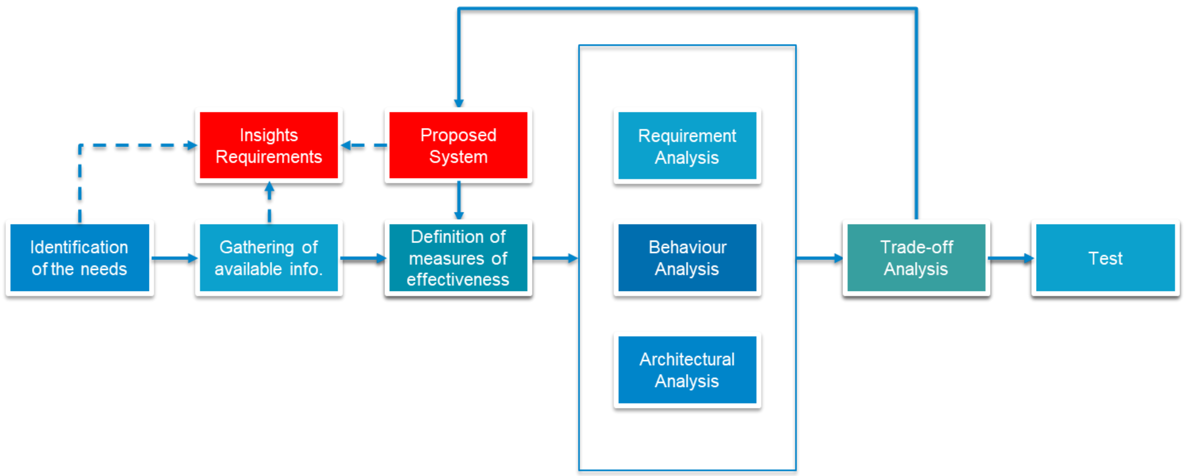

Figure 3: The adapted system engineering approach (Adapted from (Bucelli et al., 2020))

take the construction control room into these two locations. As discussed further below, this increasingly distributed nature of work, the digital nature of the research, and the implementation of demonstrator projects. This has allowed the research team to reflect on the different forms of visualization and how they support decision-making in construction across different key actors' configurations.

REQUIREMENTS, REAL-TIME ANALYTICS, AND VISUALIZATION

The authors seek to ensure this project is at the forefront of developments in data visualization, augmented and virtual reality and contribute directly to the project in three key areas: 1) identification of data requirements and collection of real-time site data from the site; 2) development of predictive capability for construction monitoring; and 3) development of data structures using linked-data for integrated construction project delivery. Figure 3 illustrates the system engineering approach adapted to effectively develop the system behind the production control room. The initial findings and the ongoing work is stated below.

Identification of the needs and available datasets

The research team engaged with weekly look-ahead planning meetings of the demonstrator projects to identify stakeholders and their requirements as well as to understand the workflows followed in these projects. These meetings aimed to coordinate the activities distributed among different subcontractors at the construction site. Most of the coordination happened over three shared resources 1) work zones, 2) deliveries, and 3) crane assignment. Work areas at the construction sites were divided into work zones and levels. Each subcontractor occupied a zone in a level, and the zone was released to another subcontractor. Therefore, it was necessary to coordinate and agree on the handover dates for different zones between different subcontractors.

Similarly, delivery gates and laydown areas and tower cranes were shared between subcontractors, and the slot assignments for the same were discussed in these meetings. These meetings used a coordination room where the AEC production control room is proposed to be installed. Building on (Soman et al., 2020), work is being done to automate the detection of such conflicts in the look-ahead programme. Further, discussions with the project manager have led to identifying a requirement to develop a ticketing system to record actions from these meetings; some of the actions get lost after the meeting. When implemented, the AEC production control room would augment these meetings with real-time information about the project and conflict information for effective decision-making to capture meeting actions and assign them to relevant teams and sub-contractors.

Main workflows to manage the production are provided for the subcontractors to submit their three-week look-ahead plan and their eight-week look-ahead plan to the main contractor for review. The main contractor then reviews the different plans submitted by the subcontractors, integrates it, and checks for clashes and conflicts using 4D BIM. Following this exercise, the conflict-free plan of work is given back to the sub-contractors. An integrated plan is then discussed and agreed upon during the look-ahead planning meetings. One of the demonstrator projects was in its early stages of construction, with digital workflows being set up between subcontractors, whereas the second project had already got workflows for managing the production at the construction site. A key issue that was identified during this process is that there is no agreed template for the submission of plans from subcontractors. Further, the subcontractors' detailed plans do not have direct links to the master plan, making it challenging to track milestones and deliverables, resulting in data silos. This has led to identifying a second requirement to better connect the

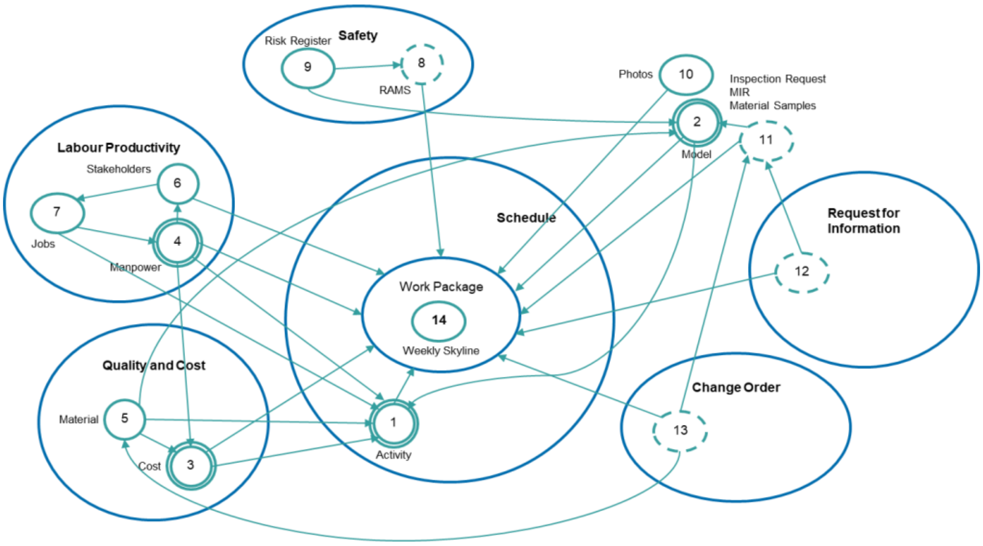

Figure 4:: Different datasets and their relationships.

master programme to the more detailed package programme submitted by subcontractors for effective use of control rooms.

In addition to the workflows, one of the projects has a custom online reporting system to replace spreadsheet-based reporting. This was developed to eliminate errors, such as data errors and redundancy. However, the data in this system was manually collated from several reports manually, and the information is not connected to each other, thus reducing its functionality. This issue has led to identifying another requirement for the control room to collate the data from the production to automate reporting so that the reporting platform will provide users with the ability to review the progress of project's construction in real-time, providing senior management with the confidence that projects are either under control or in need of assistance.

Gathering of available information

There are multiple technological solutions that are being used in these projects. These include common tools such as Common Data Environment (CDE), BIM authoring tools, 4D BIM, Project Scheduling tools, and spreadsheets. In addition to these familiar tools, there are tools for project reporting from certain service providers as well as ones developed within the contractor's research and development wing for managing deliveries, keeping track of attendance, and managing work areas. A significant issue with the current set of technologies is interoperability. Most of these technologies do not talk to each other, and the engineers on the project have to manually populate different technological solutions leading to inconsistencies in data (also observed in (Soman and Whyte, 2020)). This issue has led to the identification of data integration as one of the critical requirements for developing the control room.

To achieve effective data integration and exchange between applications, the proposed solution should achieve both semantic and syntactic interoperability (Veltman, 2001). Syntactic interoperability solutions identify an agreed exchange format to transfer data, and semantic interoperability solutions identify a set of terms and data requirements to enable interoperation using the agreed exchange format defined by syntactic interoperability. Most of the research and industry applications into construction informatics have concentrated on developing technology-driven functions and applications to overcome the syntactic interoperability barrier rather than developing computable information requirements for better semantic interoperability (Farghaly et al., 2018). Even with these applications, syntactic interoperability solutions alone cannot ensure that real-time data integration could achieve the required expected benefits and results (Farghaly et al., 2020). Therefore, we have worked on the semantic interoperability aspect through identifying the available datasets and categorizing them based on the associated KPIs, and finally, develop the required links between the datasets (Figure 4).

Proposed System

The AEC production control room will mainly consist of three screens, and each screen will show specific datasets, and the level of details and information change based on who is in the room. The three screens are:

- Dashboard screen: This screen presents a dashboard that monitors KPIs relevant to the strategic business goals and portrays the trend of the construction project's performance at-a-glance. Seven main KPIs were identified 1) construction deliverables and their status such as drawings, models, and material inspection reports, 2) Issues raised and has a process to be solved such as request for information (RFI) and change orders, 3) Schedule status such as charts for planned vs. actual, 4) Safety and Inspections, 5) Labor productivity, 6) Deliveries to the construction site, and 7) Quality and closeout.

- 4D integration screen: This screen presents 3D models and associated activities represented in the Gantt chart. The activities would link the building elements in the 3D models and the SQL datasets represented in the dashboard format. This link will provide an environment to reduce the amount of time to extract information related to a specific element, activity, and the cause of effect of the delays to achieve a specific milestone.
- Work Assign Response (WAR) screen: WAR screen sets up an environment for the ticketing system (as mentioned before). In this screen, real-time captured data and the predicted weather for the next week are also visualized.

Next Steps

The ongoing work now analyses the different data collected from construction site planning meetings' observation, interviews with end-user requirements. Once this is finished, a set of functional requirements and non-functional requirements will be shared with industrial partners. The next step would be working closely with partners to develop an integrated systems environment where data in PowerBI, 3D Repo, and Powerproject will be semantically linked. Finally, the developed integrated system will be evaluated across the three construction projects.

DISCUSSION: VISUALIZING CONSTRUCTION

This work on the AEC control room is an example of augmented virtuality, situated within the spectrum of visual applications, from a completely real to a completely virtual world. It has implications for a range of other applications to visualize construction across this spectrum, providing insight into methods for identifying data requirements for real-time data and its integration. This is important for the study of virtual and augmented reality. Our experience of working on this large-scale visual display through the pandemic is that visual solutions increasingly do not stand alone. However, the underlying datasets become accessed by teams that are partially collocated, working with the large-room displays, but may also involve remote interactions. There is a growing need for research not to treat VR and AR as standalone solutions, but to unpack and explore the diverse configurations of visualization applications that are used across a broader landscape of decision-making. In our case, there are ongoing discussions about how to bring the insights of the control room to the participants working from home, through AR and VR, so that planners and BIM managers can view the control room while they are not on-site and as if they are in the weekly meetings. This vision would include adopting other technologies, such as the Tactile Internet (Na et al., 2020).

CONCLUSIONS

This research study contributes to visualizing construction in a number of ways. First, it shows the value of working with industry to develop and use a control room for visualizing real-time data on the construction site, drawing inspiration from NASA mission operations, with its large-scale visual display. Nowadays, open standards such as Industry Foundation Classes (IFC) provides an opportunity to link 3D building information models to future dimensions of data such as time, cost, productivity, and submittals progress. This provides opportunities for developing new technological platforms and establishes more effective ways of construction monitoring and control. Second, the production control room provides a physical setting in which the real-time datasets and software behind the data integration systems platforms can be interfaced with the practical work of construction on site. This robust environment can significantly improve the understanding of progress and future decisions.

Third, this paper describes the latest developments in ongoing research concerning the development and implementation of production control in construction sites and our contributions on requirements, real-time simulation of construction data, and visualization. As the novelty of control rooms from a visualization perspective is the diversity of data presented in terms of data types, structure, and format, we have proposed an architectural interface for the control room to show all the end-users requirements. Fourth, we have developed the mapping between the different datasets to achieve these requirements. Future work would include mapping the different datasets using ontologies and evaluating the interface in workshops with the practitioners. This research study has implications for researchers working across various applications from the real world to the virtual world. It provides a unified vision for what should be in the production control room. This work can be used by VR and AR researchers in construction, both to develop work on large-scale display of real-time data, and to develop new insights into the increasingly diverse sets of visual interfaces across the collocated, hybrid and remote organization of construction work.

ACKNOWLEDGMENTS

The project has been kindly sponsored by Innovate UK grant no. 106169 - AEC Production Control Rooms.

REFERENCES

Abualdenien, J. & Borrmann, A. 2020. Vagueness visualization in building models across different design stages. *Advanced Engineering Informatics,* 45**,** 101107.

Bouchlaghem, D., Shang, H., Whyte, J. & Ganah, A. 2005. Visualisation in architecture, engineering and construction (AEC). *Automation in Construction,* 14**,** 287-295.

Chua, D.K.H., Nguyen, T.Q. & Yeoh, K.W. 2013. Automated construction sequencing and scheduling from functional requirements. *Automation in Construction,* 35**,** 79-88.

Dave, B., Kubler, S., Främling, K. & Koskela, L. 2016. Opportunities for enhanced lean construction management using Internet of Things standards. *Automation in Construction,* 61**,** 86-97.

Dave, B. & Sacks, R. 2020. Production control systems for construction at the nexus of Lean and BIM. *Lean Construction: Core Concepts and New Frontiers, New York: Routledge***,** 54-83.

Davila Delgado, J.M., Oyedele, L., Beach, T. & Demian, P. 2020. Augmented and Virtual Reality in Construction: Drivers and Limitations for Industry Adoption. *Journal of Construction Engineering and Management,* 146**,** 04020079.

Ezzeddine, A., Shehab, L., Srour, I. & Power, W. Construction Control Room for Project Monitoring and Control. Proceedings of the Creative Construction e-Conference 2020, 2020-01-01 2020. Budapest University of Technology and Economics.

Farghaly, K., Abanda, F.H., Vidalakis, C. & Wood, G. 2018. Taxonomy for BIM and Asset Management Semantic Interoperability. *Journal of Management in Engineering,* 34.

Farghaly, K., Abanda, F.H., Vidalakis, C. & Wood, G. 2020. BIM-Enabled Asset Management Information Exchange: IDM/MVD Approach. *International Journal of Digital Innovation in the Built Environment (IJDIBE),* 9**,** 49-62.

Leder, J., Horlitz, T., Puschmann, P., Wittstock, V. & Schütz, A. 2019. Comparing immersive virtual reality and powerpoint as methods for delivering safety training: Impacts on risk perception, learning, and decision making. *Safety Science,* 111**,** 271-286.

Maftei, L., Nikolic, D. & Whyte, J. 2019. Challenges Around Integrating Collaborative Immersive Technologies into a Large Infrastructure Engineering Project. *Advances in Informatics and Computing in Civil and Construction Engineering.* Springer.

Mchugh, K., Dave, B. & Craig, R. Integrated lean and BIM processes for modularised construction. 2019. 27th Annual Conference of the International Group for Lean Construction ….

Milgram, P., Takemura, H., Utsumi, A. & Kishino, F. Augmented reality: A class of displays on the reality-virtuality continuum. Telemanipulator and telepresence technologies, 1995. International Society for Optics and Photonics, 282-292.

Na, W., Dao, N.N., Kim, J., Ryu, E.S. & Cho, S. 2020. Simulation and measurement: Feasibility study of Tactile Internet applications for mmWave virtual reality. *ETRI Journal,* 42**,** 163-174.

Nikolic, D., Maftei, L. & Whyte, J. 2019. Becoming familiar: how infrastructure engineers begin to use collaborative virtual reality in their interdisciplinary practice. *Journal of Information Technology in Construction,* 24**,** 489-508.

Sacks, R., Brilakis, I., Pikas, E., Xie, H.S. & Girolami, M. 2020. Construction with digital twin information systems. *Data-Centric Engineering,* 1.

Sacks, R., Radosavljevic, M. & Barak, R. 2010. Requirements for building information modeling based lean production management systems for construction. *Automation in Construction,* 19**,** 641-655.

Smolentsev, A., Cornick, J.E. & Blascovich, J. 2017. Using a preamble to increase presence in digital virtual environments. *Virtual Reality,* 21**,** 153-164.

Soman, R.K., Molina-Solana, M. & Whyte, J.K. 2020. Linked-Data based Constraint-Checking (LDCC) to support look-ahead planning in construction. *Automation in Construction,* 120**,** 103369.

Soman, R.K. & Whyte, J.K. A Framework for Cloud-Based Virtual and Augmented Reality Using Real-Time Information for Construction Progress Monitoring. Proceedings of the Joint Conference on Computing in Construction (JC3), 2017. 833-40.

Soman, R.K. & Whyte, J.K. 2020. Codification Challenges for Data Science in Construction. *Journal of Construction Engineering and Management,* 146**,** 04020072.

Tufte, E.R., Mckay, S.R., Christian, W. & Matey, J.R. 1998. Visual explanations: Images and quantities, evidence and narrative. American Institute of Physics.

Van De Ven, A.H. 2007. *Engaged scholarship: A guide for organizational and social research,* Oxford University Press on Demand.

Veltman, K.H. 2001. Syntactic and semantic interoperability: new approaches to knowledge and the semantic web. *New Review of Information Networking,* 7**,** 159-183.

Zhang, Y., Liu, H., Kang, S.-C. & Al-Hussein, M. 2020. Virtual reality applications for the built environment: Research trends and opportunities. *Automation in Construction,* 118**,** 103311.