Editorial

Integration of Internet of Things with building information modelling (IoT-BIM)

The construction industry is inextricably linked to a country's economy because it provides infrastructure and buildings that generate national wealth, social equality and productivity performance (Owusu-Manu *et al.*, 2019). The industry is also one of the largest sectors of the global economy (Barbosa *et al.*, 2017; Opoku *et al.*, 2019), with construction-related spending accounting for 13% of the world's gross domestic product (GDP). The total annual revenue of the sector is estimated to be around US$10 trillion and is predicted to rise to US$14 trillion by 2025 (Hosseini *et al.*, 2021). Despite this, the construction industry has an unenviable reputation for being wasteful, unsustainable and a major pollutant (Brandão *et al.*, 2021), accompanied by unsatisfactory outcomes for project participants and wider society alike (Newman *et al.*, 2020; Nikmehr *et al.*, 2021). Construction productivity, in contrast to other sectors, has not grown over the last 30 years (Teicholz, 2013; Fathalizadeh *et al.*, 2021). Moreover, poor data management and information exchange inflate project delivery costs by an unnecessary 10–15% (Allen Consulting Group, 2010) while global headlines ubiquitously berate the industry for its poor and unabated safety and quality record (Alizadehsalehi and Yitmen, 2021; Ghodoosi *et al.*, 2021). These omnipresent challenges are further exacerbated by the trend for contemporary construction projects of increasing scale and complexity (Jafari *et al.*, 2021) alongside clients' project requirements for higher quality at a lower cost (Abbasianjahromi *et al.*, 2016).

To address these various challenges, the construction industry has begun to embrace digital technologies enshrined within the fourth industrial revolution (Industry 4.0) concept (Kumar *et al.*, 2020; Newman *et al.*, 2020). Adopting the Industry 4.0 concept has engendered a digital revolution in the workplace which seeks to transform traditional procedures and methods through automation (Ghosh *et al.*, 2020; Wong *et al.*, 2020). Integrating data and information on people and work processes across the entire asset life cycle (i.e. from conceptualisation to occupation or use) is a centrepiece of this initiative (Hosseini *et al.*, 2018; Chileshe *et al.*, 2019). Such data constitute the foundation upon which knowledge management within a learning organisation is based, and from this, emergent wisdom generated helps improve the sector's performance (Edwards *et al.*, 2021).

Building information modelling (BIM) is one of the technologies spearheading the shift to Industry 4.0 in the construction industry (Dudhee and Vukovic, 2021). The BIM market is projected to grow at a compound annual growth rate (CAGR) of 14.5%, from US$4.5 billion to US$8.8 billion over the period of 2020–2025 (Casasayas *et al.*, 2021). However, some have questioned the adequacy of using BIM in isolation, calling for the integration of BIM with other advanced technologies as a means of improving data management and information flows across projects (Hosseini *et al.*, 2021). BIM has the inherent capacity to embrace a coalescence of inextricably linked cyber-physical systems that fully monitor, control and automate the design, construction and facility management phases of a project's whole life cycle. The Internet of Things (IoT) is particularly suited as a complement to BIM applications, providing an effective platform for transitioning the construction industry towards Industry 4.0 (Ghosh *et al.*, 2020), moving it from a static, closed environment to a dynamic, web-based environment (Boje *et al.*, 2020). Despite the desirability of BIM-IoT integration, the

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scarcity of research in this field of science makes it difficult to evaluate the exact nature of this integration and how successful it could be.

This special issue is therefore specifically designed to breathe much needed technological modernity into contemporary BIM research, whilst simultaneously forging stronger linkages with the concept of IoT against a background of Industry 4.0. The collection of twelve carefully selected papers presented in this special issue extends knowledge beyond the current constraints of contemporary narrative where BIM and IoT are treated as isolated and loosely coupled technological innovations. In so doing, these papers provoke broader polemic debate and raise awareness of the potential to achieve IoT-BIM.

Hosseini *et al.* (2021), in their position paper, urge a progression beyond the current narrative of isolated BIM towards a broader perspective, where BIM is paired with other methodologies through the convergence of emerging technologies. They advocate a transition from BIM to the new concept of digital engineering (DE), where a coalescence of technological innovations is assembled around BIM. The exclusive focus should be shifted, they argue, from modelling at project level to achieving a smooth flow of data among various technologies at program and businesses levels of analysis, thereby engendering new operational insight and knowledge towards securing a competitive advantage.

Elghaish *et al.* (2021) advance the agenda of integrating various technological innovations as a route to tackle the omnipresent challenges that plague the construction industry. A specific focus is given to unmanned aerial vehicles (UAVs) and immersive technologies. In their conceptual paper, they provide a cogent picture of a UAV and immersive technologies application(s) landscape in the construction industry, highlight use cases and provide a way forward for the integration of these digital advancements into everyday construction procedures.

Santos and Abrishami (2021) also call for further technological innovation integration – a recurrent theme of this special issue. The authors exclusively focus on IoT and blockchain and explore the emergent synergies between them, and also with other technologies, methods and platforms like BIM. They advocate for the creation of an environment to act as a single point of connection among all digital technologies adopted. The authors describe each of these technological innovations as a layer in their framework, to be consolidated into a multi-layered central depository that is hinged around BIM.

Oke and Arowoiya (2021) also advance the agenda of technology integration. They use a survey questionnaire to elucidate upon the perception of quantity surveyors, land surveyors, builders, architects and engineers on the maturity of applying IoT in the construction industry. Their findings reveal that IoT is mostly applied within the industry to BIM, construction management, remote usage monitoring, equipment services and repair, construction tools and equipment tracking. Moreover, the authors identify areas where IoT has permeated into procedures and processes and perhaps more importantly, where further implementation is needed.

The four abovementioned papers provide a holistic view and draw attention to some foundational aspects regarding the integration of various technologies in order to benefit construction projects. The remaining eight papers within this special issue however, present a detailed discourse on various applications and use cases of advanced digital technologies. Their focus is hence shifted from the question of "why?" to "how?" and "for what?" and in some greater detail. Of these, Ogunseiju *et al.* (2021) demonstrate a promising use case of applying a digital twin framework utilising wearable sensors to track the kinematics of workers' body segments. The authors proffer that ergonomic risk can be effectively communicated based on an augmented virtual replica within a worker's field of view. Palpable benefits derived from this advancement include reducing the ergonomic risks of the construction workforce through improved awareness.

Mahmoudi *et al.* (2021) showcase the enhancement of geotechnical surveys based on a spatial estimation of subsoil to customised data structures and integrating the ground models into digital design environments. The authors present a ground model consisting of voxels based on Revit-Dynamo to represent spatial uncertainties, employing the kriging interpolation method. Here, a real-life application of BIM in engineering is demonstrated, and its efficiency in identifying the geological risky locations of a model for further geological investigations is optimised.

Eiris *et al.* (2021) pinpoint the necessity for a visual representation of human decision-making processes during indoor building inspection flight operations with drones. They present their InDrone platform for collecting expert pilot data perceptions to characterise key pilot behaviours and decision-making patterns and trends for indoor building inspection flight operations. Their focus is on the concept of visual affordances to support the communication of human decision-making in indoor building inspection flights.

Johansen *et al.* (2021) present a method for automating management activities on construction sites, replacing manual procedures such as updating the completion update of activities. A novel location tracking sensor data collection method is used to ensure continuous data acquisition with minimal human involvement. A generic and non-site-specific knowledge base (KB) is created through domain expert interviews. They present an efficient approach with promising results, where simple data, domain knowledge and a logical reasoning system are used, instead of manually acquired or information-rich sensor data.

Xiong and Tang (2021) focus on the automation of dust monitoring in workplaces and effective mitigation measures for proactive dust control. They offer a novel methodological framework to overcome the challenges of insufficient imagery data for training computer vision algorithms to monitor construction dust. They present the details of a synthetic image generation method that incorporates virtual environments of construction dust for producing training samples. Their findings reveal that training dust detection algorithms (even based merely with synthetic images) can achieve acceptable performance.

Birgonul (2021) discusses the potential for enhancing energy efficiency and comfort maximisation through the use of existing BIM database and real-time information. A user-centric platform is proposed based on IoT that combines data about real-time indoor thermal information, real-time weather information and the user's body temperature. An occupant-operated tool is presented with details of its hardware, and software based on Revit-Dynamo. The value of the platform developed is the potential to operate the system without needing knowledge and skills of any BIM software or IoT.

Lamptey *et al.* (2021) shift attention to sustainability as a polemic issue that affects the construction industry. Their focus is Ghana, a setting lagging behind developed economies in advancing the agenda of sustainability. They call for further attention on developing green business models to facilitate a transition to a circular economy and a reduction in the carbon footprint of the construction industry. Various sources of information are introduced to drive awareness, understanding and adoption of green business models. The work culminates in a framework that integrates BIM and IoT into the components for green business models for construction firms.

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