Managing risk and complexity in construction projects with digital technologies

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Editorial

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Editorial for the Special Issue “Managing Risk and Complexity in Construction Projects with Digital Technologies”

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1. Introduction

The role of projects in creating the future [1] [2] as vectors of change for net zero [3], intermediators facilitating sustainability transitions [4] and aggregation mechanisms for digital transitions [5] has long been discussed in the project management studies. These conceptualisations frame project delivery as an enabler of sustainable development goals (SDGs) but also a possible threat to transition pathways. Construction projects are considered high-risk due to their technical complexity and interconnectedness with natural and socio-economic systems, creating uncertainty about their outcomes. Managing risk and complexity in construction projects is becoming increasingly crucial as projects grow in scale and significance. Narrow definition of risk in the face of deep uncertainty and oversimplified methods of risk assessment ignoring systemic risks lead to unrealistic management plans and create an illusion of controllability, which threatens not only the achievement of specific project targets but also the achievement of SDGs.

The rapid advancement of digitalization has been widely viewed as a pathway to a more efficient, sustainable, and resilient construction industry. Digital information and technologies have been argued to change the way projects are managed, organised, and delivered [6] [7]. Digital technologies (DTs) are transforming the industry to streamline and automate construction operations, project management tasks, and decision-making across the construction value chain, promising benefits such as cost and time savings and enhanced safety. The narrative surrounding DTs suggests that they significantly enhance predictability through improved data and knowledge management. The project management literature is rich in studies exploring and demonstrating DTs' potential uses in construction. However, there is limited research on the transformative power of DT for project risk management (PRM). Most recently, bibliometric analyses have been conducted to portray the accumulated knowledge in the PRM domain, and research gaps regarding the utilisation of DTs for risk management have been identified [8] [9] [10] [11]. PRM supported by DTs is sometimes denoted as intelligent RM [8] [9], ICT-driven RM [10] or digitised RM [11]. In this Editorial, we use “digitised PRM”, which emerges as a new mode of managing risk in the construction industry with the potential to change the way risks are perceived, assessed, and managed [11]. Within the context of digitised PRM, DTs are used to facilitate risk thinking, risk-informed decision-making, and automate RM tasks throughout a construction project’s life cycle and value chain.

In the Call for Papers, we highlighted that this Special Issue will investigate how digitised PRM may address current challenges regarding the management of risk and complexity in construction projects and invite papers that propose new perspectives, methods and DT applications that would contribute to a more resilient, sustainable and smart built environment. Suggested topics included applications of DT (e.g., BIM, IoT, AI) for better risk identification, assessment, management, and communication of risk, as well as perspectives on how DT potentially could change the way risk is conceptualised and managed, leading to new developments within the construction industry. This Special Issue explores how various DTs and methodologies are reshaping risk management in construction, drawing insights from the most recent studies and advancements. This editorial summarizes the contributions of 11 papers that responded to this call and were accepted for publication among more than 30 papers submitted. Each paper addresses innovative uses of DT to enhance RM and demonstrates digitised RM approaches and methods considering emerging trends in the industry, such as off-site construction and mega infrastructure projects and grand challenges, such as sustainability and resilience. Papers tackling complex undertakings (e.g., tunnels and coastal projects) and diverse risks, such as time-cost, technical, social, health and safety, and supply chain risks, and showcasing the versatile application of DTs in improving decision-making in construction projects are brought together. The DTs proposed in the Special Issue include Building Information Modeling (BIM), Digital Twins, Explainable Artificial Intelligence (XAI), Natural Language Processing (NLP), Internet of Things (IoT), Artificial Reality/ Virtual Reality (AR/VR), and blockchain, demonstrating how specific or integrated DTs support PRM. The research designs span from primary and secondary data collection to case studies, and they surface diverse perspectives from lean philosophy to systems thinking. The demonstrative applications of DTs come from different countries, such as the UK, USA, China, Brazil and Türkiye, providing innovative, practical applications. Papers also explore potential challenges of DTs, particularly AI, blockchain and digital platforms, which provide key insights into digital transformation pathways.

2. Contributions to this Special Issue

We categorised 11 papers into three categories considering the application domain and type/scope of the suggested use of DT as follows:

2.1. Managing Occupational Health and Safety (OHS) Risks

OHS is among the most widely studied application areas of DT in construction, as evidenced by the review conducted by [11]; this Special Issue is no exception.

IoT to Reduce Safety Vulnerability

Luo et al. (2024) explore safety vulnerabilities in Prefabricated Building Projects (PBPs) using IoT technologies and highlight the potential for advancements in health and safety risk management [A1]. Using the data collected from 280 respondents from prefabricated building enterprises in China via a questionnaire, the relationships among various safety risks, vulnerability and impact factors are assessed with partial least squares structural equation modelling. Social network analysis is conducted to quantitatively analyse the mitigation effects of IoT technologies on safety vulnerability. Findings show that workers' unsafe behaviours, high work pressure, and inadequate construction supervision significantly contribute to the formation of safety vulnerability in PBPs and IoT, such as sensors and auto-ID technologies, can mitigate these risks by improving compliance with safety regulations and fostering safety commitment among managers.

VR For Hazard Recognition

Another study on using DT for OHS risk management is from [A2]. Liu et al. (2024) utilise eye-tracking technology to explore health and safety risks, specifically the role of human attention in hazard recognition on construction sites. The study suggests that safety training should incorporate immersive tools like virtual reality (VR) for improved visual search strategies among workers. A lab experiment was conducted with 49 participants to obtain participants' eye movement data and empirically assess the effect of safety backgrounds and training considering different hazard recognition levels. Among the most interesting findings is that people educated in a related field of study demonstrate an advanced level of hazard recognition abilities, while safety certificates and construction-related work experience do not appear to have a significant impact.

BIM-based Decision Support System for Safety Risk Assessment

Yilmaz and Artan (2024) introduce a digital safety risk management system for coastal construction projects, highlighting the potential integration of real-time BIM and AI-driven analysis for managing safety risks [A3]. Authors argue that coastal construction projects with unpredictable and hostile conditions require collecting, visualising and utilising OHS data for project-level risk-based decision-making and long-term safety planning. A safety risk assessment tool was developed based on risk factors and requirements identified by a comprehensive literature review and field surveys with 49 experts. The proposed safety risk assessment prototype enables real-time and structured information flow from the site and integrates digital technologies such as BIM for visualisation for better decision-making. Testing and validation of the prototype were carried out in two coastal construction projects: Cesme Ilica Harbor Project and Balikliova Fisherman's Port Project in Turkiye. The prototype may act as an example of similar RM tools being developed for different domains and purposes.

2.2. Leveraging DTs for addressing risk and complexity

Six articles demonstrate the application of DTs for managing risk and vulnerability for different contexts and purposes.

4D BIM for Planning and Control

Bataglin et al. (2024) argue that interdependencies between off-site and on-site production create a source of complexity in engineer-to-order (ETO) industrial building systems [A4]. They interpret the role of slack, a widely used concept in lean construction philosophy, as a way to deal with project complexity and mitigate risk. They develop a framework of slack categories (managerial system, space, time, capacity, inventory, contingency plans, and inventory) and strategies (flexibility and redundancy) based on findings of a research study that involved two large size companies and two projects, a university campus and a warehouse project in Brazil. Research findings show that lean construction methods and digital technologies such as 4-D BIM can play a significant role in supporting the use of Slack and enhancing decision-making and transparency.

Digital Twins Towards Sustainability and Resilience

Papadonikolaki and Anumba (2024) explore the role of digital twins in supporting complex transition pathways to net zero (NZ) [A5]. They advocate using a systems thinking approach and causal loops in exploring the role of digital twins. As a result of findings from 53 interviews and two focus groups with DT experts in the UK, they highlight the role of digital twins in breaking down silos, collaboration across the construction supply chain and the need for a data-oriented approach in assessing the input, processing, and output of the digital twins. They discuss how individual (asset-level) digital twins can support NZ targets as well as a connected digital twin as a system of systems for addressing complexity and managing risk at technical, social and policy levels.

Integration of DTs for Supply Chain Management (SCM)

SCM also benefits from DT. Luo et al. (2024) highlight the role of BIM, IoT, Augmented Reality/Virtual Reality (AR/VR), and AI in mitigating supply chain vulnerabilities in PBPs [A6]. They identify critical stakeholders in the supply chain as major sources of vulnerability and demonstrate how digital technologies can be implemented to enhance cooperation across the supply chain, reducing vulnerability. The authors demonstrate how combining BIM, IoT, AR, VR, and AI can effectively support SCM in PBPs.

Digital Platforms to Explore Social Risks

Williams et al. (2024) explore how social media platforms, particularly Twitter, can intensify social risks in large infrastructure projects, using the case of the High-Speed Two (HS2) in the UK [A7]. Authors retrieve over 950 000 tweets regarding the project from 2013 to 2019, and use Latent Dirichlet allocation (LDA) to classify ten instances of online firestorms over this period, covering the project’s environmental impacts, legislative dynamics, budget and performance. Authors argue that by understanding the firestorm dynamics of Twitter and its impact on the organisation–community interactions, organisations can effectively navigate sociotechnical complexity, manage social risks and formulate proactive strategies to mitigate them.

Blockchain (BC) Technology for RM success

Demirkesen et al. (2024) explore the role of BC technology on the success of RM in construction projects. Using the findings from a comprehensive literature survey on potential applications of blockchain and RM success indicators, they designed a questionnaire to empirically test the impact of blockchain applications on RM success [A8]. A total of 103 responses were received from the questionnaire administered in the UK and US. Statistical analysis of findings with structural equation modelling confirmed blockchain's potential and relevance in RM applications. Findings demonstrate that BC may help avoid data management risks, such as data breaches, data fraud, and data loss, and help professionals better manage RM data, especially for large and complex projects where multiple stakeholders participate in sensitive data transactions. It is also noted that careful consideration must be given to practical issues such as which aspects of the RM process should be recorded on the blockchain, what data will be stored on and off the blockchain, and how work processes and human resources will be coordinated with the adoption of BC technology.

2.3. AI for Data-driven Risk Identification and Assessment

Extracting useful information from unstructured risk data through text mining methods, and developing ontologies and AI models for risk identification and assessment have grown over the last five years [11]. Three papers in this Special Issue present applications of data-driven risk management.

Developing an Ontology with Natural Language Processing (NLP)

Erfani et al. (2024) created a risk breakdown structure (RBS) using content analysis of public risk reports by state departments of transportation in the US [A9]. They tested its validity using project risk registers of transportation projects employing NLP to calculate semantic text similarity. The results showed that RBS covers almost 81% of the identified risks in the database of 70 major projects, which cover about 6000 individual risks. This very promising finding motivates a data-driven approach for risk identification to be used in practice using historical data. Similar RBS can be developed for other contexts and project types using the data-driven approach proposed by the authors.

Explainable AI (XAI) for Risk Assessment

Zhan et al. (2024) argue that the black-box nature of AI models makes it hard for decision-makers to understand and interpret the outputs and propose the utilisation of XAI [A10]. XAI is used to identify the critical factors influencing tunnel-induced ground settlement and test whether counterfactual explanations provide better support for risk-based decision-making using the San-yang Road Tunnel Project in Wuhan, China, as a test case. The results demonstrate that Kernel principal components analysis-based deep neural network model has a better prediction performance of ground settlement risk than the baseline model. Counterfactual explanations enable transparency and trust in AI-based risk models. The findings of this study can pave the way for forthcoming research on using XAI as a risk analysis method in construction projects and can help site managers, engineers, and tunnel-boring machine operators mitigate the risk of ground settlement in tunnelling projects.

Another study related to this case is [22]. In this paper, Luo et al. (2024) propose an explainable transfer learning approach to enable transparency in understanding the source domain data as an innovative method for data-driven risk assessment. Their approach comprises feature selection and space point clustering, construction of a similarity metric, and a stacked deep neural network model with selective transfer learning. Using the same case project, the San-yang Road Tunnel Project, the authors demonstrate that the proposed transfer learning approach performs better in predicting ground settlements. They also highlight how knowledge gained in one domain can be effectively transferred and adopted to another in the context of tunnel risk assessment. The authors recommend that users of the risk models should understand the data and structure of the prediction models to make sense of risk and develop successful mitigation strategies.

3. Reflections and The Way Forward

The Special Issue demonstrates that there is a vibrant research area on digitised PRM that uses alternative research designs from lab experimentation to real case applications which explore the benefits and challenges of using DTs for a variety of purposes, including the management of safety, sustainability and social risks as well as time-cost. While the past research focused extensively on identifying and predicting individual risks like cost and schedule overruns, more recent studies, including this Special Issue, have sought to utilise DTs to improve overall project delivery, supply chain and broad impacts [11]. Researchers do not only explore technicalities of the utilisation of specific technologies in practice but also utilise alternative ways of thinking and theoretical frameworks to hypothesise why and how DTs can be used in construction projects. This paves the way for an emerging research field on digitised PRM that would contribute to theory and practice. The demonstrative case studies presented in this Special Issue show that DTs can help the industry move away from simplistic risk identification and assessment methods such as risk matrices and checklists with subjective ratings towards data-driven AI-assisted methods, which are no longer fit for purpose given the emerging patterns of complexity and dynamic risk occurrence patterns [12]. Data-driven risk management has the potential to change the way we make sense of risks (as well as opportunities) and dynamic mitigation of adverse impacts throughout the project life cycle. As evidenced by various studies, including those in this Special Issue, DTs have the potential to improve efficiency within the supply chain, and enhance predictability and resilience in construction projects, which would be an essential step towards SDGs. The Special Issues demonstrates that the future of digitised PRM lies in harnessing digital integration to address emerging risks and sustainability transitions; however, applied research in this field is still scarce. The integration of DTs in addressing interdependencies between built, social and natural environments will be crucial in shaping the sustainable, resilient, and efficient construction industry of the future. Future research on digitised PRM must focus on human-centric studies to understand risk perceptions and behaviour as well as nature-centric studies, and adopt systems thinking to navigate the evolving risk landscape. The future outlook is a construction industry that harnesses DTs to proactively address and manage risks modelling projects as system of systems, supported by a research community that places human, nature and SDGs at the centre.

Another research direction would be towards secondary risks of DTs regarding technical issues such as interoperability, liability and security, as well as impacts on organisations and the industry. The Call for Papers for this Special Issue asked for perspective papers on expected changes in the ways risks will be managed and implications for the construction industry, such as innovative project delivery systems, partnerships and business models. There is still a need for research in this area that goes beyond projects and delves into business and strategic levels.

Appendix:

Related Articles

[A1] L. Luo, Y. Li, X. Wang, X. Jin and Z. Qin, "Supply Chain Vulnerability in Prefabricated Building Projects and Digital Mitigation Technologies," in IEEE Transactions on Engineering Management, vol. 71, pp. 10686-10698, 2024, doi: 10.1109/TEM.2023.3272585.

[A2] P. Liu, C. Zhang, D. Arditi, H. Li and S. Demirkesen, "Using Eye-Tracking Technology to Assess the Effect of Daily Safety Training on Hazard Recognition Skills," in IEEE Transactions on Engineering Management, vol. 71, pp. 8548-8561, 2024, doi: 10.1109/TEM.2024.3367230.

[A3] D. I. Yilmaz and D. Artan, "An Occupational Safety Risk Management System for Coastal Construction Projects," in IEEE Transactions on Engineering Management, doi: 10.1109/TEM.2024.3369550.

[A4] F. S. Bataglin, C. T. Formoso and D. D. Viana, "Slack Categories for Managing Risks in the Delivery and Assembly of Engineer-to-Order Prefabricated Building

Systems," in *IEEE Transactions on Engineering Management*, vol. 71, pp. 14032-14045, 2024, doi: 10.1109/TEM.2024.3436563.

[A5] E. Papadonikolaki and C. J. Anumba, "Mapping the Complexity of Net Zero Transition Through a System of Digital Twin Systems," in IEEE Transactions on Engineering Management, vol. 71, pp. 13949-13962, 2024, doi: 10.1109/TEM.2024.3428641.

[A6] L. Luo, S. Hu, K. Chen, Y. Liu and C. Z. Li, "Exploring Safety Vulnerability in Prefabricated Construction and Mitigation Effects of Internet of Things," in IEEE Transactions on Engineering Management, vol. 71, pp. 8531-8547, 2024, doi: 10.1109/TEM.2024.3378840.

[A7] N. Williams, J. Ninan and Y. H. Kwak, "Online Firestorms in Twitter: Exploring Risks to Large Infrastructure Projects From Digital Communities," in *IEEE Transactions on Engineering Management*, vol. 71, pp. 13963-13974, 2024, doi: 10.1109/TEM.2024.3432712.

[A8] S. Demirkesen, A. Tezel, F. Uysal and Z. Ozturk, "Investigating the Impact of Blockchain on Project Risk Management Success: A Structural Equation Model," in IEEE Transactions on Engineering Management, vol. 71, pp. 8356-8368, 2024, doi: 10.1109/TEM.2024.3371057.

[A9] A. Erfani, Q. Cui, G. Baecher and Y. H. Kwak, "Data-Driven Approach to Risk Identification for Major Transportation Projects: A Common Risk Breakdown Structure," in IEEE Transactions on Engineering Management, vol. 71, pp. 6830-6841, 2024, doi: 10.1109/TEM.2023.3279237.

[A10] J. Zhan, W. Fang, P. E. D. Love and H. Luo, "Explainable Artificial Intelligence: Counterfactual Explanations for Risk-Based Decision-Making in Construction," in

IEEE Transactions on Engineering Management, vol. 71, pp. 10667-10685, 2024, doi: 10.1109/TEM.2023.3325951.

[A11] H. Luo, J. Chen, P. E. D. Love and W. Fang, "Explainable Transfer Learning for Modeling and Assessing Risks in Tunnel Construction," in IEEE Transactions on Engineering Management, vol. 71, pp. 8339-8355, 2024, doi: 10.1109/TEM.2024.3369231.

References

[1] H. Huemann and G. Silvius. “Projects to create the future: Managing projects meets sustainable development”. *International Journal of Project Management*, 35(6), 1066–1070, 2017.

[2] J. Whyte and L. Mottee, “Projects and interventions. International Journal of Project Management”, 40(8), 934-940, 2022.

[3] M. Terenzi, G. Locatelli, and G.M. Winch, “Projects as Vectors of Change: A Transition Toward Net-Zero Sociotechnical Systems” . *Project Management Journal*, *0*(0), 2024, https://doi.org/10.1177/87569728241270578

[4] K. Gasparro, V. Zerjav, E. Konstantinou, and C.B. Casady, C. B. “Vanguard Projects as Intermediation Spaces in Sustainability Transitions”. *Project Management Journal*, *53*(2), 196-210, 2022.

[5] G. Papachristos, E. Papadonikolaki, and B. Morgan, “Projects as a speciation and aggregation mechanism in transitions: Bridging project management and transitions research in the digitalization of UK architecture, engineering, and construction industry”. *Technovation*, 132, 102967, 2024.

[6] E. Papadonikolaki, I. Krystallis, and B. Morgan, “Digital technologies in built environment projects: Review and future directions”. *Project Management Journal*, *53*(5), 501–519, 2022.

[7] J. Whyte “How digital information transforms project delivery models”. *Project Management Journal*, *50*(2), 177–194, 2019.

[8] L. Chenya, E. Aminudin, S. Mohd, and L. S. Yap, “Intelligent risk management in construction projects: Systematic literature review”. *IEEE Access*, *10*, 72936–72954, 2022.

[9] J. Hao, J. Li, and D. Wu, “Bibliometric analysis of risk science from 1996 to 2021: Insights and implications”. *Journal of Risk Research*, *26*(5), 485–501, 2023.

[10] X. Zhao, “Construction risk management research: intellectual structure and emerging themes”. *International Journal of Construction Management*, *24*(5), 540–550, 2023 https://doi.org/10.1080/15623599.2023.2167303.

[11] I. Dikmen, H. Erol., G. Atasoy and M. T. Birgonul, “Digitised construction project risk management: Content analysis of the past and implications for the future research agenda”, EURAM 2024.

[12] A. Qazi and I. Dikmen, "From Risk Matrices to Risk Networks in Construction Projects," in *IEEE Transactions on Engineering Management*, vol. 68, no. 5, pp. 1449-1460, 2021