Industry 4.0 Solutions for Building Design and Construction

A Paradigm of New Opportunities

FARZAD POUR RAHIMIAN, JACK STEVEN GOULDING, SEPEHR ABRISHAMI, SALEH SEYEDZADEH, AND FARIS ELGHAISH

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This book provides in-depth results and case studies in innovation from actual work undertaken in collaboration with industry partners in Architecture, Engineering, and Construction (AEC). Scientific advances and innovative technologies in the sector are key to shaping the changes emerging as a result of Industry 4.0. Mainstream Building Information Management (BIM) is seen as a vehicle for addressing issues such as industry fragmentation, value-driven solutions, decision-making, client engagement, and design/process flow; however, advanced simulation, computer vision, Internet of Things (IoT), blockchain, machine learning, deep learning, and linked data all provide immense opportunities for dealing with these challenges and can provide evidence-based innovative solutions not seen before. These technologies are perceived as the "true" enablers of future practice, but only recently has the AEC sector recognised terms such as "golden key" and "golden thread" as part of BIM processes and workflows.

This book builds on the success of a number of initiatives and projects by the authors, which include seminal findings from the literature, research and development, and practice-based solutions produced for industry. It presents these findings through real projects and case studies developed by the authors and reports on how these technologies made a real-world impact.

The chapters and cases in the book are developed around these overarching themes:

- BIM and AEC Design and Optimisation: Application of Artificial Intelligence in Design
- BIM and XR as Advanced Visualisation and Simulation Tools
- Design Informatics and Advancements in BIM Authoring
- Green Building Assessment: Emerging Design Support Tools
- Computer Vision and Image Processing for Expediting Project Management and Operations
- Blockchain, Big Data, and IoT for Facilitated Project Management
- BIM Strategies and Leveraged Solutions

This book is a timely and relevant synthesis of a number of cogent subjects underpinning the paradigm shift needed for the AEC industry and is essential reading for all involved in the sector. It is particularly suited for use in Masters-level programs in Architecture, Engineering, and Construction.

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A paradigm of new opportunities

1.1. Introduction

One of the main reasons this book came to fruition was in part inspired by frustration and in part driven by a collective soliloquy of wanting to present readers with a rich picture of golden opportunities. Frustration in this sense relates to the way through which Architecture, Engineering, and Construction (AEC) has responded to change (particularly over the last 50 years), where, for example, several global reports have repeatedly mentioned that AEC needed to change. Key report recommendations have included several issues, from industry fragmentation through to the need for higher skills, improved quality, enhanced performance and productivity, better value, tangible progress in innovation, improved communication and integration, and the need for more meaningful collaborative relationships. Arguably, this list could be extended almost *ad infinitum*; however, an interesting point to note here is that several of these reports have attempted to compare the performance of the sector against others, such as automotive, aerospace, engineering, healthcare, and manufacturing – all of which seem to have performed significantly better than AEC. The question is why? Whilst this book does not seek to provide solutions to this specific question *per se*, it does open debate in several important areas, with a view of challenging the current perception and status quo (in the hope that this will inspire change). For example, the global AEC geospatial market is expected to reach US$12.26 trillion by 2023 (Narain, 2020). This is not only tangible and significant, but this also offers AEC a unique opportunity to step beyond introspection, to an industry that fervently aspires to continually evolve as new industry leaders and pioneers.

It is acknowledged from the outset that this journey may not be easy. Moreover, it would be rather naïve of the authors to focus on all issues and challenges facing the industry. That being said, we had to start somewhere; collectively, we decided to focus on some of the underpinning themes and challenges relating to design. In this respect, design-related issues have been seen as causal contributors to many of these high-level challenges. These issues include (but are not limited to): communication and information processing, technology adoption, collaboration, integration, automation, interoperability, labour, and skills (Egan, 1998; Peansupap & Walker, 2005; Goulding & Pour Rahimian, 2019; Fruchter et al., 2016; Day, 2019; Pour Rahimian et al., 2019; Elghaish et al., 2020; Leon & Laing, 2021). These factors are not only fundamental and integral (throughout the project lifecycle), but they also have a direct or indirect knock-on effect with many other support services.

To address some of these issues (particularly within the context of design), this book seeks to raise awareness by presenting several practice-based solutions, with the expressed aim of unlocking AEC's digitalisation potential. For example, whilst client organisations are predominantly seen as the core initiators of the design process, they (arguably) often tend

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to lack knowledge and awareness needed to inform or shape the professional capability to deliver real value (CLC, 2018). This lack of understanding or wider appreciation of nuance influences the project lifecycle from day one – from conceptual design through to handover, maintenance, and deconstruction. This is a significant challenge to address, especially as projects seem to be increasingly more complex. Several solutions have started to enter the market, from advanced virtual reality–based collaborative technologies (Pour Rahimian et al., 2019)to artificial intelligence–based optimisation (Pilechiha et al., 2020) and data-driven decision support systems (Seyedzadeh et al., 2019). These solutions offer AEC significant opportunities – enabling (or empowering) them to not only unlock their digital potential to improve performance and capability, but also leverage better value throughout the whole process (McKinsey, 2017). In fact, significant markets have now started to leverage success by unlocking this digital potential (Herr & Fischer, 2019; Ahuja et al., 2020).

Part of the journey of unlocking AEC's digital potential involves moving towards Industry 4.0. This may seem a little daunting to most; however, this is seen as the way forward – a real paradigm shift for the sector – a transformative journey which more purposefully engages new ways of thinking, where digital technologies converge to provide significant advantages. Whilst this transition to Industry 4.0 may not be easy, it is encouraging to note that many AEC entities have made significant progress to achieve this goal (Maskuriy et al., 2019; Alaloul et al., 2020). This paradigm shift is not only significant and transformative, but it is starting to open up many new revenue streams and divested services for AEC (Figure 1.1);

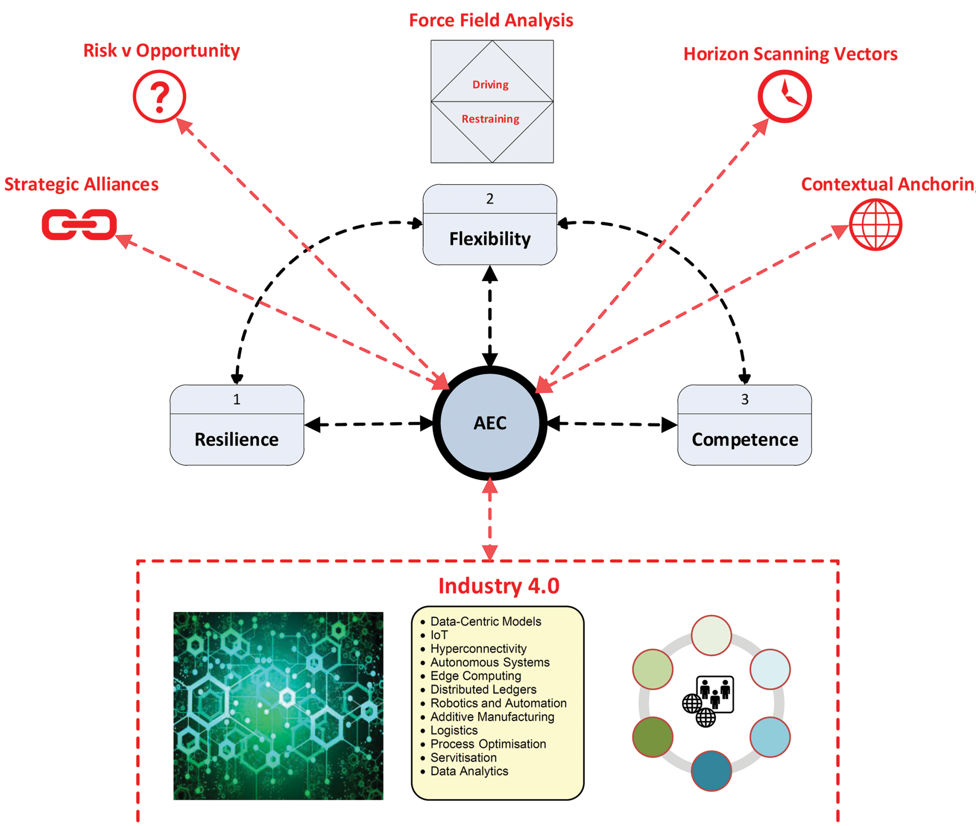

Figure 1.1 AEC and industry 4.0 transformational opportunities

however, a caveat of caution needs to be raised at this juncture. This transition is not free; it comes at a cost. This 'cost' requires conjoined thinking and a willingness (acceptance) to embrace change, not just at the individual or organisational level, but also at the macro level (involving the whole sector and supply chain). In this respect, fragmentation and siloed positioning needs to be replaced by conjoined processes and 'digital coalition'.

This not only highlights the need to become more connected, dynamic, and customer-centric, but more importantly, mechanisms through which future AEC business will need to operate. This includes the need to think about new business strategies and models – from design to procurement and delivery, even the way goods are produced and delivered. Successful companies will be those that unleash their true potential, using business models that drive innovation and deliver evidence-based value. Those that do not do this will (more than likely) fall by the wayside. Therefore, AEC organisations will need to be highly competitive (perhaps more so than they are already), using factories and warehouses (physical and virtual) to leverage economies of scale (and expertise) to become much more streamlined, agile, and efficient. In doing so, they will be able to establish several new services and opportunities, especially through the deployment of cloud computing, big data, visualisation, artificial intelligence, machine learning, the internet of things, blockchain, etc. Data will undoubtedly be seen as the main asset –not only to inform decision-making, but also to drive innovation and facilitate continuous improvement. This will also enhance customer-experience analytics, providing new end-to-end services and servitisation opportunities; where, for example, significant growth-driven potential has already been evidenced in other sectors. In summary, the inertia underpinning Industry 4.0 provides AEC with many powerful opportunities to explore, nurture, and exploit. Some of these opportunities are presented throughout the following chapters.

1.2. Thematic overview of chapters

Chapter 2: AI-based architectural design generative BIM workspace for architectural design automation

This chapter concerns the integration and automation of design. It presents and builds upon a theoretical foundation that supports process integration (particularly at the conceptual design stage), including design representation, cognition, translation, and design integrity. Building Information Model (BIM) applications supporting design automation are explored, including their use in whole design integration. The concept of advanced Generative Design (GD) is presented as a significant opportunity to enhance the design experience. Core BIM and GD facets are identified and mapped into a generative BIM (G-BIM) framework for prototype development. This prototype was evaluated through multiple projects and scenarios, the results from which culminate in a valuable set of rubrics for further exploitation (cf. supporting the conceptual design stage using GD). Specific contribution also highlights the capabilities and opportunities provided through this prototype, from advanced collaborative features to the generation of optimised (and more purposeful) design solutions.

Chapter 3: Towards intelligent structural design of buildings: a BIM solution

This chapter outlines the challenges of design coordination and integration, especially between architectural and structural engineering practices. These different design approaches are examined, along with different BIM solutions and collaborative platforms. The main concept presented here is the need to provide automated synergy (given that these two disciplines are co-dependent). In this respect, these two approaches are examined in detail, noting the requirements needed for linking architectural models with structural engineering models. In doing so, an automated procedure and proof of concept is presented for discussion. This explores an automated approach that engages computational systems and toolsets into a solution that 'binds' architectural and structural models (for tall buildings). This prototype automatically generates, updates, and produces alternatives for structural models based on inputs from the architectural model. Findings highlight that solution generation can provide much richer optimum designs to meet set criteria. This work is acknowledged as being one of the first of its kind to automatically generate optimised structural design solutions based on architectural models.

Chapter 4: BIM and design for manufacturing and assembly

This chapter discusses the current state of integration of Design for Manufacturing and Assembly (DfMA) and BIM within AEC throughout the whole project lifecycle. The rationale of this chapter was to evaluate recurrent challenges such as low productivity and poor quality, high variances in predictability, along with greater building performance and energy use control. In doing so, a conceptual framework and BIM library for offsite manufactured components is presented for discussion. This work engaged a case study to demonstrate the implementation of BIM and DfMA. Findings present new and novel approaches for delivering synergy, highlighting the need to focus on the development of a new digital manufacturing–driven industry. This work also acknowledges the need for continuous improvement, highlighting a number of opportunities for exploitation, especially using a BIM-based DfMA approach to improve consistency and standardisation, reduce design discrepancies, reduce waste, improve safety, increase design flexibility, and maximise end-user value.

Chapter 5: Virtual reality–based cloud BIM platforms for integrated AEC projects

Chapter 5 reflects on the need to integrate collaborative design teams' project data to help coordinate the design, engineering, fabrication, construction, and maintenance of various trades (to facilitate project integration and interchange). In doing so, it evaluates a number of opportunities, including the implementation of BIM Level 3 (Cloud) as an innovative way of further enhancing the design, management, and delivery processes. This work proffers the need for change from 'traditional' approaches to those aligned with Integrated Project Delivery (IPD). This chapter also acknowledges that web-based platforms are particularly beneficial, as these are able to visualise, integrate, and share building components (in real time) and through geographically dispersed locations. A cloud-based virtual reality (VR) Construction Site Simulator was presented as a potential solution. This engaged a game environment supported by a web-based virtual reality cloud platform. Findings presented new insight and understanding into the development of training programs of this nature, particularly the use of the Unified Software Development Process and iterative phases of Elaboration, Construction, and Transition. Finally, this work offers new understanding and insight into the causal drivers and influences associated with successful decision-making design in non-collocated design teams, providing a stepping-stone for developing new relationship models in collaborative environments.

Chapter 6: XR-openBIM integration for supporting whole-life management of offsite manufactured houses

Chapter 6 advocates the need to understand the importance of integration from a granular level. In doing so, it critiques project integration across the AEC supply chain using offsite manufactured housing as an exemplar. This analysis included tools, technologies, and processes, and especially BIM and data models – noting that AEC needed to manage diverse project information. One of the major challenges in this area was interoperability, particularly the level of data compatibility, and how this affects collaboration and decision-making. This chapter argued that media-rich VR and augmented reality (AR) environments could help users better understand design solutions. It was proffered that a solution could be developed on the capabilities of openBIM and industry foundation class (IFC) schema, using the BIM server concept to provide concurrent multiuser engagement (with low-latency communication between applications). A prototype of an offsite manufactured integrated virtual showroom was presented for discussion. This exemplar used openBIM-Tango, BIM models, and data from IFCs. This enabled users to interact with these models though VR immersive and AR environments (including Google Tango-enabled devices). Findings highlight several new innovative approaches for interrogating data. It also presented wider AEC opportunities, noting that this concept could mitigate the need for advanced technical skills, as it allows decision-makers (with different skillsets or areas of expertise) to access and engage with data and information in a more accessible and meaningful way.

Chapter 7: A centralised cost management system: exploiting earned value management and activity-based costing within integrated project delivery

This chapter introduces the concepts of earned value management (EVM) and activity-based costing (ABC) within AEC. In doing so, it evaluates risk/reward sharing opportunities through IPD, advocating the need for a decentralised, automated, and secure financial platform for managing and controlling financial transactions. In pursuance of this goal, mathematical models for determining the three main IPD financial transactions were evaluated. This includes coding of reimbursed costs, profit and cost saving, and engagement of IPD smart contract functions. The development of this proof-of-concept prototype (Centralised Cost Management System) was validated through an IPD case project. Findings highlight the benefits of using this system to automate financial transactions, whilst also demonstrating several other advanced features. In summary, this work advocated the need for AEC to embrace IPD adoption as a means of resolving some of the existing financial challenges. Recommendations included the incorporation of technologies such as IBM's Blockchain Platform for IBM Cloud and Fabric v2.x for smart contract lifecycle management.

Chapter 8: Success factors driving cost management practices through integrated project delivery

This chapter evaluates the pivotal forces and concepts underpinning cost management practices in AEC. It promotes the need to support effective cost management practices, especially those that share cost data with all project stakeholders. Emphasis was placed on accuracy, timeliness, and transparency (to support governance and trust). From this focus, IPD was critically reviewed as a mode of project procurement, along with the application of cost management approaches and success factors underpinning these. This included the need for an integrated and resilient cost information system to support IPD. A questionnaire survey was conducted with leading IPD experts to identify challenges, priorities, and opportunities, especially factors driving the implementation of IPD. Findings revealed that ABC and EVM were particularly effective at identifying and appropriating costs. Moreover, that there was a greater need to develop these further in order to support accounting transparency. In pursuance of this task, the use of mathematical models could be generated to propagate equitable risk/reward distribution. Findings from this work endorse the role of BIM-enabled web-based management systems to not only enhance IPD-based cost management effectively but also encourage wider uptake.

Chapter 9: 4D BIM for structural design and construction integration

This chapter introduces the challenges of monitoring, inspecting, and evaluating work, particularly for concrete pouring. These issues were explored through literature, culminating in the need to support AEC with better monitoring/assessment measures, especially to support structural design, production processes, concrete pouring, integration, joint assessment, etc. This research observed that meticulous planning was required to achieve this goal, especially to ensure aesthetic and structural integrity (in order to mitigate structural defects and construction rework). Challenges included the need to manage several issues, not least design challenges, but also critical path dependencies and onsite operational constraints. In order to address these issues, a 4D BIM approach was presented as a solution. This used an automated concrete joint positioning (proof-of- concept) solution to help support design professionals and contractors. This engaged structural modelling information from Revit and spatial information on construction joints, linking these through Microsoft (MS) Excel and Matlab spreadsheets with Dynamo software. Findings presented significant benefits, including an automated system for optimising design solutions, a cost-effective and accurate methodology for addressing previous limitations, and a new way of designing construction joints and planning pours. These innovative solutions support the need for wider integration of structural design considerations with construction and site operational procedures. This novel application of BIM in structural engineering also highlighted how the different capabilities of various software applications could be integrated.

Chapter 10: BIM integrated project delivery: an automated earned value management–based approach

This chapter challenges current thinking on IPD, highlighting the need for robust and defendable systems to appropriate and manage project costs. In doing so, it presented a discussion on IPD and cost management practices used to determine the risk/reward ratio. This discussion included the concepts and application of EVM and ABC, especially in relation to supportive technologies such as BIM. It was proffered that AEC needed some form of solution that integrated IPD with BIM as an optimal approach for delivering construction projects. Acknowledging this knowledge gap, this chapter presented a bespoke model that could be used to exploit EVM – to structure the compensation approach in IPD (using ABC to optimise the cost structures). This innovative approach was expressly designed to exploit the capabilities of these techniques coupled with BIM to automate/optimise the process of IPD risk/reward sharing. Findings observed that the mathematical equations underpinning this risk/reward sharing approach could be used to strengthen IPD parties' relationships, especially through the EVM-Web grid, as this enabled project participants to track their costs more effectively. This research also suggested the need to incorporate future 4D/5D BIM platforms and developments with openBIM to further improve the accessibility, usability, and management of AEC digital data.

Chapter 11: Revolutionising cost structure within integrated project delivery: a BIM-based solution

Chapter 11 reflects on the cost structures underpinning IPD, highlighting the need to improve cost estimation, especially at the 'front end' of IPD projects (where project information is seldom fully available). This work explores several cost estimation approaches, methods, and tools currently used in IPD. In doing so, it presents a novel theoretical argument and new approach to enhance cost estimation. This approach incorporated target value design (TVD), ABC, and Monte Carlo simulation into an IPD cost structure within a BIM-enabled platform. A framework was developed to present the proposed methodology of cost estimation throughout all IPD stages. A case project was used to validate the practicality of this solution by comparing the profit-at-risk percentage for each party, using both traditional cost estimation and the proposed solution. Research findings highlighted the benefits of adopting such an approach as a workable solution for BIM–IPD integration. This produced reliable cost data from different sources and project delivery modes, noting that the use of BIM (as a means of developing a conceptual model to address client criteria) could enable costing professionals to build statistical models with higher levels of cost certainty and predictability.

Chapter 12: Dynamic sustainable success prediction model for infrastructure projects: a rough set–based fuzzy inference system

This chapter recognises the importance of being able to successfully implement sustainability in projects, particularly infrastructure projects. It acknowledges that whilst the definition of project success was subjective, it predominantly encompassed measures and criteria associated with time, quality, and cost. More importantly perhaps, it noted that several studies failed to address other success indicators associated with criteria, such as environmental compliance, building performance, client satisfaction, socio-political drivers, etc. To address this challenge, this study presents a decision support system (DSS) for evaluating and predicting project success against sustainability criteria. This used rough set theory (RST) for rules generation. The generated rulesets were filtered through a fuzzy inference system (FIS) to support the DSS. This tool was then tested and validated by applying data from a real infrastructure project. Research findings highlighted that the developed rough set fuzzy method was able to evaluate and predict project success through robust rulesets to support enhanced prediction. This tool also enabled decision-makers to dynamically evaluate and predict project success based on customisable sustainability criteria.

Chapter 13: Multi-objective optimisation to support building window design

This chapter investigates the concepts of configuring window systems design in office buildings, cognisant of such issues as energy performance, daylighting levels, visual comfort, etc. The need to produce better-quality evaluation tools to support the design process was highlighted. In this respect, a new multi-objective method of analysing and optimising the window system design process was presented for discussion. This system incorporated simultaneous consideration of multiple and conflicting design objectives, using rubrics based on the fundamental recognition that the process of optimising parameters on issues such as building energy loads via window system design can often reduce the quality of the view to outside (including the received daylight). This study developed a multi-objective method of assessment, using a reference room that was parametrically modelled against real climate data. A method of Pareto frontier and a weighting sum was applied for multi-objective optimisation to determine the best outcomes – ergo, one that balances design requirements and criteria. Findings present a new approach for quantifying the Quality of View in office buildings, one that balances energy performance and daylighting, thereby enabling and facilitating improved window design optimisation. This work provides decision-makers with a novel approach of window design evaluation based on performance criteria and desired outcomes.

Chapter 14: Artificial intelligence image processing for on-demand monitoring of construction projects

One of the continual challenges facing AEC is the need to monitor project performance. This chapter posits that whilst inspections and progress monitoring are a vital part of the process, in some instances, the actual process of comparing 'as-planned' with 'as-built' progress does not readily add any tangible intrinsic value to the process. It argues that for large-scale construction projects in particular, a better system is needed for monitoring and inspection. In this respect, a new framework and proof-of-concept was presented for discussion. This used AI-based Image Processing and Computer Vision for on-demand monitoring. This prototype also engaged ML, image processing, BIM, and VR, using the Unity game engine to integrate data from the original BIM models with as-built images. These were processed via various computer vision techniques, including object recognition and semantic segmentation (to identify different structural elements). Findings provide a unique insight into alternative approaches of monitoring and inspection through a 3D virtual environment. This prototype was proffered as being able to support project managers and the inspection team – to help them make better informed decisions, much quicker than through conventional approaches. Moreover, this work provides a technical exemplar for integrating ML with image processing approaches together with immersive and interactive BIM interfaces. The algorithms and programme codes presented could also help other specialists in different contexts/settings with issues of replicability.

Chapter 15: Digitalisation of Architecture, Engineering, and Construction: immersive technologies and unmanned aerial vehicles

This chapter investigates the concepts and applications of using Unmanned Aerial Vehicles (UAVs) and immersive technologies in AEC. In doing so, it presents a critical literature review of these areas and aligns key studies using meta-synthesis to focus on optimisation. This work examined immersive technologies and UAV technologies applications in order to evaluate and integrate these findings into a single context. The findings from this research were assessed and contextualised to AEC needs. Findings highlighted that whilst the uptake and use of UAVs and immersive technologies was steadily improving, there was still a greater need to accelerate these initiatives as part of the progress towards wider digital transformation. Several benefits and opportunities were discussed, showcasing potential applications of these technologies, noting the importance of integration. It was proffered that UAVs and immersive technologies could be used in conjunction with 4D BIM to assess project progress, undertake compliance checking of geometric design models, evaluate and control certain parts of construction projects remotely, undertake quality control, and help assess health and safety issues, etc. In summary, the opportunities presented were seemingly endless – with new avenues to explore, including thermal and acoustic sensors, links to developments in augmented reality (AR), mixed reality (MR), and BIM (including blockchain and distributed ledgers), all of which support AEC's transition to Industry 4.0.

Chapter 16: Optical code division multiple access–based sensor network for monitoring construction sites affected by vibrations

Chapter 16 presents a critical review on the need to engage effective and accurate sensors to monitor the structural health of large facilities in order to mitigate risk at the very early stages (before these risks develop further). In doing so, it evaluates a range of technologies and sensors currently deployed in AEC, specifically focussing on aspects such as vibration. From this study, literature highlighted the need to engage more accurate structural health-monitoring systems to support large-scale facilities such as modern high-speed railways and bridges. It was advocated that this required additional development in optical sensor networks (OSNs), as this could help mitigate challenges associated with conventional electric sensors (*cf*. their sensitivity to electromagnetic interferences); however, this chapter observed that existing fibre-optic infrastructures were not widely used by OSNs due to the lack of appropriate multiplexing techniques. Given this challenge, an Optical Code Division Multiple Access System (OCDMA)–based sensor network for monitoring construction sites affected by vibrations was developed and presented for discussion. This prototype supports vibration sensing of unequally distributed points, taking advantage of multiple wavelengths and spectral amplitude encoding optical code division multiple access (SAC-OCDMA) techniques. Findings highlighted that this prototype did not require traffic management or system synchronisation, and that this was resilient to performance degradation often caused by fibre non-linearities. These advantages were proffered as being particularly beneficial for AEC professionals wishing to improve their structural health monitoring systems' performance.

Chapter 17: Blockchain integrated project delivery: an automated financial system

This chapter evaluates the technologies and processes supporting IPD in AEC. In doing so, it advocated the need to incorporate more robust systems to support financial transactions, particularly concerning the appropriation of risk/reward sharing and deferral of parties' profit payments. Suggestions included the need to embrace some form of decentralised, automated, and secured financial platform, where project parties can monitor, control, and track financial transactions. In pursuance of this, blockchain technology was considered a viable solution, as it had the ability to discretely manage data transactions with a high level of fidelity and veracity. From this, a framework adopting blockchain technology for IPD projects was presented for discussion. This framework enabled core project team members to automatically execute financial transactions through IPD coding parameters of reimbursed costs, profit, and cost saving. This aligned to IPD smart contract functions. This proof-of-concept prototype was validated through an IPD case project and was presented for discussion. Findings highlighted significant improvements in control and monitoring, reinforced by BIM, the Hyperledger Fabric, and IBM Blockchain Platform free 2.0 beta. This prototype was acknowledged as being one of the first AEC frameworks to incorporate blockchain technology with IPD projects, with the express purpose of enabling core project team members to automatically execute financial transactions.

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