Guest editorial: Enabling the development and implementation of digital twins

In spite of its significant impact on industrial employment (i.e. over 6.6% contribution) and representation of 9.8% of the UK's gross domestic product (Rhodes, 2019), the AEC industry has been continuously criticised because of its fragmentation for over five decades, resulting in several major industry reports. Many studies have identified the knowledge gap between design and construction as a major reason for this discontinuity (Abrishami *et al.*, 2014; Fruchter *et al.*, 2016; Goulding and Pour Rahimian, 2019; Goulding *et al.*, 2015; Pour Rahimian *et al.*, 2019; Pour Rahimian *et al.*, 2008; Rahimian *et al.*, 2011).

Meanwhile, the wider world (including the built environment) is experiencing a kind of paradigm shift because of the emergence of the industry 4.0 (I4.0) revolution. Recent technological and other process-based advances and innovative technologies in the built environment mentioned above have a key role in this process. As widely reported in the popular and scientific media, the nine pillars supporting I4.0 are: the Internet of Things (IoT), big data, augmented reality, advanced visualisation, VR and simulation, additive manufacturing, system integration, cloud computing, autonomous systems and cybersecurity.

In the case of the built environment sector, these nine pillars can be said to be underpinned by BIM, widely regarded as the tool of choice to address key issues such as industry fragmentation, value-driven solutions, decision-making, client engagement and design/process flow to name but a few. Therefore, it could be argued that Construction 4.0 has ten pillars, including the nine I4.0 pillars and BIM. Exemplars from other industries such as automotive, aerospace and oil and gas currently demonstrate the power and application of these technologies. However, the built environment has only just recognised terms such as "golden key" and "golden thread" as part of BIM processes and workflows (Johansen *et al.*, 2021). Construction 4.0 offers a portfolio of potential solutions to bridge the knowledge and information gaps between design, construction and operations (Gomez-Trujillo and Gonzalez-Perez, 2021; Newman *et al.*, 2020; Sawhney *et al.*, 2020).

This has led to the emergence of a series of cutting edge technologies in the AEC realm, including but not limited to virtual reality-based collaboration technologies (Pour Rahimian *et al.*, 2019), artificial intelligence-based optimisation (Pilechiha *et al.*, 2020), data-driven decision support (Seyedzadeh *et al.*, 2019), smart data modelling (Seyedzadeh *et al.*, 2020), blockchain and distributed ledger technologies (Alizadehsalehi and Yitmen, 2021; Brandín and Abrishami, 2021; Elghaish *et al.*, 2020; Wong *et al.*, 2020) and computer vision and graphics (Moshtaghian *et al.*, 2020; Pour Rahimian *et al.*, 2020). For example, these advancements can assist decision-making in predicting the cost and performance of optimal design proposals (Elghaish and Abrishami, 2020).

Previous research has demonstrated real-time centralised solutions for OpenBIM. In addition, research has begun to demonstrate the feasibility of decentralising these OpenBIM systems (Oliver *et al.*, 2020). Collectively, these developments are forcing a paradigm shift in design from asynchronous to real-time data exchanges, which are impervious to repudiation, ultimately improving inter-organisational perceptions of social presence (Oliver, 2019) and imbuing confidence in the design shift expected of OpenBIM.

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The industry is experiencing an increasing drive towards digital technology because of increased processing and computing speeds, the rollout of 5G networks, a flourishing software market and interest from academics in exploring the extent of digital possibilities in construction. Distributed ledger technologies complement these advancements by introducing consensus-based decision-making, removing the social identity and bad faith communications at the heart of many disruptive conflicts in a collaborative project (Jaffar *et al.*, 2011). In addition, advancements in cryptography and read-only data management optimisation are paving the way for fully fledged distributed ledger technologies for digital twinning and asset lifecycle management (Alizadehsalehi and Yitmen, 2021; Ogunseiju *et al.*, 2021).

AI and DLT hold great promise for resolving problems that we face today: building trust in contracts, extending the life and getting more efficient operation of our existing built infrastructure and fair sharing of scarce resources in construction – which has traditionally been perceived as fragmented and adversarial. As the world faces sustainability and resource challenges, the research landscape evolves. The recent move towards online activity, accelerated by the COVID-19 pandemic and ensuing restrictions on physical movement, has underlined the need to build resilient digital networks. Blockchain, smart contracts and deep learning are fast developing technologies with great potential for good in the construction industry. It is hoped that this special issue will act as a primer for those researching these technologies.

Deep learning technology is a machine learning technology based on a "neural network" that effectively tries to mimic the brain. It has the potential to automate construction tasks – initially, the research focuses on relatively simple tasks, but in time and the technology is developed and trust built in this concept, more and more complex tasks will be able to be automated. For example, this technology could connect and control sensors through the IoT, help predict and manage risk on a construction site, identify and classify structural cracks in pavements and buildings and monitor construction progress, as explored in this special issue. There are 12 papers cherry-picked in this special issue to cover the abovementioned challenges and present innovative solutions based on real-life industry-based projects.

Hajirasouli *et al.* (2022) presented a comprehensive review, critical analysis and implications of the AR application and implementation in the construction industry arena and demonstrated the gaps along with the future research agenda. They indicated that the application of AR could be most effective in the following four stages of a project lifecycle: design and constructability review session; construction operation; construction assembly; and site management and maintenance, including site management and inspection and defect.

Sadeghineko and Kumar (2021) firstly outlined the framework previously developed for generating semantically enriched three-dimensional (3D) retrofit models. Secondly, they proposed a framework focusing on facilitating the information exchange and interoperability for existing buildings. Finally, semantic Web technologies and standards, such as Web Ontology Language and existing AEC domain ontologies, were used to enhance and improve the proposed framework. They evaluated the proposed framework by implementing an example application and the resource description framework data produced by the previously developed framework. The proposed approach contributes to the asset/facilities management (FM) domain. It will be of interest to various FM practices for existing assets, such as the building information/knowledge management for design, construction and O&M stages of an asset's life cycle.

Reyes Veras *et al.* (2021) addressed the level of awareness identified as the first step towards implementing the big data concept within the construction industry in the

Dominican Republic. They adopted a qualitative methodology, conducting 21 semi-structured interviews using situational awareness. As a result, four levels of awareness were developed based on Endsley's situation awareness model. The results showed that nearly 95% of the interviewees had either no knowledge or very basic awareness of the big data requirements or intermediate awareness. Still, only 5% had applied big data concepts in the construction industry. The study highlighted the gaps in the understanding and implementation of big data concepts in the construction industry. This paper established the need to develop continuous professional development programmes for construction professionals and a need to update the curriculum in construction-related education.

Nguyen *et al.* (2021) developed a building BIM-based mixed reality (MR) application to enhance and facilitate the process of managing bridge inspection and maintenance works remotely from the office. They targeted two key issues: creating a BIM-based model for bridge inspection and maintenance and developing this model in an MR platform based on Microsoft Hololens. They ascertained that the inspection information management could be enhanced because the inspection database can be systematically captured, stored and managed through BIM-based models. Furthermore, they claimed that the inspection information in MR environment had improved the interpretation, visualisation and visual interpretation of 3D models because of intuitively interactive real-time simulation.

Getuli *et al.* (2021) argued that health and safety training via immersive VR in the construction sector is still limited to a few early adopters, in spite of the benefits it could provide in training effectiveness. Furthermore, they addressed the lack of an organised digital content asset dedicated to producing VR site scenarios that emerged as one of the most limiting factors for implementing BIM and VR for construction workers' safety training. Therefore, a dedicated site object library was proposed to improve this critically time-consuming process. This study defines a structured library of construction site objects dedicated to producing VR scenarios for safety training comprising 168 items, implemented and validated.

Jacobsen *et al.* (2021) asserted that accidents resulting from poorly planned or set up work environments are a major concern within the construction industry. They claimed that while traditional education and personnel training offer well-known approaches for establishing safe work practices, serious games in VR are increasingly being used as a complementary approach for active learning experiences. They advocated that by taking full advantage of data collection and the interactions possible in the virtual environment, the education and training of construction personnel improve by using non-biased feedback and immersion. This research presents a framework for the generation and automated assessment of VR data. Encouraging results on the participants' experiences are presented and discussed based on actual needs in the Danish construction industry. Finally, an outlook presents future avenues towards enhancing existing learning methods.

Elghaish *et al.* (2021b) argued that the massive number of pavements and buildings coupled with the limited financial and human inspection resources to detect distress and recommend maintenance actions lead to rapid deterioration, decreased service life and lower level of service and increased community disruption. They provided a state-of-the-art literature review concerning deep learning techniques for detecting distress in both pavements and buildings, research advancements per asset/structure type and future recommendations in deep learning applications for distress detection. The results showed that the utilisation of deep learning to detect pavement cracks is advanced compared to assessing and evaluating the structural health of buildings. They argued that there is a need for studies that compare different convolutional neural network models to foster the development of an integrated solution that considers the data collection method.

Elghaish *et al.* (2021a) asserted that digital construction transformation requires using emerging digital technology such as deep learning to automate implementing tasks. Therefore, they evaluated the current state of using deep learning in the construction management tasks to enable researchers to determine the current solution's capabilities and find research gaps to carry out more research to bridge revealed knowledge and practice gaps. Firstly, they conducted a scientometric analysis for 181 articles to assess the density of publications on different topics of deep learning-based construction management applications. After that, a thematic and gap analysis was conducted to analyse the contributions and limitations of key published articles in each area of application. The scientometric analysis indicated four main applications of deep learning in construction management: automating progress monitoring, automating safety warnings for workers, managing construction equipment and integrating IoT with deep learning to collect data from the site automatically. The thematic and gap analysis refers to many successful cases of deep learning in automating site management tasks; however, more validations are recommended to test developed solutions. Finally, they suggested that additional research is required to consider practitioners' and workers' perspectives to implement existing applications in their daily tasks.

Taniguchi *et al.* (2022) proposed a method for vulnerable pedestrians to visualise potential obstacles on sidewalks. They argued that currently, barrier-free maps and street-view applications could be used by wheelchair users to check possible routes and the surroundings of their destinations in advance. However, they noted that identifying physical barriers that threaten vulnerable pedestrians *en route* is often difficult. This study used photogrammetry to create a digital twin of the existing walking space's 3D geometry by collecting photographic images taken on sidewalks. This approach allows for high-resolution digital elevation models of the entire physical sidewalk surface from which physical barriers such as local gradients and height differences can be detected by uniform image filtering. Furthermore, the method can be used with a web-based data visualisation tool in a geographical information system, permitting first-person views of the ground and accurate geolocation of the barriers on the map.

Talebi *et al.* (2022) mentioned that emerging technologies for the inspection of bridges have remarkably increased. They noted in particular that non-destructive testing (NDT) technologies are deemed a potential alternative for costly, labour-intensive, subjective and unsafe conventional bridge inspection regimes. Therefore, they developed a framework to overcome the limitations of conventional inspection regimes by deploying multiple NDT technologies to carry out digital visual inspections of masonry railway bridges. A digitally enhanced visual inspection framework was developed by using complementary optical methods. The study claimed that the new approach requires fewer subjective interpretations compared to the conventional inspection regimes because of the additional qualitative and quantitative analysis. It was also noted that the application was safer and needed fewer operators on site, as the actual inspection can be carried out remotely.

Elghaish *et al.* (2022) explored the emerging relationship between I4.0 digital technologies and the construction industry's gradual transition into a circular economy (CE) system to foster the adoption of CE in the construction industry. They conducted a critical and thematic analysis of 115 scientific papers and revealed a noticeable growth in adopting digital technologies to leverage a CE system. They also developed a conceptual framework to show the inter-relationship between different I4.0 technologies to foster the implantation of CE in the construction industry. They argued that the coalescence of different technologies is highly recommended to enable tracking of building assets' and components' (e.g. fixtures and fittings and structural components) performance, which enables users to optimize the salvage value of components by reusing or recycling them just-in-time and extending assets' operating lifetime. Finally, they asserted that circular supply chain management must be adopted for both new and existing buildings to realise the industry's CE ambitions. Hence, they advocated that further applied research is required to foster CE adoption for existing cities and their infrastructure.

Rashidi *et al.* (2022) advocated the growing popularity of deep learning and extended reality (XR) technologies in the built environment. They asserted that many research efforts had been dedicated to automating construction-related activities and visualising the construction process. Therefore, they investigated potential research opportunities in integrating deep learning and XR technologies in construction engineering and management. Based on strict data acquisition criteria, they presented a literature review of 164 research articles published in Scopus from 2006 to 2021. They concluded that the proposed research directions could be categorised into four areas, including

- realism of training simulations;
- integration of visual and audio-based classification;
- automated hazard detection in head-mounted displays (HMDs); and
- context-awareness in HMDs.

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