Archives of Computational Methods in Engineering (2021) 28:689–711
https://doi.org/10.1007/s11831-020-09455-9

ORIGINAL PAPER

Methodological-Technological Framework for Construction 4.0

F. Muñoz-La Rivera[1,2,3] · J. Mora-Serrano[1,2] · I. Valero[1,2] · E. Oñate[1,2]

Received: 29 April 2020 / Accepted: 18 June 2020 / Published online: 29 June 2020

Abstract

The construction industry has traditionally been characterised by the high diversity of its agents and processes, high resistance to change and low incorporation of technology compared to manufacturing industries. However, the construction sector is experiencing now a strong renovation process in methodology and tools due to the incorporation of the Building Information Modelling, Lean Construction and Integrated Project Delivery. Meanwhile, in production systems, "Industry 4.0" is a new paradigm that proposes automation, monitoring, sensorisation, robotisation, and digitalisation to improve production and distribution processes. In this context, some authors have proposed the concept of "Construction 4.0" as the counterpart of Industry 4.0 for the construction sector, although the methodological-technological implications are not clear. This research shows a methodological-technological framework adapted to the Architecture, Engineering, Construction, and Operations industry. This papers includes a detailed proposal for a reference frameworks and related technologies that could impact on this sector, responding to its complexities and specific challenges, such as the unique spaces for each work, which are difficult to standardise, arbitrary cost overruns and a productivity far below the average for other industries, increasing competitiveness and globalisation, as opposed to its traditionally local deployment, and an increasing demand to reduce the carbon footprint for all its activities.

1 Introduction

The Architecture, Engineering, Construction, and Operations (AECO) industry seems to be far behind the latest technological trends in other industries. Most of the production processes in the construction industry are traditionally manual or handicraft in nature, organised with simple management tools and low incorporation of technology [1]. This lack of automation explains productivity results far below from other industries, which is worrying in a relevant sector for the development of countries in terms of GDP, for the quality of spaces such as homes and offices and thus the well-being of people, and because that production uses large amounts of raw materials, with strong impact to the environmental sustainability and the circular economy [2].

✉ F. Muñoz-La Rivera
felipe.munoz@pucv.cl

1 International Center for Numerical Methods in Engineering (CIMNE), Barcelona, Spain

2 School of Civil Engineering, Universitat Politècnica de Catalunya, Barcelona, Spain

3 School of Civil Engineering, Pontificia Universidad Católica de Valparaíso, Valparaiso, Chile

The traditional development of the construction industry can be attributed to the different characteristics that distinguish it, such as the fragmentation of its processes and actors, the low knowledge management, the routinely rigid activities, the sequential processes with strong dependencies, and an overlying culture of resistance to change [3]. Even so, in the last decade the construction industry has accelerated the implementation of important innovations for its management and design processes. The development of management philosophies such as LC that proposes continuous improvement and waste reduction in processes, IPD for contractual integration between all project participants [4] and BIM for the generation and management of multidimensional parametric models, together with the integration of all agents in the design, construction and operation processes [5], are making evolve the industry and bringing it into line with its counterparts in the automotive or aeronautical sector.

Industry 4.0 is a new paradigm for production systems and manufacturing companies, which could be extended to all other sectors. It can be summarised as follows:

(a) It is a combination of advanced production techniques with highly connected technological and intelligent management and operation systems at the level of organisation, assets, and personnel [6]

(b) It promotes the virtualisation of control and management systems in real-time, focusing on the collection of data from physical processes, for decision-making and learning, allowing flexibility, high levels of innovation and participation of all stakeholders [7].
(c) It incorporates the changing requirements of customers, taking into account their specific needs [8].
(d) It proposes methodological changes in the traditional operation of companies:

- *Vertical Networking* to react efficiently to changes in production demand
- *Horizontal Integration* to maximise the efficiency of product design and production processes
- Innovation *Through-Engineering* for innovation throughout the product life cycle, together with the use of
- *Exponential Technologies* to maximise processes and product quality [9, 10].

This requires high levels of integration, connectivity and real-time collaboration, along with the adoption of smart technology innovations that meet the demand for customised and sustainable products [11].

(e) The most used tools to achieve this fourth industrial revolution are: *Cyber-Physical Production Systems* (CPPSs), *Artificial Intelligence* (AI), *Massive data storage* and *analysis technologies* (Big Data), *Data management and security* (Blockchain), *sensors* (Internet of Things, IoT), *Digital Twins* (DT) and human–computer interaction (HCI) [12].

Many productive sectors have already begun to incorporate most of these elements of Industry 4.0. The manufacturing industry is the most advanced, with highly automated processes, which seeks higher levels of efficiency, optimises its processes and responds to the changing and specific requirements of modern consumers [13].

We can consider the term Construction 4.0 as the response of the construction sector for the adoption and deployment of Industry 4.0 at the building site. Indeed, Construction 4.0 proposes to automate and digitise the design and construction processes, with a strong component of real-time data capture and the incorporation of sensors in the on-site construction processes, to optimise time and costs, quality control and worker safety [14]. Actually, some technologies of Industry 4.0 have already been tested and deployed in construction, obtaining some promising but partial results, so currently the implementation of Construction 4.0 is not yet a reality. BIM shows a great potential to provide a global framework and to act as catalyst to drive a two-way collaboration between digital data systems and real physical systems. Thus, since BIM models can be used throughout the whole life cycle of a project, this connection can be maintained over time, driving the implementation of Industry 4.0 in construction [15].

This work aims to generate a methodological-technological framework of Construction 4.0 as a counterpart to Industry 4.0, adapting its characteristics and principles to construction, in response to its specific problems and challenges. It develops a more specific context map to outline the roadmap and needed technologies towards reaching the benefits of Construction 4.0, warning about the complexities and challenges to achieve them. This goal can be formulated through the following research questions:

1. What are the characteristics, problems and challenges of the construction industry today?
2. What are the benefits, principles, features, attributes and technologies of the Industry 4.0?
3. How can we adapt the methodological and technological framework of Industry 4.0 to the particularities of the construction industry?
4. What is the methodological-technological roadmap to achieve Construction 4.0, according to its specific challenges?

2 Research Methodology

This research analyses the Industry 4.0 in order to explore its potential benefits for the construction sector and to propose a methodological-technological framework. The research follows a deductive research approach [16]. At the first stage, the differential characteristics and context of the construction industry is reviewed, focusing on its main problems and interactions. The principles, characteristics, attributes, and technologies of Industry 4.0 are also compiled, in the context of the requirements, benefits, and challenges of this specific industry, and lastly mapped to the characteristics of Construction 4.0. The literature review is carried out using the following sources: Web of Science, Scopus, technical manuals and international conferences. At the second stage, a methodological-technological framework for the sector is proposed by considering the attributes of Industry 4.0, the characteristics of construction industry and the applications of Construction 4.0. Finally, At the third stage, the challenges and complexities to implement Industry 4.0 in construction are identified. Figure 1 shows the workflow for the research methodology.

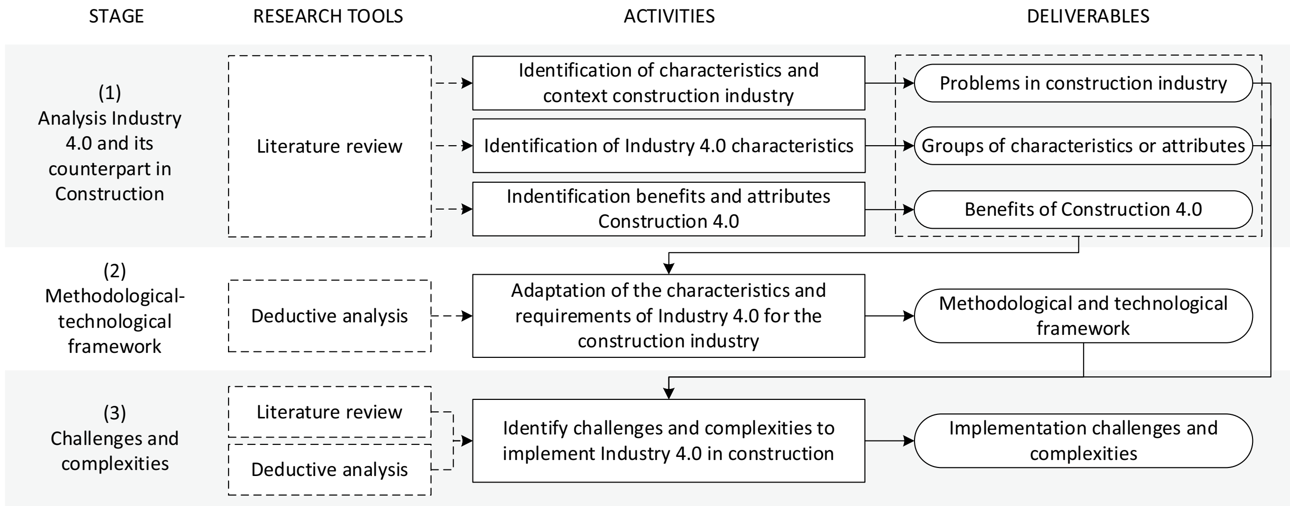


Fig. 1 Research methodology—workflow

3 Literature Review

3.1 Context of the AECO Industry

The construction sector plays a key role in the countries' economies, contributing an average of 6% world GDP and with significant growth projections. The development of construction industry is a relevant to improve quality of life of people [17], with direct influence on comfort and well-being at home or in workplaces, spaces where the majority of the population spends most of their daily life. Despite this important role, this industry has been characterised by low productivity indicators associated with time, cost and quality of projects, with special attention to the problem of costs overruns [18]. These indicators are the result of a fragmented supply chain, with multiple participants with different visions of the common project, entering at different times and maintaining limited interconnection, in a linear and waterfall workflow, and often working in repetitive tasks, to name a few of the problems [19].

The construction industry has some well-known problems, many of them quite permanent for decades but even though have not been yet successfully solved. These problems get more complicated as the number of processes and participants increase, that is, with the complexity of the projects at their different stages and with different approaches. Differently to other industries such as automotive or aeronautics, it is not possible to have an exact control of the manufacturing site, due to internal and external variables, but mainly because their products are unique and are located in weakly controlled open spaces. Fragmentation and the traditional culture of construction make also difficult changing processes [20]. Table 1 describes the main problems of the construction industry, focusing on its interaction dynamics.

The construction industry has also been characterised by focus its innovation in their traditional disciplines, for example the study of materials, surface coatings, wood, concrete and its derivatives, claddings, plastering, lighter and more resistant structures, but with a low level of adoption of information and communication technologies, especially if it is compared to industries (manufacturing, communications, among others), preserving traditional machinery and equipment with a strong semi-craft component in the implementation of projects.

In terms of management, the AECO Industry has been incorporating project management methodologies to improve productivity and efficiency for some years now. Worth noting the Lean Construction methodology, to promote continuous improvement in construction companies, minimising waste and maximising the value of final projects, through clear guidelines and planning and control systems [1]. Furthermore, the Building Information Modelling (BIM) methodology is one of the most important changes for the construction industry in the entire building life cycle beyond what specifically implies in terms of modelling software. BIM proposes the integrated management of the project by using parametric digital models and incorporating time, cost, environmental variables, security and facilities management [27]. This whole management of the project from several variables (multidimensional nD models) allows the incorporation of all the aspects of interest for all the agents of the construction, offering a complete vision of the project [28]. On the other hand, to solve the integration problems among the project's actors, Integrated Project Delivery (IPD) proposes a multi-part contract that incorporates all the project's

Table 1 Problems of the Construction Industry

Problem	Description
Cost overruns and delays	Delays and cost overruns are one of the most serious problems in the construction industry, with causes ranging from inherent technical difficulties to administrative and legal difficulties in carrying out tendering procedures. These over costs and delays distort the natural mechanisms of competitiveness as they make it significantly more difficult for different construction agents to foresee the proper fulfilment of the contract on time and in form [1]
High dependency and low interaction with suppliers	There is a high dependency of construction companies on their external suppliers (60–70% of total activities depending on them), a situation that can also be seen in other industries, such as manufacturing. However, in the AECO industry this dependence is not accompanied by systematic and methodological agreements of interaction or co-development. As a result, construction companies are conditioning their growth on te acquisition or incorporation of external innovation and learning [2]
Ineffective knowledge management	In construction companies, there are limited internal networks which does not allow for efficient access to information from previous projects and sometimes not even from the current project. Lessons learned from projects generally remain in individual teams and do not reach the entire organisation, especially technical information, actual budget and execution times, deviations, incident handling and on-site problem solving specific to the sector [2]
Focus on classic routine activities	Focus on repetitive processes without or with little innovation and no use of the learning of the different teams in the company due to a lack of collection and limited dissemination of information [1, 2]. There is not systematic treatment of global information both for each work and among the company's set of jobs over time
Extensive regulation limiting innovation	Construction projects operate in public and private regulated contexts, related to consumer protection, safety, and technical and environmental standards. Some regulations may be an obstacle to innovation when their original intention is distorted, specifically in the case of certain bidding processes that slow down and make the execution of the work more expensive, or the rigor of technical regulations that often lack the agility to adapt to changes in the sector [2]
High diversity of agents leading to fragmentation	Large and complex projects are carried out, built by temporary alliances of unequal companies, which in turn are involved in other similar projects. Each company involved has different equipment, profiles, training, culture and above all, interests while seeking to complete its activities in the shortest time possible, to be able to use its resources in other projects [21]. Fragmentation in the production process generates a hierarchy of processes with few long-term relationships between teams, generating conflicts between prime contractors and subcontractors and ultimately makes it difficult to integrate the supply chain [2]
Lack of skilled workers	The industry has a low-skilled workforce, with high job rotation, rising average age of employees, with little turnover. This is mainly because the sector is unattractive to young and trained workers (safety, wages, working conditions) [22]
Poor financial management	The industry has financial management problems. Problems in giving payments to the company, from public or private funds, which impact to the company's payments to employees and sub-contractors. This generates problems in the schedule, lack of credibility and bad practices in the construction [1, 22]
Poor asset management	The traditional value chain in the construction sector implies that its agents tend to concentrate their concern and responsibility in the current stage, either planning, construction, operations and maintenance, or demolition. The value progressively decreases working like this, compared to a process considering the complete construction cycle [2]
Design changes during construction	Changes in design during construction are recurrent, for different reasons: inconsistencies, owner modifications, regulatory changes, but above all, early tenders where the economic criteria prevails over the technical quality of the design and energy efficiency or environmental considerations, as second priorities, which cause alterations in the costs and schedule (due to timeouts, demolitions or reworks) [2, 22, 23]
Poor planning and programming	Planning and programming problems in the construction processes, which generate delays and reworks due to the lack of availability of material, equipment, people and other factors [24, 25]
High accident rate	The construction environment and its traditional interaction dynamics generate an accident-prone environment, with low trained and unmotivated personnel lacking a suitable safety culture. These problems are further increased by poor construction health and safety plans, along with well-established bad practices [26]

agents, sharing costs and benefits, and achieving an effective collaboration and a greater potential for the integration of these management methodologies and all the most recent new technologies [29].

3.2 Industry 4.0

Industry 4.0 refers to the fourth industrial revolution, a new level of organisation, control, and development of processes and products, throughout their entire life cycle. It applies technologies to successive generations of advanced tools and techniques for the optimisation of processes in a synchronised and efficient way [6]. It is considered the next phase in the digitalisation of industry, especially in the manufacturing sector, focusing on computing and data power, analytical and artificial intelligence capabilities, new forms of human–machine interaction and improvements in the transfer of digital operations to the physical world [30]. The new integrated manufacturing systems connect the physical elements with complex information technologies. The intelligent manufacturing provides a computer controlled flexible production process that can be adapted to individual customer needs, while maintaining high quality standards [31]. It also contributes to sustainable manufacturing and the circular economy by designing and developing new sustainable production systems, supply chains, sustainable products and policy in these areas [32].

They are six principles relevant to the implementation of Industry 4.0 [33–36]: (1) interoperability (successful connection between team members and production systems via IoT), (2) virtualisation (use of digital twins of industrial facilities for control and efficiency of production systems), (3) decentralisation (independent decision-making in the plant, aligned with the organisation's objectives), (4) real-time capability (real-time data collection and monitoring for efficient process management), (5) service orientation (ability of companies to identify customer needs in advance, to offer a service that exceeds their expectations) and (6) modularity (product architecture should be decoupled into subsystems with few direct dependencies, increasing production speed and the potential for rapid independent updating).

Industry 4.0 is categorised into four groups of characteristics or attributes: (1) Vertical Networking, (2) Horizontal Integration, (3) Through-Engineering and (4) Exponential Technologies. These categories allow us to group the "philosophical pillars" necessary for the proper functioning of Industry 4.0, in order to have a conceptual framework to better understand its complete meaning. In this way, the requirements and areas of Industry 4.0 can be understood at a high and medium level, with each category assigned to existing or future technologies linked to different kind of solutions that allow the achievement of the objectives [10, 34].

Vertical Networking of an intelligent production system uses a *Cyber-Physical Production System* (CPPSs) to efficiently react to changes in demand, failures and production specifications, due to the requirements moving from outside inside, while allowing specific productions according to differences between customers [10]. The physical and digital components are interconnected, working in different times and spaces, from the craft to the automated, aware of environmental changes [35]. A full automated management of production, maintenance, and integral management can be achieved by automatically connecting in real-time materials and resources with products [37]. Three types of solutions must be considered To achieve the objective of Vertical Networking: (1) IT Integration, (2) Data Analysis and Management, and (3) Cloud Computing [10, 34]. Achieving IT Integration requires to support good network connections and new IT solutions that are not fragmented, such as the integration of control systems, sensors, communication networks, and customer and business-oriented applications [33]. The industry 4.0 generates a large amount of data, implying information to be captured, processed, analysed and used efficiently, requiring a solid technological real-time data management and human support [38]. The systematic use of cloud computing will be essential to take advantage of all the existing digital services for the proper functioning of vertical networks and the other Industry 4.0 features. A large amount of data stored and processed requires a robust storage system, allowing access almost anywhere and by any of the interested parties, within or outside the network, allowing a global management, control, and analysis of the data [12].

The *Horizontal Integration* generates value-creating networks, integrated and optimised in time, easing transparency and flexibility to respond to failures and problems of systems and work teams, whether local or global, generating new business models and cooperation, optimising production in many different aspects [10]. The organisation in networks increases the capacities of the teams, achieving more innovations in the products and in a continuous improvement process, and making a much more dynamic industry dynamic, with a more wise investment in human capital [39]. The supply chain (or production flow) should be designed with the same flexibility of these collaborative networks to take full advantage [36]. Three types of solutions need to be considered to achieve the objective of Horizontal Integration: (1) Intelligent Supply Chain, (2) Optimised Business Model and (3) IT Management. Interconnected databases are key for the development of a more transparent, efficient and smart supply chain which takes into account the needs of the client and of all stages of the product development cycle [37]. The optimised business model is necessary for the changes involved in Industry 4.0. Employees and teams must develop new skills, incorporating innovation processes into the traditional business model focused on the horizontal development of companies. IT Management is relevant for efficient and secure data handling. Note that all company information will be in digital format: economic, strategic, process, and intellectual property information, among others, facilitating the work of decision-makers. Special care should be paid to processes and management systems for data protection and curation [40].

Through-Engineering enables the design, development and integrated manufacture of products and production systems, throughout their entire life cycle. It promotes the constant generation of synergies, establishing more flexible processes for the redesign and continuous improvement of products [10]. Two types of solutions must be considered to achieve the goal of integral engineering: Innovation Management and Life Cycle Management. Innovation management is relevant to the company's strategy, organisation, projects and product management, and allows the contribution of all stakeholders in open and flexible innovation processes, accelerating the development and improvement of products [41]. Lifecycle management uses real-time data, generating preventive and predictive measures through the means of artificial intelligence. This management is optimised by comparing and mixing the company's local and global databases for product development and decision making [42].

Exponential Technologies promote and accelerate the generation and development of individualised and flexible industrial processes, with time and cost savings. These technologies allow the development of autonomous, flexible, reliable and safe processes, in constant improvement [10]. Two types of solutions are necessary to implement Exponential Technologies: Corporate Investment and Organisational Learning, that is, to keep the R&D capital in the form of know-how and training. Corporate investment in new ventures facilitates the competitiveness in the long term, incorporating innovation and new technologies into their current processes and products, capturing ideas from external or internal entrepreneurs and developers. Organisational learning is key to the long-term development of the company. The integration of exponential technologies must include efficient knowledge management that generates a continuous improvement in processes and products [34].

3.3 Construction 4.0

Despite the many existing definitions and lack of a clear standard, there seems to be consensus to consider the Construction 4.0 as the application of Industry 4.0 to the construction sector, in other words, the construction digitalisation in a wide sense. Therefore, this term has BIM at its core, but not as the only element, as is described below.

Automation in the construction sector is not yet representative enough to confirm the values of increased productivity, but these preliminary tests and successful experiences in other industries are promising evidences to support its development [43]. Particularly, the benefits of the manufacturing industry in terms of performance and productivity are a good example for the construction industry, where the deployment of IT technologies are key for its efficiency [14]. Through digitalisation and an automated continuous and accurate monitoring process of all activities, Industry 4.0 eases a better diagnosis and prognosis of what has happened, is happening or may happen and why, for the entire manufacturing process, with a direct impact on improved production capabilities. Therefore, these new digitalisation technologies may make evolve the AECO industry towards higher levels of control and flexibility in construction, optimising time and costs [44].

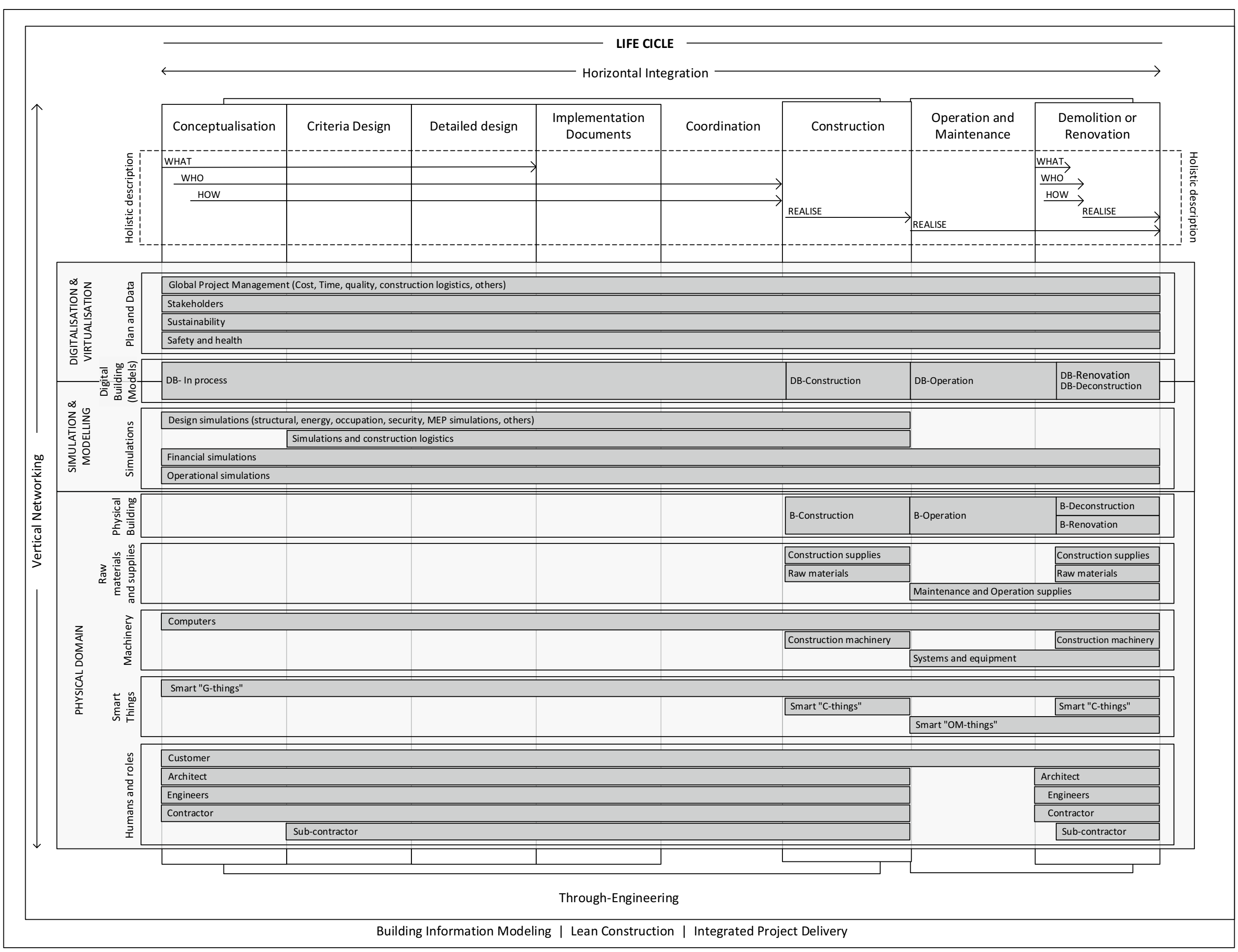
A systematic framework is needed for a successful technology adoption and digitisation in the construction industry. Companies must know their workflows for a better integration and transition of their people, data and project information, measuring the success of implementations and achieving sustainable systems over time [45]. Project managers and project directors have to acquire new skills for the efficient use of technologies in the field, to achieve successful coordination between workers, processes, and technologies, including the upcoming robotisation [15]. Roles in construction are also changing, evolving many of them and creating some others. The digitalisation of projects makes the responsibilities and tasks of workers more sophisticated, leaving behind unsafe and repetitive tasks, to evolve towards the supervision and control of technology [44]. Human workers are going to be trained to work with robots and many more technological tools, as in other sectors, being responsible of the project control, technology management, and very specific and safe jobs [46].

The AECO industry has characteristics that can push it towards the required innovation for a better productivity. The incorporation of new project management methodologies provides guidelines for efficient organisation. Although all projects are unique, there are many possibilities for standardisation of some elements and construction processes, with the possibility of building a local and global network [2]. BIM can act as a catalyst towards deeper adoption of digitisation, thanks to the quick and good acceptance it has received. BIM promotes communication, collaborative working, team integration, parametric modelling and visualisation, automatic document generation, different building simulations and management throughout its life cycle [47]. The bidirectional coordination between the physical and virtual domains, which leads to the digital twin, improve the control and optimisation of the construction process, generating also valuable data for the company record. That is, the updates of the BIM models in the different phases of the projects provide relevant data for their operation/maintenance phase, as well as for the design and planning phase of future constructions [15].

4 Technological-Methodological Framework

Construction 4.0 can be classified in technological terms attending to the following three scenarios [14, 15, 20]: (1) Physical Domain/Automation, (2) Simulations and Modelling and (3) Digitalisation and Virtualisation. Scenario 1 refers to the digital end to end engineering integration, considering technologies for the automation of the physical manufacturing environment, whereas the second one includes modelling and simulation tools for the design, construction, and operation of buildings and infrastructures. Finally, the third scenario refers to digitalisation and virtualisation tools for industrial processes and products, to link domains 1 and 2.

Figure 2 shows a methodological framework for the Construction 4.0, which synthesizes the life cycle stages of an AECO industry project, the implications of the new methodologies for this industry, and the principles of Industry 4.0. The methodological proposal is supported by the three main methodological trends in the construction industry: Lean Construction (LC), Building Information Modelling (BIM) and Integrated Project Delivery (IPD). The sequence of the different stages of the project is defined through the principles of lossless production and efficient management models, the integration and use of collaborative models, and the relations between the different agents of the project. The aim is to answer the "what", "who" and "how" questions since the very beginning of the project, during the Conceptualisation stage, incorporating the key professionals with relevant information for these questions. The project is created by means of a joint and integrated processes, roles and contracts, by following the *Criteria Design*, *Detailed Design*



DB: Digital Building | B: Building | G: Generic | C: Construction | OM: Operation and Maintenance

Fig. 2 Construction 4.0 methodological framework and *Implementation Documents* stages. The *Coordination* stage ranges from the first stage to the construction phase (there is also coordination in the *Operations and Maintenance* and *Demolition* or *Renovation* stage, but focused on the management of the facilities). Then the *Construction* stage contains the execution of the main building, but also affecting the *Operations and Maintenance* and *Demolition* or *Renovation*, given the modifications and finishing that could arise (the projects are dynamic in time). This cycle is repeated in the Demolition or Renovation stage.

Following the *Horizontal Integration* principle of Industry 4.0, detailed processes are connected throughout the life cycle while maximising transparency, integration and knowledge gathering. Equally, On the other hand, a *Vertical Network* is established to link and connect actors and instances, generating capacity of identification and reaction to changes, failures or specifications of the client or the environment. The already mentioned three large groups are used: *Physical Domain*, *Simulations and Modelling*, and *Digitalisation and Virtualisation*. Within the Physical Domain are all the physical elements that make up an industry project. It contains: (1) *Physical Building*, corresponding to the construction of the building and its complementary works (including the pre-fabricated parts), (2) *Raw material and supplies* required for the construction and operation phase, (3) *Machinery* required for the whole process (which changes throughout the project, depending on each stage), (4) *Humans and roles* that are assumed in the life cycle and (5) *Smart Things*, physical electronic elements to capture of data from the environment. Within the *Digitalisation and Virtualisation*, there is the digital documentation of the project planning (*Plans*) and the data of the project in execution and of other previous or open databases to which one has access (*Data*), including all the current paper documentation. *Simulations and Modelling* encompasses the different types of simulations needed for decision making in the calculation, architectural design, mechanical, electrical and plumbing installations (*Mechanical, electrical and plumbing, MEP*), logistics, operation, among others. The *Digital Building* is shared in the *Simulations and Modelling* and *Digitalisation and Virtualisation* scenarios, corresponding to the dynamic digital representation of the building throughout its life cycle.

Industry 4.0 proposes the use of a wide range of emerging technologies to optimise processes throughout their life cycle and allow the interconnection of all their processes, agents and products. Table 2 shows a description of 47 technologies belonging to Industry 4.0. Each technology is described with some current or potential uses that could have in the AECO Industry, according to the literature review process.

Figure 3 shows graphically how the three proposed scenarios coexist: (a) *Physical domain*, (b) *Simulations and Modelling*, and (c) *Digitalisation and Virtualisation*, according to the methodological framework in Fig. 2. The main building with all the complementary works within the real physical environment receives materials and inputs, which are transported, transformed and assembled using tools and machinery, handled by various professionals covering different roles. The entire physical environment is interconnected using *"Smart Things"* to collect and send real information to the models and simulation environments for updating, and send that data to the *Digitalisation and Virtualisation* layer for storage, analysis, and efficient use. The process is bidirectional, taking also information from the top, the digital repository, through the simulation environments and provides data, indications and answers (e.g., controlling actions) to the physical elements of the project. All the operation is given around the real building interconnected with the virtual model (at the different stages, dynamic in time). The 47 technologies identified have been distributed for each of the three scenarios. The technologies allow to take and receive the physical data to supervise and execute actions in the real environment in the *Physical Domain*; the technologies are used to process the data in the domain of *Simulations and Modelling*, making possible to have an in-depth knowledge of the expected behaviour of the work, such as, for example, when calculating structures, which also allows to predict different phenomena and build many digital scenarios of the project; and, finally, the technologies deal with the storage, maintenance and transfer of data, in safe and efficient environments in the domain of *Digitalisation and Virtualisation*.

Figure 4 shows the 47 technologies grouped according to (1) *Physical/automation Domain*, (2) *Simulations and Modelling*, and (3) *Digitalisation and Virtualisation*. The potential impact of each technology has been indicated for the different stages of the life cycle of an AECO industry project (CON, CDE, DDE, IMP, DCO, CON, OPE, D/R), using a scale of three values: Value 1—Low potential effect, Value 2—Medium potential effect and Value 3—High potential effect.

5 Complexities and Challenges

It is not simple to implement in an AECO project the elements and technologies described in the methodological framework. The *Horizontal Integration* and *Vertical Integration*, as connecting elements of people, products and processes along the whole life cycle of the project and for all the stakeholders is one of the main challenges proposed by Industry 4.0 and a key component in the proposed framework, what is especially complex in an industry characterised by fragmentation and waterfall planning for the processes and performance stages of its disciplines and professionals. These barriers must be overcome, both within and outside the organisation, by making

Table 2 Glossary of building technologies 4.0 (own elaboration)

Technologies	Description
5G	5G is the fifth generation of wireless communication standards and technologies, scaling in bandwidth and average speed, with decreased latency for a greater number and density of connected devices [48]. 5G allows for efficient and real-time interconnection of the sensor, communication, monitoring and execution devices during construction execution as well as in operation throughout their life, easing the implementation of Digital Twins [49–51]
Additive manufacturing (AM)	Additive manufacturing refers to the construction of 3D objects by adding and superimposing ultra-thin layers of material, achieving high levels of precision and reducing construction times. It can be used to automatically build at the same construction site as well as to make exact scale building models or components [52, 53]
Mobile applications (Apps)	Apps are computer applications connected to the network, used in mobile devices such as smartphones or tablets, for the capture, processing, and synchronisation of data collected on-site with those available in the cloud, interconnecting them with progress management systems [54, 55]. Apps are also the gateway to access all the information available at the office with the detail of systems, elements and general information of the buildings, in the different stages of their life cycle and emergencies [56–58]
Artificial intelligence (AI)	Artificial intelligence refers to the ability of machines to solve complex problems using algorithms that mimic and are inspired by human intelligence. AI optimises the processes of design, monitoring, and prediction of the behaviour of structures and their elements, in the areas of structural engineering, energy, safety, among others [59–61]. AI also enhances prediction models for water resources and natural phenomena which can affect structure of the building [62]
Augmented reality (AR)	Augmented reality is a technology to overlaid virtual elements on the real environment, using display devices (commonly AR glasses or tablets) [63]. It is a powerful and necessary complement to visualise and interact with BIM models at the building site [64]. AR eases the coordination of systems and their components, such as structures and installations, and the optimisation the projects in the design and planning stages [65]. Thanks to the AI, workers understand and better exploit the construction plans during the construction phase, by dynamically visualising 3D models, managing the actual placement of facilities in their exact location, reinforcing risk prevention measures for the safety and health of workers, identifying spaces through virtual labelling with multiple layers of information and facilitating the logistics of materials and equipment on-site, among other applications [66–68]. Finally, AR is especially interesting for Facility Management during the operations stage, by simultaneously displaying the digital version of the facilities overlaid the actual construction, along with labels and procedure guides [69]
Automated regulation checking and audits (ARCA)	The Automated regulation checking and Audits carries out a systematic and autonomous treatment of the processes of revision, audit, and control, by capturing and processing field data. It automates the review processes of engineering designs according to regulations and design codes [70, 71], in addition to the processes of control and monitoring of construction projects and asset management. This is done thanks to the processing of digital model data (BIM), which avoids lengthy manual review processes [72]
Big data (BD)	Big data involves techniques and technologies for handling data sets or combinations that are difficult to store, process and analyse by traditional technologies and in a concentrated manner, due to their huge size, complexity and great speed of growth. These techniques should be used the more important it is to interrelate the large volumes of information generated by the construction (now of digital character) [73, 74]
Big data analytics (BDA)	Big Data Analytics process large amounts of data, identify patterns, trends or correlations of interest, and extract useful information. BDA serves in the AECO industry to process and obtain useful information for the optimisation of the processes of design, construction, and maintenance [73, 75]
Blockchain (B)	A Blockchain is a "distributed public list" that records all validated discrete and encrypted digital data events and transactions that are executed or shared among participants in a network [76]. The Blockchain is relevant in safety and efficiency by providing automatic verification of design codes and regulations, security and greater ease in tracking change control and permit management, as well as by providing tools for the generation of intelligent contracts [77–79]

Table 2 (continued)

Technologies	Description
Building information modelling (BIM)	Building Information Modelling is a collaborative working methodology for the design, construction, and operation of construction projects. From a technological point of view, BIM can be seen as an evolution of traditional CAD tools towards a parametric digital modelling, based on 3D models, and incorporating variables of time, cost, sustainability, occupational safety and management, through the integration of the project stakeholders [80]. It is also contributing significantly to the digitalisation of construction data, providing multidisciplinary information to be processed and used throughout many project purposes, allowing interconnection with many other technologies in the industry [81–83]
Cloud computing (CC)	Cloud Computing provides access to computing resources and applications through a network of "in the cloud" storage, without tough hardware or software requirements for local devices. Having all the information and applications in remote servers simplifies the multi-site use of sophisticated modelling and simulation tools, the exchange of data and files between design and planning offices with each of the building sites [73, 84]
Common data environment (CDE)	The Common Data Environment refers to a common digital space for the storage, retrieval and transfer of information models, with well-defined areas, responsibilities, and access restrictions shared between parties based on interoperability between technology platforms. This common environment is of especial importance in the AECO industry to reduce fragmentation in the flow of information and access throughout the project, by standardising the exchange of information in a CDE for the stakeholders [85–87]
Cyber-physical systems (CPS)	Cyber-Physical Systems are mechanisms that establish bi-directional integration between physical and computational components, through integrated networks of monitoring and control of physical processes that perform physical actions and provide feedback to digital systems [88]. CPS is an key element for the coordination between the virtual models (BIM models, for example) with the physical assets, to verify that "what built" corresponds to "what planned", whereas the behaviour of the construction can be monitored throughout its life cycle, in the areas of engineering, energy, maintenance, and general management [89–92]
Cybersecurity (C)	Cybersecurity is the area responsible for the protection of computer infrastructure, software, hardware, networks and data in general, through the use and implementation of standards and tools [93]. Vulnerability risks for network data increase with high levels of information integration, with increased volume and variability of data type [94]. Parametric digital models of buildings and infrastructures generate a large amount of data, which requires special protection for not compromising their security and regular operations throughout their life cycle [95, 96]
Data mining (DM)	Data Mining is a set of techniques and technologies to explore databases in a semi-automatic or automatic way, identifying repetitive patterns that explain their behaviour [97]. DM is used to find trends and alterations in the patterns of registered data of energy consumption, structural behaviour and productivity in general (times, costs, measurements, among others), being able to identify causes and corrective measures [98–100]
Data sharing (DS)	Data Sharing refers to the sharing of data between stakeholders, mainly associated with research and development activities, for open cooperation and free use [101]. DS includes the dissemination and exchange of data, experiences, results and good practices of the design and construction processes among the different engineering companies, thus contributing to the reduction of the fragmentation of the AECO industry [102]
Deep learning (DL)	Deep Learning are hierarchical and structured algorithms designed to obtain knowledge and learning automatically, without prior programmed rules, inspired by human learning [103]. It can be used in AECO projects to identify the use and state of security elements, to control equipment and machinery, the presence or movement of people [104, 105]. More specifically, it can also identify and classify patterns and features of interest in structures, such as cracks in concrete [103, 106]
Digital signage (DS)	Digital Signage is the system of smart and rugged displays used to show content to a given audience, usually in an open environment, with interactive features for delivering targeted content [107]. A DS device may be used to provide collective instructions to workers, warning about the personal safety equipment, personal access requirements, signage and multiple individualised information [108–110]

Table 2 (continued)

Technologies	Description
Digital twin (DT)	Digital Twin consists of a virtual replica of a physical system able to be part of different simulation disciplines characterized by the synchronization between the virtual and actual system, by means of sensed data and connected smart devices, mathematical models and real time collected data. It is used for the optimisation, monitoring, diagnosis, and prognosis of the real system [111]. Digital Twins of buildings can be considered as the most complete digitalisation level for preventive and predictive maintenance, connected to actual construction [112–114]
Edge computing (EC)	Edge Computing relies on data processing as close to where it is generated, bypassing and central server or cloud, to minimise the traffic and bandwidth required to manage the data, reducing latency times and real-time response requirements [96, 115]. EC is used in control, monitoring, supply management, security and other construction processes requiring rapid responses. EC also provides better reaction times to alerts and maintenance in the operation phase of buildings and infrastructure [116–118]
Embedded system (ES)	An Embedded System is a combination of computer software and hardware (fixed or programmable) designed to perform specific dedicated functions within a more complex system [119, 120]. ES provide real-time processing tasks, using small memory and processors. ES are used for automation of repetitive simple tasks
Geographic information system (GIS)	A Geographic Information System is a digital framework to store, manage and analyse data of different types, considering their spatial location in maps [121]. A GIS connected to the digital models of the buildings (BIM models or Digital Twins) allows the management and geolocation of the construction, suppliers and urban elements, as part of the Smart Cities network [122]. The GIS storages data facilitating the design and location of the constructions thanks to many information layers: hydrological, geographic, geological, of old projects, among others [123, 124]
Human–computer interaction (HCI)	Human–Computer Interaction is the discipline that designs, evaluates and implements the human use of computer systems in an ergonomic, intuitive and efficient way [125]. The interaction of workers and professionals with the new technological devices that are being incorporated in the construction industry should be carefully studied to adapt them adequately and facilitate their adoption. In particular, the good designs of the interface between people and machines are defining new ways of designing, modelling and interacting with virtual buildings [126–128]
Improve asset utilisation (IAU)	Improving Asset Utilisation refers to encouraging the use of methodologies and technologies to optimise asset management [129], that is, having control of buildings and infrastructures during their useful life, facilitating their preventive and predictive maintenance, in addition to the delivery of inputs (data) for similar constructions in the future [130]
Industrial internet (II)	The Industrial Internet refers to the convergence of data and machines in the global industry, through the use of advanced computing and connectivity [131]. This development is strongly related to the Internet of Things, requiring a robust support for the real-time connection of data and equipment, connected with analytics for decision making in industry environments [132–134]
Internet of things (IoT)	The Internet of Things is the networking of objects and physical devices to capture data and interact with the environment [135]. IoT is applied in the construction industry to connect digital BIM models with physical devices for on-site control and monitoring (workers, materials, equipment, health and safety, work progress), optimising communication, and construction logistics in general. IoT is also used for energy and disaster monitoring and facilities management during the operations phase [136, 137]
Machine learning (ML)	Machine Learning is an Artificial Intelligence discipline for making systems evolve as if they were learning, using algorithms based on existing data to predict future behaviour. ML automates many parts of the designs, based on data from previous works and the study of their behaviour over time, from structural and architectural aspects to installations, as examples [138–140]. It also supports the automation of decision making in safety, logistics, and processes during the construction phase [141]
Mass customisation (MCu)	Mass Customisation is the creation of goods and services tailored to the specific requirements of each client. Paradoxically, for the construction industry, characterised by the fact that each building or infrastructure is a unique product, it is not easy to implement high levels of customisation due to current rigid workflows. However, the upcoming flexibility and automation of design processes, the 3D visualisation, modularisation and additive manufacturing, could help to promote MCu, which is being increasingly required by developers and users [119, 142–145]

Table 2 (continued)

Technologies	Description
Mixed reality (MR)	Mixed Reality is the combination of Augmented Reality (AR) and Virtual Reality (VR), creating spaces for the interaction of objects, people and virtual scenarios with the real ones. The real space is not only the background or container of the virtual models, but it takes part and interacts with the digital world. MR eases the visualisation of digital models and systems in an immersive way, as well as field inspection tasks, visualisations in the design phase, day a day tasks checks such as the potential interaction between machines and workers prior to the actual construction [146–148]
Mobile computing (MC)	Mobile Computing refers to devices and related services designed to be transported during usage, able to interact with network data from anywhere without being connected by cable. MC is used at the building site for real-time monitoring without needing a wired communication infrastructure, for the management of tasks and processes, the management of security, increasing communication, the visualisation of projects and the connection with external agents [149–151]
Modularity (M)	Modularity is the ability of a system to be handled (subdivided) into smaller, independent modules (subsystems), linked and assembled using standardised rules. Modularity it is applied for the treatment of digital information to better manage the building construction, by subdividing it into work packages optimised according to accessibility, location limitations, dimensions and parts of the structure or systems, among other factors [152–154]
3D scanner (3DS)	3D scanners are devices to capture the geometry and colour of an object, to generate its 3D virtual reconstruction. 3D scanners are used in construction to generate 3D digital models of the terrain, the infrastructure already built, for monitoring, repair, reconstruction, structural health study (cracks, for example), among others [155]
Photogrammetry (Ph)	Photogrammetry is a technique to obtain geometric properties of objects and their spatial location, by processing aerial photographs and reconstructing three-dimensional models of reality. This digital reconstruction, based on "point clouds", is used for remote inspection, to obtaining information from the site, thus monitoring the progress of construction [55, 156, 157], to identify, measure and study cracks and geometric features of the site [158, 159], and for digital terrain survey and topography generation [160]
Predictive maintenance (PM)	Predictive Maintenance is aimed to predict future failures in installations, systems or equipment, through simulations or early detection of key indicators. The PM links BIM models, simulation software and sensors for data collection, predicting and performing maintenance before failure, without altering the operation of the building (equipment, systems, and structural elements), as a natural evolution of the Computer-assisted Maintenance Management Systems (CMMS) in the AECO industry. It is expected a reduction of between 10 and 15% in maintenance costs by using PM [149, 161, 162]
Off-site construction (OSC)	Prefabrication, modular or Off-site Construction is a construction procedure based on components and subsystems built-in series outside the final location, and then placed and assembled there. OSC brings to the construction site structural 2D or 3D elements (complete spaces, such as bathrooms or kitchens, for example) manufactured in controlled industries, requiring only assembly and installation on-site, optimising time, logistics and quality of finishes. Therefore, the technical aspects of the prefabricated elements are controlled in a factory, applying rigorous management and quality control principles, systematising the construction processes and without exposure to uncertain weather conditions at the building construction site. A greater adoption of BIM facilitates OSC, providing the component breakdown from the digital models and all the details of the facilities [163–167]
Product-lifecycle-management (PLM)	Product-Lifecycle-Management is the process that manages the different phases of conception, design, manufacturing, use, and recycling of a product through integrated IT solutions and with all the actors involved, optimising the relationships with customers, suppliers, and resources. The application of PLM to the AECO industry enables a truly integrated vision of the lifecycle of buildings and infrastructures, contributing to mitigate the fragmentation of the sector. One of the most relevant aspects of BIM is precisely this holistic vision of construction for all phases, including the interconnectivity between models and processes [168–170]

Table 2 (continued)

Technologies	Description
Radio frequency identification (RFID)	Radio Frequency Identification uses electromagnetic fields, radio frequency waves, to automatically identify, geolocate and track tags attached to objects. RFID enables the tracing of materials and machinery for their control at construction sites [171, 172]. RFID also facilitates the study of the behaviour of structures through the movement of these tags (the measurement of deformation, expansion of materials, among others) [173–175], and the monitoring and management of the labelled equipment in facilities [176]
Robotics (R)	Robotics is the science and technique that deals with the design, manufacture, and use of robots; that is, machines that can be programmed to interact autonomously with objects to perform tasks of different kinds. Robots are used in industry to collect real-time information from the environment time by walking around the site (e.g., temperature, images) [177, 178] and perform repetitive manufacturing tasks. In the AECO sector, robots could work according to BIM models, for welding, structural reinforcement bending, element cutting, among others tasks [179, 180]
Self-sustainability and self-sufficiency (SS)	Self-Supply is related to the possibility of a system requiring little or no resources from outside. A SS building in the construction industry is mainly related to the energy and water efficiency, by incorporating elements for self-generation and optimal use of energy, water recirculation, and recycling [181, 182]
Sensors (S)	Sensors are electronic devices to determine the variation of a physical or chemical magnitude, by transforming them into electrical variables. Sensors are used in construction to monitor the structural health of buildings and infrastructures, to check the correct operation of machinery, workers, equipment, systems, thermal comfort, and many others [183–185]
Simulations models and tools (SMT)	Simulations Models and Tools aim to replicate and thus predict the behaviour of systems and processes. Simulations are widely used in the AEO industry to analyse structures during the design phase, to predict energy consumption and to simulate a fire evacuation, for example. Simulations are also strongly linked to the optimisation of construction processes and the functioning of systems and buildings during their operation [186–189]
Social media (SM)	Social Media are "online" communication applications based on "Web 2.0", for the exchange of information directly generated by users. It is a very agile communication channel, with massive contents, immediate and multidirectional consumption. SM may intensify the communication between construction workers (either via messages or documents), especially in complex works and with large extensions of land [75, 190]
Supply chain management (SCM)	Supply Chain Management is the process of planning, executing, and controlling an efficient supply network. It is applied to systems and procedures to link the knowledge, procedures, and learning of the supply logistics of the different projects [191], optimising the purchase and distribution of materials (quality and specific requirements) [192]. SCM brings together and improves relationships between all stakeholders in the construction sector, by clarifying processes and distribution of roles and risks [193]. BIM contributes to the SCM by connecting digital models of materials and inputs [194]
Unmanned aerial vehicle (UAV)	UAVs are systems that perform aerial missions remotely. They have flight autonomy and can transport different elements, including sensors and devices to capture different types of signals, magnitudes, photographs, depending on the different accessories. UAVs used at the construction sites to monitor projects from the air, obtain global views, verify structure details, and reach hard-to-reach places, whether for security, monitoring, progress control, or maintenance. They also can transport materials and equipment, simplifying distribution logistics [195–197]
Virtual reality (VR)	Virtual Reality is a technology designed to generate scenes with a real appearance from computer systems. Therefore, they can provide a full immersion in three-dimensional BIM models through the use of glasses or in a CAVE (Cave automatic virtual environment), either to perform design and usability reviews in the early stages of the project with a virtual tour through the building site, or to work interactively in real-time and at scale on the (architectural, structural, usability) optimisation of the design [198, 199]. Another representative application is the creation of immersion environments for orientation of workers before the first day at work in subjects such as health and safety or construction logistics, outlining the different risks that could occur. [199, 200]
Wearable technology (WT)	Wearable Technology refers to any smart electronic device attached to the user's clothing, for the sensorization of the behaviour and movement, capturing and processing the data generated. WT are directly used in the construction industry to verify compliance with occupational risk prevention measures, through real-time monitoring of workers, their movements and actions at the construction site [75, 77, 78, 190]

Table 2 (continued)

Technologies	Description
Neural networks (NNs)	Artificial Neural Networks are computational models that are basically inspired by biological neural networks. They use interconnected nodes that process information at different input–output levels, generating automatic predictions and learning. These NN are used in the construction industry to make predictions and study the behaviour of structures based on previous behaviours [201–205]. Similarly, they can be used to make estimates of worker behaviour and construction logistics processes [206]

suppliers to actively participate into the logistics and innovation processes.

Through-Engineering promotes the design, development and integrated construction of products and systems, focused on the generation of constant synergies by making processes more flexible and by deploying continuous improvement. There are many routines and semi-handicraft construction processes that can be migrated to systematic and automated tasks, generating logistical and worker training challenges. Paradoxically, it is the availability of a digital version of the entire construction, with all tasks planned and monitored, that adds flexibility for providing a better response to design changes during the construction or operation stages due to geotechnical, meteorological or other unforeseen events. The industry faces the need to improve and optimise the management and control processes, anticipating decision making and inclusion of stakeholders from early stages, with permanent monitoring of their observations. All the agents of the construction industry have tools to make much more transparent the administrative processes, with focus on a better financial, time, cost and safety control of the workers. *Exponential technologies* promote and accelerate the development of the industry, helping in the above mentioned three domains: physical/automation domain, simulation and modelling, and digitalisation and virtualisation. These dimensions keep interconnected the different agents, stages, and elements of the project.

Despite these challenges, the AECO industry is now under a strong change processes, coming from the implementation of *Lean Construction* (LC), *Integrated Project Delivery* (IPD) and *Building Information Modelling* (BIM). These initiatives are making a more dynamic industry and generating an ideal scenario to advance in the complete digitalisation of the sector, and thus integrating also the principles of Industry 4.0. All kind of innovations: corporate, process and technology innovation, are key to boost the industry to a new development era.

6 Conclusions

A diagnosis of the AECO industry has been made by reviewing its characteristics, complexities, and problems. This review includes the roles, interactions, and the new methodological trends that are being used, as well as the list of the industry's main problems, which are related to management systems, fragmentation, accident rate, training, and low technological implementation. On the other hand, the conceptual framework of Construction 4.0 has been identified, defined, and classified, detailing its principles and action scenarios, according to its parallelism with Industry 4.0.

The proposed methodological framework incorporates the principles of Industry 4.0 to the workflows of the AECO industry. It is framed in the current trends of *Lean Construction* (LC), *Integrated Project Delivery* (IPD) and *Building Information Modelling* (BIM), incorporating agents, processes and products based on these methodological proposals, linked and adapted to incorporate the potential of Industry 4.0. Thus, the aspects of *Vertical Networks, Horizontal Integration, Engineering*, and *Exponential Technologies* are included in the project life cycle, also classifying the project components in scenarios of the physical/automation domain, simulation and modelling, and digitalisation and virtualisation. In this way, we can achieve a methodological synergy between the components of the AECO industry and Industry 4.0, and generate an easily understandable framework.

An extensive route through 47 emerging technologies has been presented, mainly from Industry 4.0, defining the Construction 4.0 and to be applied to the AECO industry. Their general uses have been identified, together with incipient or potential applications throughout the life cycle of a construction project. These technologies have been also categorised according to the proposed classification scenarios, physical/automation domain, simulation and modelling, and digitalisation and virtualisation, and assessed according to their potential impact on the different stages of an AECO industry project.

The incorporation of the principles of Industry 4.0 to the AECO industry, in the so-called "Construction 4.0", poses multiple foreseeable challenges, such as reducing fragmentation and promoting the transversal integration of people, processes, and products, achieving higher levels of flexibility, and improving the complete management of the project throughout its life cycle, in order to improve its productivity levels. There are still few experiences of incorporating these principles and emerging technologies into the AECO

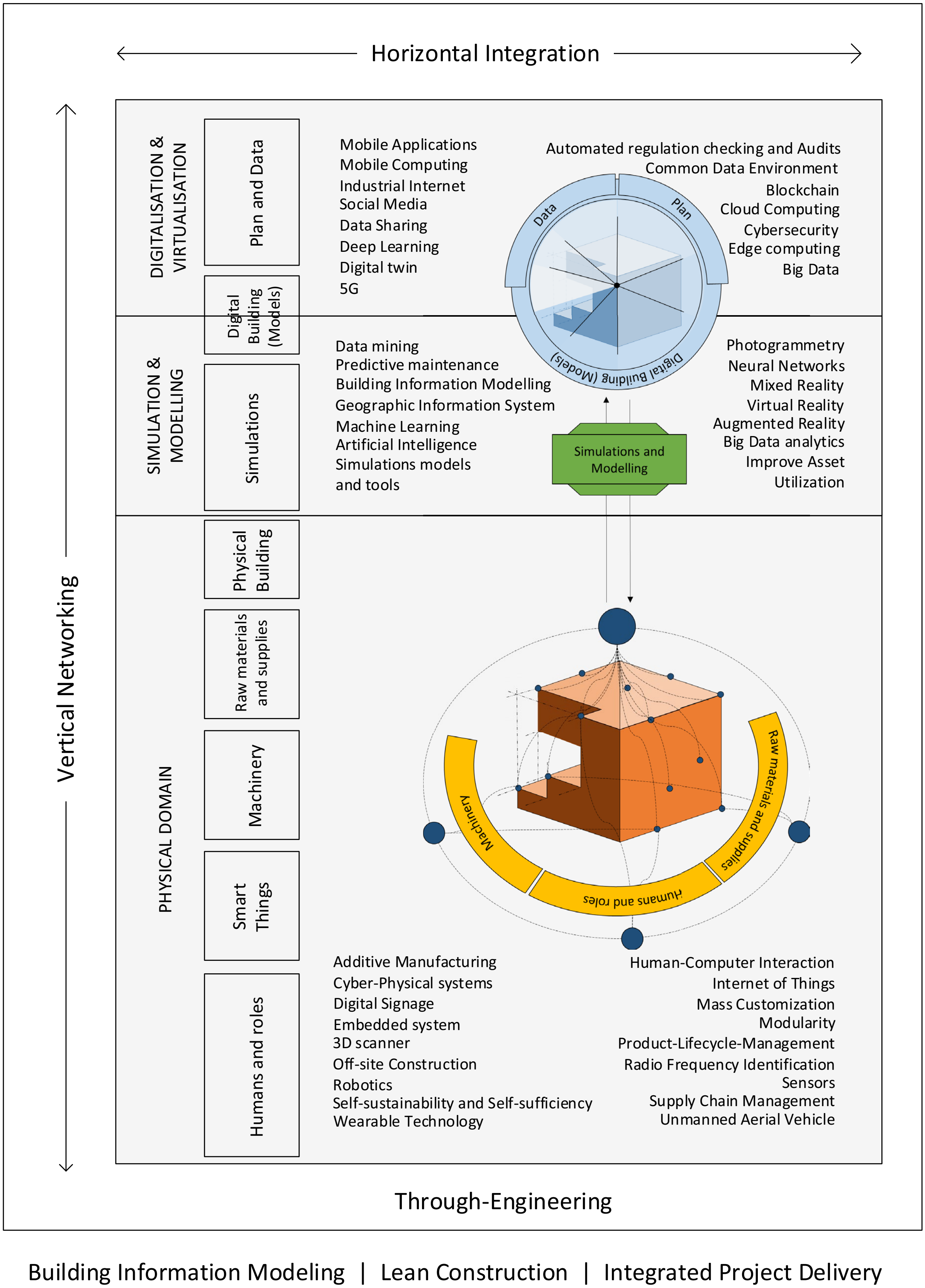


Fig. 3 Interrelationship between proposed scenarios and support technologies

	Technology		Conceptualisation CON	Criteria Design CDE	Detailed design DDE	Implementation Documents IMP	Coordination DCO	Construction CON	Operation and Maintenance OPE	Demolition or Renovation D/R
Physical Domain / Automation	Additive Manufacturing	AM	1	1	1	1	1	3	1	3
	Cyber-Physical systems	CPS	1	2	3	3	3	3	3	2
	Digital Signage	DSi	1	1	1	1	1	3	3	2
	Embedded system	ES	1	1	1	1	1	3	2	2
	Human-Computer Interaction	HCI	1	3	2	2	2	3	2	2
	Internet of Things	IoT	1	1	1	1	1	3	3	2
	Mass Customization	MCu	3	3	3	2	1	1	2	2
	Modularity	M	1	1	1	2	2	3	2	2
	3D scanner	3DS	1	1	1	1	2	3	2	2
	Off-site Construction	OSC	1	2	1	1	2	3	1	2
	Product-Lifecycle-Management	PLM	3	3	3	3	3	3	3	3
	Radio Frequency Identification	RFI	1	1	1	1	1	3	2	2
	Robotics	R	1	1	1	1	2	3	2	2
	Self-sustainability and Self-sufficiency	SS	1	1	2	1	1	1	3	1
	Sensors	S	1	1	1	1	1	2	3	2
	Supply Chain Management	SCM	1	1	1	1	1	3	3	2
	Unmanned Aerial Vehicle	UAV	1	1	1	1	1	3	2	2
	Wearable Technology	WT	1	1	1	1	1	3	3	2
Simulation and Modelling	Simulations models and tools	SMT	1	2	3	2	3	3	3	2
	Artificial Intelligence	AI	1	3	3	2	3	3	3	2
	Machine Learning	ML	2	3	3	2	3	3	3	2
	Data mining	DM	2	3	3	2	3	3	3	2
	Neural Networks	NNs	1	3	3	2	3	3	3	1
	Predictive maintenance	PM	2	3	1	1	2	1	3	3
	Improve Asset Utilization	IAU	1	2	1	1	1	1	3	2
	Big Data analytics	DBA	2	3	3	1	2	3	3	1
	Augmented Reality	AR	1	2	3	1	3	3	2	2
	Virtual Reality	VR	1	3	3	1	3	3	2	2
	Mixed Reality	MR	1	2	3	1	3	3	2	2
	Building Information Modelling	BIM	3	3	3	3	3	3	3	3
	Photogrammetry	Ph	1	2	3	1	2	3	2	1
	Geographic Information System	GIS	2	3	3	2	2	2	2	1
Digitalisation and Virtualisation	5G	5G	1	1	1	2	1	3	3	1
	Mobile Applications	APPs	1	2	1	3	2	3	3	2
	Mobile Computing	MCo	1	1	1	1	2	3	3	2
	Industrial Internet	II	1	1	3	2	1	3	3	1
	Social Media	SM	2	2	2	2	3	3	2	2
	Automated regulation checking and Audits	ARCA	1	2	3	3	3	2	2	1
	Big Data	BD	2	3	2	2	2	2	3	2
	Blockchain	B	1	2	3	3	3	2	3	1
	Cloud Computing	CC	1	2	1	3	2	2	3	1
	Common Data Environment	CDE	2	2	2	3	3	2	3	2
	Cybersecurity	C	1	2	2	3	3	3	3	2
	Data Sharing	DSh	2	3	3	1	1	1	3	2
	Deep Learning	DL	1	2	3	2	3	2	2	1
	Digital twin	DT	1	2	3	3	3	3	3	2
	Edge computing	EC	1	1	1	1	2	3	3	2

3	High potential effect
2	medium potential effect
1	Low potential effect

Fig. 4 Expected impact of technologies in the life cycle of the project

industry. The real implications of these and the upcoming adoptions need to be studied in greater depth, focusing on certain indicators that accurately reflect the changes in traditional processes, the consequences on workers who should adopt new roles and profiles, the challenges in education and training, and the evolution to the new business and development models.

Acknowledgements The first author, Felipe Muñoz-La Rivera, acknowledges CONICYT for its economic support, being beneficiary of a pre-doctoral Grant (Reference Number CONICYT - PCHA/International Doctorate/2019-72200306). The authors also acknowledge the financial support from the Spanish Ministry of Economy and Competitiveness, through the "Severo Ochoa Programme for Centres of Excellence in R&D (CEX2018-000797-S)".

Compliance with Ethical Standards

Conflict of interest The authors declare that they have no conflict of interest.

References

1. Yeganeh AA, Azizi M, Falsafi R (2019) Root causes of design-construction interface problems in iranian design-build projects. J Constr Eng Manag 145(12):1–14. https://doi.org/10.1061/(ASCE)CO.1943-7862.0001727
2. Håkansson H, Ingemansson M (2013) Industrial renewal within the construction network. Constr Manag Econ 31:40–61. https://doi.org/10.1080/01446193.2012.737470
3. Nasrun M, Nawi M, Baluch N, Bahauddin AY (2014) Impact of fragmentation issue in construction industry: an overview 3 discussions. In: MATEC Web of conferences 15
4. Elghaish F, Abrishami S, Hosseini MR, Abu-Samra S, Gaterell M (2019) Integrated project delivery with BIM: an automated EVM-based approach. Autom Constr. https://doi.org/10.1016/j.autcon.2019.102907
5. Pezeshki Z, Ali S, Ivari S (2016) Applications of BIM: a brief review and future outline. Arch Comput Methods Eng. https://doi.org/10.1007/s11831-016-9204-1
6. Sanghavi D, Parikh S, Raj SA (2019) Industry 4.0: tools and implementation. Manag Prod Eng Rev 10(3):3–13. https://doi.org/10.24425/mper.2019.129593
7. Piccarozzi M, Aquilan B (2018) Industry 4.0 in management studies: a systematic literature review. Sustainability 10:1–24. https://doi.org/10.3390/su10103821
8. Agostini L, Filippini R (2019) Organizational and managerial challenges in the path towards Industry 4.0. Eur J Innov Manag. https://doi.org/10.1108/EJIM-02-2018-0030
9. Thoben K, Wiesner S, Wuest T (2017) "Industrie 4.0" and smart manufacturing: a review of research issues and application examples. Int J Autom Technol 11(1):4–16
10. Deloitte (2015) Challenges and solutions for the digital transformation and use of exponential technologies. Zurich
11. Fatorachian H, Kazemi H (2018) A critical investigation of Industry 4.0 in manufacturing: theoretical operationalisation framework. Prod Plan Control 7287:1–12. https://doi.org/10.1080/09537287.2018.1424960
12. Becker Da Costa M, Lima L, Schaefer J, Baierle I, Benitez E (2019) Industry 4.0 technologies basic network identification. Scientometrics. https://doi.org/10.1007/s11192-019-03216-7
13. Kipper LM, Furstenau LB, Hoppe D, Frozza R, Iespen S, Mahlmann L, Kipper LM (2019) Scopus scientific mapping production in industry 4.0 (2011–2018): a bibliometric analysis. Int J Prod Res. https://doi.org/10.1080/00207543.2019.1671625
14. Alaloul WS, Liew MS, Amila N, Abdullah W, Mohammed BS (2018) Industry revolution IR 4.0: future opportunities and challenges in construction industry. MATEC Web Conf 203:1–7. https://doi.org/10.1051/matecconf/201820302010
15. Maskuriy R, Selamat A, Ali KN, Maresova P, Krejcar O (2019) Industry 4.0 for the construction industry: How ready is the industry? Appl Sci 9:2819
16. Creswell JW (2009) Research design: qualitative, quantitative, and mixed methods approaches. Sage, Oaks
17. Craveiro F, Pinto J, Bartolo H, Jorge P (2019) Additive manufacturing as an enabling technology for digital construction: a perspective on Construction 4.0. Autom Constr 103:251–267. https://doi.org/10.1016/j.autcon.2019.03.011
18. Rosenfeld Y (2014) Root-cause analysis of construction-cost overruns. J Constr Eng Manag. https://doi.org/10.1061/(ASCE)CO
19. Freire J, Alarcón LF (2002) Achieving lean design process: improvement methodology. J Constr Eng Manag 128(June):248–256. https://doi.org/10.1061/(ASCE)0733-9364(2002)128:3(248)
20. Oesterreich TD, Teuteberg F (2016) Computers in Industry Understanding the implications of digitisation and automation in the context of Industry 4.0: a triangulation approach and elements of a research agenda for the construction industry. Comput Ind 83:121–139. https://doi.org/10.1016/j.compind.2016.09.006
21. Kannimuthu M, Ekambaram P, Raphael B, Kuppuswamy A (2018) Resource unconstrained and constrained project scheduling problems and practices in a multiproject environment. Adv Civ Eng. https://doi.org/10.1155/2018/9579273
22. Yap Hui BJ, Chow IN, Shavarebi K (2019) Criticality of construction industry problems in developing countries: analyzing malaysian projects. J Manag Eng. https://doi.org/10.1061/(ASCE)ME.1943-5479.0000709
23. Dubois A, Gadde L (2002) The construction industry as a loosely coupled system: implications for productivity and innovation. Constr Manag Econ 20:621–631. https://doi.org/10.1080/01446190210163543
24. Zidane YJ, Andersen B, Zidane YJ, Andersen B (2018) The top 10 universal delay factors in construction projects delay factors. Int J Manag Proj Bus 11(3):650–672. https://doi.org/10.1108/IJMPB-05-2017-0052
25. Shen L, Lin Y (2014) Strategies in using building information modeling (BIM) to solve problems in project management of chinese construction enterprises. Appl Mech Mater 504:2700–2705. https://doi.org/10.4028/www.scientific.net/AMM.501-504.2700
26. Shuai L, Li H (2013) Problems and effective countermeasures in construction safety management. Appl Mech Mater 439:1702–1705. https://doi.org/10.4028/www.scientific.net/AMM.438-439.1702
27. Muñoz-La Rivera F, Vielma J, Herrera RF, Carvallo J (2019) Methodology for building information modeling (BIM) implementation in structural engineering companies (SEC). Adv Civ Eng. https://doi.org/10.1155/2019/8452461
28. Herrera R, Muñoz-La Rivera F, Vargas C, Antio M (2017) Uso e impacto de los modelos nD como herramienta para la dirección de uso e impacto de los modelos nD como herramienta para la dirección de proyectos en la industria de la arquitectura, ingeniería y construcción use and impact of nd models as a tool for. Inf Tecnol 28(4):169–178. https://doi.org/10.4067/S0718-07642017000400019
29. Mesa HA, Molenaar KR, Alarcón LF (2019) Comparative analysis between integrated project delivery and lean project delivery.

Int J Proj Manage 37(3):395–409. https://doi.org/10.1016/j.ijproman.2019.01.012
30. Sung TK (2018) Technological forecasting & social change Industry 4.0: a Korea perspective. Technol Forecast Soc Chang 132:40–45. https://doi.org/10.1016/j.techfore.2017.11.005
31. Mehrpouya M, Dehghanghadikolaei A, Fotovvati B (2019) The potential of additive manufacturing in the smart. Appl Sci. https://doi.org/10.3390/app9183865
32. Machado CG, Winroth MP, Hans E, Ribeiro D (2019) Sustainable manufacturing in Industry 4.0: an emerging research agenda. Int J Prod Res. https://doi.org/10.1080/00207543.2019.1652777
33. Lu Y (2017) Journal of industrial information integration Industry 4.0: a survey on technologies, applications and open research issues. J Ind Inf Integr 6:1–10. https://doi.org/10.1016/j.jii.2017.04.005
34. Rejikumar G, Raja V, Arunprasad P, Persis J, Sreeraj K (2019) Industry 4.0: key findings and analysis from the literature arena. Benchmarking Int J. https://doi.org/10.1108/BIJ-09-2018-0281
35. Da Xu L, Xu EL, Li L (2018) Industry 4.0: state of the art and future trends. Int J Prod Res 56(8):2941–2962. https://doi.org/10.1080/00207543.2018.1444806
36. Brettel M, Friederichsen N, Keller M, Rosenberg M (2014) How virtualization, decentralization and network building change the manufacturing landscape: an Industry 4.0 perspective. Int J Inf Commun Eng 8(1):37–44
37. Hozdić E (2015) Smart factory for industry 4.0: a review. Int J Mod Manuf Technol 7(1):28–35
38. Mohamed M (2018) Challenges and benefits of Industry 4.0: an overview. Int J Supply Oper Manag 5(3):256–265
39. Jaehne DM, Li M, Riedel R, Mueller E (2009) Configuring and operating global production networks. Int J Prod Res 47(8):2013–2030. https://doi.org/10.1080/00207540802375697
40. Shin WS, Lee YS, Dahlgaard JJ (2019) Total quality management & business excellence a pattern-based decision framework in the era of Industry 4.0. Total Qual Manag. https://doi.org/10.1080/14783363.2019.1665840
41. Wang S, Wan J, Zhang D, Li D, Zhang C (2016) Towards smart factory for industry 4.0: a self-organized multi-agent system with big data based feedback and coordination. Comput Netw J 101:158–168. https://doi.org/10.1016/j.comnet.2015.12.017
42. Mujahid A, Mani V (2019) International journal of information management role of real-time information-sharing through SaaS: an industry 4.0 perspective. Int J Inf Manag 49:301–315. https://doi.org/10.1016/j.ijinfomgt.2019.05.026
43. Chen Q, García B, Soto D, Adey BT (2018) Construction automation: research areas, industry concerns and suggestions for advancement. Autom Constr 94(May):22–38. https://doi.org/10.1016/j.autcon.2018.05.028
44. García de Soto B, Agustí-Juan I, Hunhevicz J, Joss S, Graser K, Habert G, Adey BT (2018) Productivity of digital fabrication in construction: cost and time analysis of a robotically built wall. Autom Constr 92:297–311. https://doi.org/10.1016/j.autcon.2018.04.004
45. Hossain M, Nadeem A (2019) Towards digitizing the construction industry: state of the art of Construction 4.0. Interdepend Struct Eng Constr Manag. https://doi.org/10.14455/ISEC.res.2019.184
46. Awais M, Henrich D (2013) Human–robot interaction in an unknown human intention scenario. In: 11th international conference on frontiers of information technology, pp 89–94
47. Akinade OO (2017) Bim-based software for construction waste analytics using Artificial intelligence hybrid models. University of the West of England, Bristol
48. Gupta R, Tanwar S, Tyagi S, Kumar N (2019) Tactile internet and its applications in 5G era: a comprehensive review. Int J Commun Syst. https://doi.org/10.1002/dac.3981
49. He D, Ai B, Member S, Guan K, Zhong Z, Member S, Kim I (2017) Channel measurement, simulation, and analysis for high-speed railway communications in 5G millimeter-wave band. IEEE Trans Intell Transp Syst 19:1–15
50. Yan L, Fang X, Fang Y (2017) A novel network architecture for C/U-plane staggered handover in 5G decoupled. IEEE Trans Intell Transp Syst 19:1–13
51. Qamar F, Hindia MHDN, Dimyati K, Ariffin K, Iraj N, Amiri S (2019) Interference management issues for the future 5G network: a review. Telecommun Syst 71(4):627–643. https://doi.org/10.1007/s11235-019-00578-4
52. Plocher J, Panesar A (2019) Review on design and structural optimisation in additive manufacturing: towards next-generation lightweight structures. Mater Des J. https://doi.org/10.1016/j.matdes.2019.108164
53. Attaran M (2017) The rise of 3-D printing: the advantages of additive manufacturing over traditional manufacturing. Bus Horiz 60(5):677–688. https://doi.org/10.1016/j.bushor.2017.05.011
54. Khan G, Bueff A, Mihov I, Tessema N, Garrido J, Russel C, Parnia A (2016) Development of transportation asset management and data collection system (TAMS) using mobile applications. Procedia Eng 161:1180–1186. https://doi.org/10.1016/j.proeng.2016.08.536
55. Moon D, Chung S, Kwon S, Seo J, Shin J (2018) Comparison and utilization of point cloud generated from photogrammetry and laser scanning: 3D world model for smart heavy equipment planning. Autom Const. https://doi.org/10.1016/j.autcon.2018.07.020
56. Işık MF, Işık E, Bülbül MA (2018) Application of iOS/Android based assessment and monitoring system for building inventory under seismic impact. Građevinar 70(12):1043–1056. https://doi.org/10.14256/JCE.1522.2015
57. Pang Z, Xu P, Neill ZO, Gu J, Qiu S, Lu X, Li X (2018) Application of mobile positioning occupancy data for building energy simulation: an engineering case study. Build Environ 141(4800):1–15. https://doi.org/10.1016/j.buildenv.2018.05.030
58. Vallero A, Cimellaro GP, Mahin S (2015) Earthquake rapid loss assessment using communication systems to improve resilience of emergency responders. Struct Congr 2015:1538–1549
59. Naser MZ (2019) Fire resistance evaluation through artificial intelligence: a case for timber structures. Fire Saf J. https://doi.org/10.1016/j.firesaf.2019.02.002
60. Dede T, Kankal M, Vosoughi AR, Grzywinski M, Kripka M (2019) Artificial intelligence applications in civil engineering. Adv Civ Eng. https://doi.org/10.1155/2019/8384523
61. Salehi H, Burgueño R (2018) Emerging artificial intelligence methods in structural engineering. Eng Struct 171:170–189. https://doi.org/10.1016/j.engstruct.2018.05.084
62. Ghorbani MA, Khatibi R, Karimi V (2018) Learning from multiple models using artificial intelligence to improve model prediction accuracies: application to river flows. Water Resour Manag 32(13):4201–4215. https://doi.org/10.1007/s11269-018-2038-x
63. Wang X, Truijens M, Hou L, Wang Y, Zhou Y (2014) Integrating augmented reality with building information modeling: onsite construction process controlling for lique fi ed natural gas industry. Autom Constr 40:96–105. https://doi.org/10.1016/j.autcon.2013.12.003
64. Preface (2013) Special issue on the applications of augmented reality in architecture, engineering, and construction. Autom Constr 33:1–2. https://doi.org/10.1016/j.autcon.2013.05.003
65. Khalek IA, Chalhoub JM, Ayer SK (2019) Augmented reality for identifying maintainability concerns during design. Adv Civ Eng. https://doi.org/10.1155/2019/8547928
66. Wang X, Love PED, Jeong M, Park C, Sing C, Hou L (2013) A conceptual framework for integrating building information

modeling with augmented reality. Autom Constr 34:37–44. https://doi.org/10.1016/j.autcon.2012.10.012
67. Zaher M, Greenwood D, Marzouk M (2018) Mobile augmented reality applications for construction projects applications. Constr Innov. https://doi.org/10.1108/CI-02-2017-0013
68. Li X, Yi W, Chi H, Wang X, Chan APC (2018) A critical review of virtual and augmented reality (VR/AR) applications in construction safety. Autom Constr 86:150–162. https://doi.org/10.1016/j.autcon.2017.11.003
69. Baek F, Ha I, Kim H (2019) Augmented reality system for facility management using image-based indoor localization. Autom Constr 99:18–26. https://doi.org/10.1016/j.autcon.2018.11.034
70. Kim H, Lee J, Shin J, Choi J (2018) Visual language approach to representing KBimCode-based Korea building code sentences for automated rule checking. J Comput Des Eng. https://doi.org/10.1016/j.jcde.2018.08.002
71. Nawari N, Alsaffar A (2017) The role of BIM in simplifying construction permits in kuwait. AEI 2017:855–866
72. Bukhsh FA, Weigand H (2017) Compliance checking of shipment request by utilizing process mining concepts: an evaluation of Smart Auditing Framework. Int Conf Front Inf Technol Compliance. https://doi.org/10.1109/FIT.2017.00049
73. Chou J, Ngo N, Chong WK, Gibson GE (2016) Big data analytics and cloud computing for sustainable building energy efficiency. Start-Up Creation. https://doi.org/10.1016/B978-0-08-100546-0.00016-9
74. Abaker I, Hashem T, Yaqoob I, Badrul N, Mokhtar S, Gani A, Ullah S (2015) The rise of “big data” on cloud computing: review and open research issues. Inf Syst 47:98–115. https://doi.org/10.1016/j.is.2014.07.006
75. Ghani NA, Hamid S, Abaker I, Hashem T (2018) Big social media data analytics: a survey. Comput Hum Behav. https://doi.org/10.1016/j.chb.2018.08.039
76. Zheng Z, Xie S, Dai H, Chen X, Wang H (2017) An overview of blockchain technology: architecture, consensus, and future trends. IEEE Int Cong Big Data. https://doi.org/10.1109/BigDataCongress.2017.85
77. Nawari NO, Ravindran S (2019) Blockchain and the built environment: potentials and limitations. J Build Eng. https://doi.org/10.1016/j.jobe.2019.100832
78. Nawari NO, Ravindran S (2019) Blockchain and building information modeling (BIM): review and applications in post-disaster recovery. Buildings 9:149. https://doi.org/10.3390/buildings9060149
79. Dakhli Z, Lafhaj Z, Mossman A (2019) The potential of blockchain in building construction. Buildings. https://doi.org/10.3390/buildings9040077
80. Succar B (2009) Building information modelling framework: a research and delivery foundation for industry stakeholders. Autom Constr 18(3):357–375. https://doi.org/10.1016/j.autcon.2008.10.003
81. Chan DWM, Olawumi TO, Ho AML (2019) Perceived benefits of and barriers to Building Information Modelling (BIM) implementation in construction: the case of Hong Kong. J Build Eng. https://doi.org/10.1016/j.jobe.2019.100764
82. Jin R, Zhong B, Ma L, Hashemi A, Ding L (2019) Integrating BIM with building performance analysis in project life-cycle. Autom Constr 106:102861. https://doi.org/10.1016/j.autcon.2019.102861
83. Vilutiene T, Hosseini MR, Pellicer E, Zavadskas EK (2019) Advanced BIM applications in the construction industry. Adv Civ Eng. https://doi.org/10.1155/2019/6356107
84. Rajabion L, Shaltooki AA, Taghikhah M, Ghasemi A (2019) Healthcare big data processing mechanisms: the role of cloud computing. Int J Inf Manag 49:271–289. https://doi.org/10.1016/j.ijinfomgt.2019.05.017
85. Radl J, Kaiser J (2019) Benefits of implementation of common data environment (CDE) into construction projects. IOP Conf Ser Mater Sci Eng. https://doi.org/10.1088/1757-899X/471/2/022021
86. Parn EA, Edwards D (2019) Cyber threats confronting the digital built environment Common data environment vulnerabilities and block chain deterrence. Eng Constr Archit Manag. https://doi.org/10.1108/ECAM-03-2018-0101
87. Sik D, Csorba K, Ekler P (2017) Implementation of a geographic information system with big data environment on common data model. In: 8th IEEE international conference on cognitive infocommunications, Debrecen, pp 181–184
88. Yuan X, Anumba CJ, Parfitt MK (2016) Cyber-physical systems for temporary structure monitoring. Autom Constr 66:1–14. https://doi.org/10.1016/j.autcon.2016.02.005
89. Akanmu A, Anumba C (2015) Cyber-physical systems integration of building information models and the physical construction. Eng Constr Archit Manag 22(5):516–535. https://doi.org/10.1108/ECAM-07-2014-0097
90. Antonio D, Garcia L, Anumba CJ (2019) Overview of supporting technologies for cyber-physical systems implementation in the AEC industry. In: ASCE international conference on computing in civil engineering 2019, Atlanta. https://doi.org/10.1061/9780784482438.063
91. Kan C, Anumba CJ, Messner JI (2017) Potential use of cyber-physical systems (CPS) for planning and operation of mobile cranes on construction sites. ASCE Int Workshop Comput Civ Eng. https://doi.org/10.1061/9780784480830.018
92. Kan C, Anumba CJ (2019) Digital twins as the next phase of cyber-physical systems in construction digital twins as the next phase of cyber-physical systems in construction. ASCE Int Conf Comput Civ Eng. https://doi.org/10.1061/9780784482438.033
93. Morley K, Germano J (2019) Priority on cybersecurity. J AWWA. https://doi.org/10.1002/awwa.1246
94. Habibzadeh H, Nussbaum BH, Anjomshoa F, Kantarci B, Soyata T (2019) A survey on cybersecurity, data privacy, and policy issues in cyber-physical system deployments in smart cities. Sustain Cities Soc 50:101660. https://doi.org/10.1016/j.scs.2019.101660
95. Zhao X, Miers I, Green M, Mitrani-reiser J (2018) Modeling the cybersecurity of hospitals in natural and man-made hazards. Sustain Resil Infrastruct 9689:1–14. https://doi.org/10.1080/23789689.2018.1448666
96. Daniel KB, Görges D (2019) Advances in service and industrial robotics. In: 28th international conference on robotics in Alpe-Adria-Danube Region, Adria
97. Xiao F, Fan C (2014) Data mining in building automation system for improving building operational performance. Energy Build 75:109–118. https://doi.org/10.1016/j.enbuild.2014.02.005
98. Ashouri M, Haghighat F, Fung BCM, Lazrak A, Yoshino H (2018) Development of building energy saving advisory: a data mining approach. Energy Build. https://doi.org/10.1016/j.enbuild.2018.04.052
99. Bai S, Li M, Kong R, Han S, Li H, Qin L (2019) Data mining approach to construction productivity prediction for cutter suction dredgers. Autom Constr 105(May):102833. https://doi.org/10.1016/j.autcon.2019.102833
100. Sun C, Zhang R, Sharples S, Han Y, Zhang H (2019) Thermal comfort, occupant control behaviour and performance gap: A study of office buildings in north-east China using data mining. Build Environ 149:305–321. https://doi.org/10.1016/j.buildenv.2018.12.036
101. Huang H, Chen X, Wang J (2020) Blockchain-based multiple groups data sharing with anonymity and traceability. Sci China 63:1–13. https://doi.org/10.1007/s11432-018-9781-0

102. Karaguzel OT, Elshambakey M, Zhu Y, Hong T, Tolone WJ, Wang H (2019) Open computing infrastructure for sharing data analytics to support building energy simulations. J Comput Civ Eng 33(6):1–12. https://doi.org/10.1061/(ASCE)CP.1943-5487.0000857
103. Cha Y, Choi W, Buyukozturk O (2017) Deep learning-based crack damage detection using convolutional neural networks. Comput-Aided Civ Infrastruct Eng 32:361–378. https://doi.org/10.1111/mice.12263
104. Kim S, Kang S, Ryu KR, Song G (2019) Real-time occupancy prediction in a large exhibition hall using deep learning approach. Energy Build J 199:216–222. https://doi.org/10.1016/j.enbuild.2019.06.043
105. Wu J, Cai N, Chen W, Wang H, Wang G (2019) Automatic detection of hardhats worn by construction personnel: a deep learning approach and benchmark dataset. Autom Constr 106:102894. https://doi.org/10.1016/j.autcon.2019.102894
106. Daneshgaran F, Zacheo L, Di Stasio F, Mondin M (2019) Use of deep learning for automatic detection of cracks in tunnels: prototype-2 developed in the 2017–2018 time period. J Transp Res Rec. https://doi.org/10.1177/0361198119845656
107. Farinella GM, Farioli G, Battiato S, Leonardi S, Gallo G (2014) Face re-identification for digital signage applications. Int Workshop Video Anal Audience Meas Retail Digital Signage 1:40–52. https://doi.org/10.1007/978-3-319-12811-5
108. Lee S, Sohn M, Kim H (2015) Implementation of age and gender recognition system for intelligent digital signage. Eighth Int Conf Mach Vis (ICMV 2015) 9875:3–8. https://doi.org/10.1117/12.2228520
109. Hikita K, Miwa H (2018) Evacuation guidance method by using augmented reality and digital signage. Adv Intell Netw Collab Syst. https://doi.org/10.1007/978-3-319-65636-6
110. Sethi M, Lijding M, Di Francesco M, Aura T (2015) Flexible management of cloud-connected digital signage. In: 015 IEEE 12th Intl Conf on Ubiquitous intelligence and computing and 2015 IEEE 12th Intl conf on autonomic and trusted computing and 2015 IEEE 15th Intl conf on scalable computing and communications and its associated workshops, Beijing, pp 205–212. https://doi.org/10.1109/UIC-ATC-ScalCom-CBDCom-IoP.2015.52
111. Liau Y, Lee H, Ryu K (2018) Digital Twin concept for smart injection molding. IOP Conf Ser Mater Sci Eng. https://doi.org/10.1088/1757-899X/324/1/012077
112. Negri E, Fumagalli L, Macchi M (2017) A review of the roles of digital twin in CPS-based production systems. Procedia Manuf 11:939–948. https://doi.org/10.1016/j.promfg.2017.07.198
113. Lu R, Brilakis I (2019) Digital twinning of existing reinforced concrete bridges from labelled point clusters. Autom Constr 105:102837. https://doi.org/10.1016/j.autcon.2019.102837
114. Tao F, Qi Q, Wang L, Nee AYC (2019) Digital twins and cyber: physical systems toward smart manufacturing and industry 4.0: correlation and comparison. Engineering 5(4):653–661. https://doi.org/10.1016/j.eng.2019.01.014
115. Editorial (2019) Special section on cloud-of-things and edge computing: recent advances and future trends. J Parallel Distrib Comput 133:170–173. https://doi.org/10.1016/j.jpdc.2019.07.004
116. Hui Y, Su Z, Luan TH, Cai J, Member S (2018) Content in motion: an edge computing based relay scheme for content dissemination in urban vehicular networks. IEEE Trans Intell Transp Syst. https://doi.org/10.1109/TITS.2018.2873096
117. Chen L, Englund C (2018) Every second counts: integrating edge computing and service oriented architecture for automatic emergency management. J Adv Transp. https://doi.org/10.1155/2018/7592926
118. Kochovski P, Stankovski V (2018) Supporting smart construction with dependable edge computing infrastructures and applications. Autom Constr 85:182–192. https://doi.org/10.1016/j.autcon.2017.10.008
119. Jensen K, Nielsen K, Brunoe T (2016) Application of mass customization in the construction industry. In: IFIP international conference on advances in production management systems (APMS)
120. Schätz B, Pretschner A, Huber F, Philipps J (2002) Model-based development of embedded systems. In: Advances in object-oriented information systems, OOIS 2002 workshops, pp 298–312
121. Zagvozda M, Dimter S, Moser V, Zagvozda M, Zagvozda M, Dimter S, Moser V (2019) Application of GIS technology in pavement management systems. Građevinar 71(4):297–304. https://doi.org/10.14256/JCE.1980.2017
122. Zhu J, Wang X, Chen M, Wu P, Jeong M (2019) Integration of BIM and GIS: iFC geometry transformation to shapefile using enhanced open-source approach. Autom Constr 106:102859. https://doi.org/10.1016/j.autcon.2019.102859
123. Abbas A, Salloom G, Ruddock F, Alkhaddar R (2019) Modelling Data of an urban drainage design using a geographic information system (GIS) database. J Hydrol. https://doi.org/10.1016/j.jhydrol.2019.04.009
124. Le C, Le T, Jeong HD, Lee E (2019) Geographic information system-based framework for estimating and visualizing unit prices of highway work items. J Constr Eng Manag 145(8):1–12. https://doi.org/10.1061/(ASCE)CO.1943-7862.0001672
125. Pargman D, Eriksson E, Kirman B, Comber R, Hedman A, Van Den Broeck M (2019) The future of computing and wisdom: insights from human–computer interaction. Futures. https://doi.org/10.1016/j.futures.2019.06.006
126. Ge L, Kuester F (2014) Integrative simulation environment for conceptual structural analysis. J Comput Civ Eng 29(4):1–10. https://doi.org/10.1061/(ASCE)CP.1943-5487.0000405
127. Malkawi AM, Srinivasan RS (2005) A new paradigm for human-building interaction: the use of CFD and augmented reality. Autom Constr 14:71–84. https://doi.org/10.1016/j.autcon.2004.08.001
128. Kalantari S, Poustinchi E, Ahmadi N (2017) Human-computer interaction in the form-making process. In: 22nd international conference ofthe association for computer-aidedarchitectural design research in Asia (CAADRIA), pp 529–538
129. Neijens B (2017) Improving asset utilization with an asset investment planning and management methodology. Water Pract Technol 12(1):43–47. https://doi.org/10.2166/wpt.2017.005
130. Rokstad MM, Ugarelli RM, Sægrov S (2016) Improving data collection strategies and infrastructure asset management tool utilisation through cost benefit considerations. Urban Water J. https://doi.org/10.1080/1573062X.2015.1024692
131. Taleb T, Afolabi I, Bagaa M (2018) Orchestrating 5G network slices to support industrial internet and to shape next-generation smart factories. IEEE Netw. https://doi.org/10.1109/MNET.2018.1800129
132. Xu Z, Raymond KK, Dehgantanha A, Parizi R, Hammoudeh M (2020) Cyber security intelligence and analytics. Adv Intell Syst Comput. https://doi.org/10.1007/978-3-030-15235-2
133. Urbina M, Acosta T (2019) Smart sensor: soC architecture for the industrial internet of things. IEEE Internet Things J. https://doi.org/10.1109/JIOT.2019.2908264
134. Arnold C, Voigt K (2018) Determinants of industrial internet of things adoption in German manufacturing companies. Int J Innov Technol Manag. https://doi.org/10.1142/S021987701950038X
135. Gubbi J, Buyya R, Marusic S, Palaniswami M (2013) Internet of Things (IoT): a vision, architectural elements, and future directions. Future Gener Comput Syst 29(7):1645–1660. https://doi.org/10.1016/j.future.2013.01.010

136. Tang S, Shelden DR, Eastman CM, Pishdad-bozorgi P, Gao X (2019) A review of building information modeling (BIM) and the internet of things (IoT) devices integration: present status and future trends. Autom Constr 101:127–139. https://doi.org/10.1016/j.autcon.2019.01.020
137. Louis J, Dunston PS (2018) Integrating IoT into operational work fl ows for real-time and automated decision-making in repetitive construction operations. Autom Constr 94:317–327. https://doi.org/10.1016/j.autcon.2018.07.005
138. Kifokeris D, Xenidis Y (2019) Risk source-based constructability appraisal using supervised machine learning. Autom Constr 104:341–359. https://doi.org/10.1016/j.autcon.2019.04.012
139. Potočnik P, Vidrih B, Kitanovski A, Govekar E (2019) Neural network, ARX, and extreme learning machine models for the short-term prediction of temperature in buildings. Build Simul 12(6):1077–1093. https://doi.org/10.1007/s12273-019-0548-y
140. Luo H, German-Paal S (2019) A locally weighted machine learning model for generalized. Comput-Aided Civ Infrastruct Eng. https://doi.org/10.1111/mice.12456
141. Tixier AJ, Hallowell MR, Rajagopalan B, Bowman D (2016) Application of machine learning to construction injury prediction. Autom Constr 69:102–114. https://doi.org/10.1016/j.autcon.2016.05.016
142. Marchesi M, Matt DT (2017) Design for mass customization: rethinking prefabricated housing using axiomatic design. J Archit Eng 23(3):1–20. https://doi.org/10.1061/(ASCE)AE.1943-5568.0000260
143. Aditra RF, Widyowijatnoko A (2016) Combination of mass customisation and conventional construction. In: 21st international conference of the association for computer-aided architectural design research in Asia CAADRIA 2016, pp 777–786
144. Lee XS, Khamidi MF, Kuppusamy S, Tuck C (2017) Client-oriented building mass customization (CoBMC). IOP Conf Ser Mater Sci Eng. https://doi.org/10.1088/1757-899X/291/1/012011
145. Paoletti I (2017) Mass customization with additive manufacturing: new perspectives for multi performative building components in architecture. Procedia Eng 180:1150–1159. https://doi.org/10.1016/j.proeng.2017.04.275
146. Brilakis I (2017) Mixed reality constructs a new frontier for maintaining the built environment. Civ Eng 170:53. https://doi.org/10.1680/jcien.2017.170.2.53
147. Dunston PS, Wang X (2005) Mixed reality-based visualization interfaces for architecture, engineering, and construction industry. J Constr Eng Manag 131:1301–1310
148. Wu W, Issa RRA (2014) BIM execution planning in green building projects: leed as a use case. J Manag Eng 31(1):A4014007. https://doi.org/10.1061/(asce)me.1943-5479.0000314
149. Chen Y, Kamara JM (2011) A framework for using mobile computing for information management on construction sites. Autom Constr 20(7):776–788. https://doi.org/10.1016/j.autcon.2011.01.002
150. Kim C, Park T, Lim H, Kim H (2013) On-site construction management using mobile computing technology. Autom Constr. https://doi.org/10.1016/j.autcon.2013.05.027
151. Zhang H, Chi S, Yang J, Moon S (2013) Development of a safety inspection framework on construction sites using mobile computing. J Manag Eng. https://doi.org/10.1061/(ASCE)ME
152. Isaac S, Bock T, Stoliar Y (2016) A methodology for the optimal modularization of building design. Autom Constr 65:116–124. https://doi.org/10.1016/j.autcon.2015.12.017
153. Sharafi P, Rashidi M, Samali B, Ronagh H, Mortazavi M (2018) Identification of factors and decision analysis of the level of modularization in building construction. J Archit Eng 24(2):1–12. https://doi.org/10.1061/(ASCE)AE.1943-5568.0000313
154. Tserng HP, Yin YL, Jaselskis EJ, Hung W, Lin Y (2011) Modularization and assembly algorithm for efficient MEP construction. Autom Constr 20:837–863. https://doi.org/10.1016/j.autcon.2011.03.002
155. Xiong X, Adan A, Akinci B, Huber D (2013) Automatic creation of semantically rich 3D building models from laser scanner data. Autom Constr 31:325–337. https://doi.org/10.1016/j.autcon.2012.10.006
156. Javadnejad F, Simpson C, Gillins D, Claxton Olsen MJ (2017) An assessment of UAS-based photogrammetry for civil integrated management (CIM) modeling of pipes. Pipelines 2017:112–123
157. Braun A, Borrmann A (2019) Combining inverse photogrammetry and BIM for automated labeling of construction site images for machine learning. Autom Constr. https://doi.org/10.1016/j.autcon.2019.102879
158. García-Luna R, Senent S, Jurado-Piña R, Jimenez R (2019) Structure from Motion photogrammetry to characterize underground rock masses: experiences from two real tunnels. Tunn Undergr Space Technol 83:262–273. https://doi.org/10.1016/j.tust.2018.09.026
159. Napolitano R, Glisic B (2019) Methodology for diagnosing crack patterns in masonry structures using photogrammetry and distinct element modeling. Eng Struct 181:519–528. https://doi.org/10.1016/j.engstruct.2018.12.036
160. Reinoso J, Goncalves J, Pereira C, Bleninger T (2018) Cartography for civil engineering projects: photogrammetry supported by unmanned aerial vehicles. Iran J Sci Technol Trans Civ Eng 42:91–96. https://doi.org/10.1007/s40996-017-0076-x
161. Nowogonska B (2019) Diagnoses in the aging process of residential buildings constructed using traditional technology. Buildings. https://doi.org/10.3390/buildings9050126
162. Slika W, Saad G (2016) An Ensemble Kalman Filter approach for service life prediction of reinforced concrete structures subject to chloride-induced corrosion. Constr Build Mater 115:132–142. https://doi.org/10.1016/j.conbuildmat.2016.04.025
163. Miao F, Dong S, Liang H, Wang X (2018) Manufacture and prefabrication practice on a test model of a novel six-bar tetrahedral cylindrical lattice shell. Adv Struct Eng. https://doi.org/10.1177/1369433218784040
164. Li X, Wu P, Yue T (2019) Integrating building information modeling and prefabrication housing production. Autom Constr 100:46–60. https://doi.org/10.1016/j.autcon.2018.12.024
165. Jang S (2018) Comparative analysis of multi-trade prefabrication construction methods. J Asian Archit Build Eng. https://doi.org/10.3130/jaabe.17.503
166. Jang S, Lee G (2018) Process, productivity, and economic analyses of BIM: based multi-trade prefabrication—a case study. Autom Constr 89:86–98. https://doi.org/10.1016/j.autcon.2017.12.035
167. Navarro-Rubio J, Pineda P, García-Martínez A (2018) Sustainability, prefabrication and building optimization under different durability and re-using scenarios: potential of dry precast structural connections. Sustain Cities Soc 44:614–628. https://doi.org/10.1016/j.scs.2018.10.045
168. Sullivan DTJO, Keane MM, Kelliher D, Hitchcock RJ (2004) Improving building operation by tracking performance metrics throughout the building lifecycle (BLC). Energy Build 36:1075–1090. https://doi.org/10.1016/j.enbuild.2004.03.003
169. Shin HM, Lee HM, Oh SJ, Chen JH (2011) Procedia engineering analysis and design of reinforced concrete bridge column based on BIM. Procedia Eng 14:2160–2163. https://doi.org/10.1016/j.proeng.2011.07.271
170. Vanlande R, Nicolle C, Cruz C (2008) IFC and building lifecycle management. Autom Constr J 18:70–78. https://doi.org/10.1016/j.autcon.2008.05.001

171. Jaselskis EJ, El-misalami T (2003) Implementing radio frequency identification in the construction process. J Constr Eng Manag 129:680–688
172. Xue F, Chen K, Lu W, Niu Y, Huang GQ (2018) Linking radio-frequency identification to Building Information Modeling: status quo, development trajectory and guidelines for practitioners. Autom Constr 93:241–251. https://doi.org/10.1016/j.autcon.2018.05.023
173. Ma G, Jiang J, Shang S (2019) Visualization of component status information of prefabricated concrete building based on building information modeling and radio frequency identification: a case study in China. Adv Civ Eng. https://doi.org/10.1155/2019/6870507
174. Judd J, Schmidt R, Danforth M, Branscomb J, Jung M (2018) Radio-frequency identification triggering system for structural health monitoring of highway bridges. Exp Vib Anal Civ Struct. https://doi.org/10.1007/978-3-319-67443-8_9
175. Zhang Y, Bai L (2015) Rapid structural condition assessment using radio frequency identification (RFID) based wireless strain sensor. Autom Constr 54:1–11. https://doi.org/10.1016/j.autcon.2015.02.013
176. Ko C, Pan N, Chiou C (2013) Maintenance, management, life-cycle design and performance web-based radio frequency identification facility management systems. Struct Infrastruct Eng 9(5):465–480. https://doi.org/10.1080/15732479.2010.546804
177. Charron N, Mclaughlin E, Phillips S, Goorts K, Narasimhan S, Waslander SL (2019) Automated bridge inspection using mobile ground robotics. J Struct Eng 145(11):1–18. https://doi.org/10.1061/(ASCE)ST.1943-541X.0002404
178. Mantha BRK, Menassa CC, Kamat VR (2018) Robotic data collection and simulation for evaluation of building retro fit performance. Autom Constr 92:88–102. https://doi.org/10.1016/j.autcon.2018.03.026
179. Davtalab O, Kazemian A, Khoshnevis B (2018) Perspectives on a BIM-integrated software platform for robotic construction through Contour Crafting. Autom Constr 89:13–23. https://doi.org/10.1016/j.autcon.2018.01.006
180. Tavares P, Costa CM, Rocha L, Malaca P, Costa P, Moreira AP, Veiga G (2019) Collaborative welding system using BIM for robotic reprogramming and spatial augmented reality. Autom Constr 106:102825. https://doi.org/10.1016/j.autcon.2019.04.020
181. Gooding L (2017) Enabling a self-sufficient energy efficient retrofit services sector future: a qualitative study. Energy Build. https://doi.org/10.1016/j.enbuild.2017.09.072
182. Aguacil S, Lufkin S, Rey E (2019) Active surfaces selection method for building-integrated photovoltaics (BIPV) in renovation projects based on self-consumption and self-sufficiency. Energy Build 193:15–28. https://doi.org/10.1016/j.enbuild.2019.03.035
183. Liu S, Schiavon S, Das HP, Jin M, Spanos CJ (2019) Personal thermal comfort models with wearable sensors. Build Environ 162:106281. https://doi.org/10.1016/j.buildenv.2019.106281
184. Barrias A, Casas JR, Villalba S (2019) Fatigue performance of distributed optical fiber sensors in reinforced concrete elements. Constr Build Mater J 218:214–223. https://doi.org/10.1016/j.conbuildmat.2019.05.072
185. Taheri S (2019) A review on five key sensors for monitoring of concrete structures. Constr Build Mater 204:492–509. https://doi.org/10.1016/j.conbuildmat.2019.01.172
186. Muroni A, Gaetani I, Hoes P, Hensen JLM (2012) Occupant behavior in identical residential buildings: a case study for occupancy profiles extraction and application to building performance simulation. Build Simul 12(6):1047–1061
187. Baochen F, Chunchang Z, Xi H (2019) Simulation of nonlinear behavior of beam structures based on discrete element method. Int J Steel Struct. https://doi.org/10.1007/s13296-019-00228-0
188. Cuerda E, Guerra-Santin O, Sendra JJ (2019) Comparing the impact of presence patterns on energy demand in residential buildings using measured data and simulation models. Build Simul 12(6):985–998. https://doi.org/10.1007/s12273-019-0539-z
189. Wang X, Kim RE, Kwon O, Yeo I, Ahn J (2019) Continuous real-time hybrid simulation method for structures subject to fire. J Struct Eng 145(12):1–12. https://doi.org/10.1061/(ASCE)ST.1943-541X.0002436
190. Azhar S, Asce AM, Riaz Z, Robinson D (2019) Integration of social media in day-to-day operations of construction firms. J Manag Eng 35(1):1–7. https://doi.org/10.1061/(ASCE)ME.1943-5479.0000660
191. Duryan M, Smyth H (2018) Service design and knowledge management in the construction supply chain for an infrastructure programme. Built Environ Proj Asset Manag. https://doi.org/10.1108/BEPAM-04-2018-0060
192. Chen P, Nguyen TC (2019) A BIM-WMS integrated decision support tool for supply chain management in construction. Autom Constr 98:289–301. https://doi.org/10.1016/j.autcon.2018.11.019
193. Shahbaz MS, Chandio AF, Oad M, Ahmed A, Ullah R (2018) Stakeholders management approaches in construction supply chain: a new perspective of stakeholders theory. Int J Sustain Constr Eng Technol 9(2):16–26. https://doi.org/10.30880/ijscet.2018.09.02.002
194. Deng Y, Gan VJL, Das M, Cheng JCP, Anumba C, Asce F (2019) Integrating 4D BIM and GIS for construction supply chain management. J Constr Eng Manag 145(4):1–14. https://doi.org/10.1061/(ASCE)CO.1943-7862.0001633
195. Fernando P, Ruiz A, Hernán L, Lara M, Manuel A, Pereira DJ (2017) Standardization of policies of the use of distance aircraft systems and aircraft systems (RPAS/UAS) in ecuador. Adv Intell Syst Comput. https://doi.org/10.1007/978-3-319-56541-5
196. Golizadeh H, Hosseini MR, Edwards DJ, Abrishami S, Taghavi N, Banihashemi S (2019) Barriers to adoption of RPAs on construction projects: a task: technology fit perspective. Constr Innov. https://doi.org/10.1108/CI-09-2018-0074
197. Trhan O (2017) The creation of space vector models of buildings from RPAS photogrammetry data. Slovak J Civ Eng 25(2):7–14. https://doi.org/10.1515/sjce-2017-0007
198. De Klerk R, Mendes A, Pires D, Pinto J (2019) Usability studies on building early stage architectural models in virtual reality. Autom Constr 103:104–116. https://doi.org/10.1016/j.autcon.2019.03.009
199. Wolfartsberger J (2019) Analyzing the potential of Virtual Reality for engineering design review. Autom Constr 104:27–37. https://doi.org/10.1016/j.autcon.2019.03.018
200. Wu W, Hartless J, Tesei A, Gunji V, Ayer S, London J (2019) Design Assessment in virtual and mixed reality environments: comparison of novices and experts. J Constr Eng Manag. https://doi.org/10.1061/(ASCE)CO.1943-7862.0001683
201. Hwang H, Baek J, Kim J, Kim C (2019) Prediction of bond performance of tension lap splices using artificial neural networks. Eng Struct 198(May):109535. https://doi.org/10.1016/j.engstruct.2019.109535
202. Fan G, Li J (2019) Lost data recovery for structural health monitoring based on convolutional neural networks. Struct Control Health Monit. https://doi.org/10.1002/stc.2433
203. Alipour M, Harris DK, Miller GR (2019) Robust pixel-level crack detection using deep fully convolutional neural networks. J Comput Civ Eng 33(6):1–14. https://doi.org/10.1061/(ASCE)CP.1943-5487.0000854
204. Cadini F, Giglio M (2019) Particle filtering-based adaptive training of neural networks for real-time structural damage diagnosis

and prognosis. Struct Control Health Monit 2451:1–19. https://doi.org/10.1002/stc.2451
205. Nikose TJ, Sonparote R (2019) Dynamic wind response of tall buildings using artificial neural network. Struct Des Tall Spec Build. https://doi.org/10.1002/tal.1657
206. Liu M, Han S, Lee S (2017) Potential of convolutional neural network-based 2D human pose estimation for on-site activity analysis of construction workers. Comput Civ Eng 2017:141–149