Implementation of technologies in the construction industry: a systematic review

Xichen Chen and Alice Yan Chang-Richards
Department of Civil and Environmental Engineering, The University of Auckland, Auckland, New Zealand

Antony Pelosi
School of Architecture, Victoria University of Wellington, Wellington, New Zealand

Yaodong Jia
Callaghan Innovation, Lower Hutt, Wellington, New Zealand

Xuesong Shen
School of Civil and Environmental Engineering, University of New South Wales, Sydney, Australia

Mohsin K. Siddiqui
Department of Civil and Environmental Engineering, University of Delaware, Newark, Delaware, USA, and

Nan Yang
Callaghan Innovation, Lower Hutt, Wellington, New Zealand

Abstract

Purpose – With interest in modern construction methods and new technologies on the rise, construction companies globally are increasingly looking at how to embrace new ideas and engage with new approaches to do things better. A significant amount of work has been carried out investigating the use of individual technologies in the construction sector. However, there is no holistic understanding of the new and emerging technologies that have had proven benefits for construction projects. To fill this gap, this paper aims to provide a landscape of technologies that have been implemented in the construction industry and the benefits associated with their implementation.

Design/methodology/approach – A systematic review approach and PRISMA guidelines were used. A total of 175 articles published between 2001 and 2020 were identified and thoroughly reviewed.

Findings – The results show that a total of 26 technologies were identified from the literature, and these can be categorised into five groups in terms of their functionality in construction process, namely: (1) data acquisition, (2) analytics, (3) visualisation, (4) communication and (5) design and construction automation. Digital technologies, especially for data acquisition and visualisation, generally appear to underpin and enable innovation in many aspects of construction. Improvements in work efficiency, health and safety, productivity, quality and sustainability have been cited as being the primary benefits of using these technologies. Of these, building information modelling (BIM) appears to be the single most commonly used technology thus far. With the development of computer technology, BIM has constantly been used in combination with other technologies/tools such as unmanned aerial vehicles/systems (unmanned aerial vehicle (UAV)/UAS), geographic information systems (GIS), light detection and ranging (LiDAR) and multidimensional modelling to realise a specifically defined benefit.

Practical implications – The findings from this review would help construction practitioners identify the types of technologies that can be implemented in different stages of construction projects to achieve desired outcomes, and thus, make appropriate decisions on technology investment and adoption. This review also

The authors would like to thank the China Scholarship Council (CSC) and the University of Auckland Joint Doctoral Scholarship and the funding from the Building Research Association of New Zealand (Project number LR120069). Without the funding supports from both sources, this research would not have been possible.
suggestions that to reap the full potential that these technologies offer, aside from construction companies changing their culture and business models, corresponding changes in the construction sector’s operating systems related to building regulation, education and training, as well as contracting and procurement are required.

**Originality/value** – This paper undertakes a comprehensive systematic review of studies on technology implementation in the construction sector published between 2001 and 2020. It is the first attempt internationally to provide a holistic picture of technologies that have been studied and implemented in construction projects.

**Keywords** Technology, Innovation, Construction industry, Technology implementation, Systematic review

**Paper type** Research paper

### 1. Introduction

The construction sector is considered one of the largest revenue-generating sectors in the world, producing approximately $10 trillion of construction related goods and services each year. However, construction has fallen behind other sectors in terms of productivity, creating a $1.6 trillion value gap (McKinsey Global Institute, 2017). With urban areas growing in population by 200,000 people per day, more affordable housing and utility infrastructure are needed to cope with this growing demand. These trends, however, present both challenges and opportunities for the construction sector to accelerate its transformation through innovation and leveraging technologies (World Economic Forum, 2016).

There is a growing trend in the construction sector to introduce new technologies into the practice of design and construction in response to pressures to reduce costs, improve efficiency, productivity, safety and meet sustainability goals (Loosemore, 2014). According to Sepasgozar and Davis (2018), construction technologies refer to new tools, machines and modifications that can help achieve a goal, perform a specific function or solve a problem. As suggested by Duncan et al. (2018), technologies can provide the necessary strategies to achieve a better response to current and future demands and enhance performance and productivity in the construction industry. Case studies of technology implementation and evidence have shown that the application of the additive manufacturing (AM) or 3D printing in construction, for instance, has been found to be beneficial in terms of waste reduction, providing design flexibility and constructability, as well as saving manpower. Similarly, there are numerous productivity benchmark studies that show the tangible and intangible benefits of using building information modelling (BIM). For example, Stanford University’s Center for Integrated Facilities Engineering suggested 7%, 40% and 80% reductions in project time, cost and time spent on cost estimation, respectively (Azhar, 2011). Over the past decade, implementing new technologies in construction practice has been recognised as an important business strategy (Rahman, 2014; Sepasgozar et al., 2016) and has drawn increased attention from stakeholders of many kinds in the construction sector (Sepasgozar and Davis, 2018).

However, a significant amount of work has been conducted looking at the use of individual technologies in the construction sector. For instance, Bilal et al. (2016) reviewed the adoption of big data analytics in the construction industry and elaborated on how it can be used in combination with other technologies to improve the construction process. Guo et al. (2017) conducted a comprehensive review of visualisation technologies such as AR (augmented reality)/VR and how they have been implemented in construction health and safety management and noted perceived implementation barriers in the wider industry. Similarly, Tay et al. (2017) undertook a review of the research and application of 3D printing/AM and summarised the challenges, limitations and future works in the construction sector. A recent review by Cai et al. (2019) on automation and robotic technologies in the construction industry identified the gaps of their current applications and set out the underlining scientific and technological conditions that will enable its effective implementation in the sector.
When implementing technologies, several technological, cultural and organisational barriers have been identified in previous studies. These include a lack of investment in technology and research and development due to the cost being perceived as high (Jaillon and Poon, 2010; Pan et al., 2011), insufficient training and skills development to match technology implementation (Pan et al., 2011), interoperability between new tools/technologies with existing systems (Tibaut et al., 2016) and social inertia that resists change (Cooperative Research Centre for Construction Innovation, 2007). The questions that construction professionals and practitioners often ask are whether there are new ways of doing things, have they been beneficial for the companies that have adopted them, and whether the construction sector is capable of implementing such technologies? (Duncan et al., 2018). To answer these questions, we need an improved understanding of the technology landscape of the construction sector.

This paper provides such an understanding through using a systematic review approach. The following research questions were developed to guide this systematic review:

RQ1. What types of technology have been applied in the construction industry and how are they categorised?

RQ2. How have the identified technologies been implemented?

RQ3. What are the benefits associated with technology implementation?

To address these research questions, we will first use an existing article search and identification protocol to carry out the systematic review. Based on the articles identified and selected, we will examine the types of technologies studied in these articles and how they are implemented, thus identifying the application areas and their categorisations. We will also extract data from the selected articles about any commentary or evidence that refer to the perceived or actual benefits associated with the implementation of technologies cited and categorise these benefits into groups such as productivity, sustainability and health and safety that are commonly known to construction practitioners. Categorisation will offer insights into the kinds of activities and objectives that construction companies aim to improve by using different technologies.

The review also delves into the conditions necessary to enable successful technology implementation, which sets the direction for construction companies to self-assess their status in regard to technology adoption and tackle challenges in order to be technology-ready now and in the future. The remaining sections of this paper are outlined below. The following section introduces the systematic review methodology and how the article search and identification was conducted. This is followed by the results and discussion sections that focus on presenting the data in response to the three research questions and the implications of our findings for both theory and practice. The conclusion section summarises the reflections of the authors in terms of research limitations and future research directions.

2. Materials and methodology

A systematic review approach was adopted to identify globally available technologies and where their implementation proved to be effective in the construction sector. Compared with a conventional literature review, a systematic review adopts a structured protocol to identify, interpret, appraise and summarise key research findings from articles that are most relevant to the chosen review topic (Green, 2005). By setting the research strategy and criteria for article selection, a systematic review allows work to be assessed in an explicit and replicable way (Saieg et al., 2018). Systematic reviews have increasingly been adopted by the scientific community due to their objectivity and transparent nature (Hallinger, 2013). A systematic
A limitation of using a systematic review approach is related to the probability of bias in the selection of publications (Saieg et al., 2018). To ensure quality data sources, the type of article was limited to those from reputable journals. However, the use of inclusion and exclusion criteria may lead to the omission of relevant papers that did not meet these criteria. Therefore, there is a risk that some relevant studies published elsewhere, or that does not meet the inclusion criteria, might have been omitted during the search.

With the research questions in mind, a systematic review was undertaken from October 2019 to March 2020. The review comprised four distinct stages (Figure 1), namely: (1) identification of articles; (2) screening of articles; (3) checking the eligibility of articles and (4) inclusion of selected articles and synthesis. The researchers first formulated the research questions that guided the review process. The protocol for the systematic review was developed in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines (Moher et al., 2015). PRISMA was first developed as a protocol to support the documentation and review of publicly available publications (Shamseer et al., 2015). It has been used to guide the development of protocols of systematic reviews and meta-analyses. By adopting a transparent literature screening process, PRISMA can produce evidence-based outcomes and at the same time enhance the reporting quality of the review (Moher et al., 2015). Compared with other review protocols such as the Quality of

![Figure 1. Flowchart of PRISMA systematic review process](image-url)
Reporting of Meta-Analyses (QUOROM) (Moher et al., 2000) and RepOrting standards for Systematic Evidence Syntheses (ROSES) (Haddaway et al., 2018), the methodological and analytic approach of PRISMA is more clear and straightforward (Shamseer et al., 2015). This protocol was therefore adopted to specify the steps taken and number of articles arrived at through each step as shown in Figure 1.

2.1 Step 1: identification of articles
In this initial step, six electronic databases were searched, namely: Scopus, Web of Science, Engineering Village, IEEE, SpringerLink and Google Scholar. The first five databases were used to identify the most relevant articles, while Google Scholar was mainly used for search result validation. These six databases were selected because they contain wide and up-to-date coverage of both peer-reviewed and non-peer-reviewed research materials (Aghaei Chadegani et al., 2013; Falagas et al., 2008). Additionally, they are all reputable AEC (architecture, engineering and construction) databases as Aghaei Chadegani et al. (2013) suggest.

Key search schemas were selected and applied in the preliminary search after considering both relevant and alternative terms commonly used to represent technologies applied in the construction industry. The search terms ((technolog* OR techni* OR innovat*) AND ("construction industry" OR “construction sector” OR “construction company” OR “construction firm” OR “construction organization” OR “building industry” OR “building sector” OR “building project”)) were used to search in the article title or abstract or keywords fields in all six databases. The search was also limited to documents written in English. As shown in Figure 1, the initial identification stage resulted in a total of 113,252 results.

2.2 Step 2: screening of articles
During the screening step, the title and abstract of each article were screened to assess the relevance to the research questions. The initial online database screening returned 12,706 articles including journal and conference papers, book chapters, industry reports and research reports. These returned articles were imported into Mendeley reference management software. Duplicates were then removed and a total of 8,269 papers remained.

2.3 Step 3: checking eligibility of articles
At the eligibility step, full texts of 278 articles were thoroughly reviewed which met three inclusion and exclusion criteria (see Table 1).

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Content</th>
</tr>
</thead>
<tbody>
<tr>
<td>Relevance</td>
<td>Rating scale Description</td>
</tr>
<tr>
<td>1 (low)</td>
<td>Articles that only examine technology itself without discussing its implementation in construction (exclusion)</td>
</tr>
<tr>
<td>2 (medium)</td>
<td>Articles that describe the theory and conceptual application of the technology without providing practical examples of how the technology was implemented (exclusion)</td>
</tr>
<tr>
<td>3 (high)</td>
<td>Articles that present empirical findings such as real-world examples or case studies to demonstrate technology implementation in construction (inclusion)</td>
</tr>
<tr>
<td>Document type</td>
<td>Peer-reviewed journal articles (inclusion)</td>
</tr>
<tr>
<td>Currency</td>
<td>Other material types such as books, book chapters and reports (exclusion)</td>
</tr>
<tr>
<td></td>
<td>Articles published from 2001 to 2020 (inclusion)</td>
</tr>
<tr>
<td></td>
<td>Materials published during other time periods (exclusion)</td>
</tr>
</tbody>
</table>

Table 1. Inclusion and exclusion criteria applied in literature search
First, the relevance of each article was assessed in accordance with a rating scale that was used by previous studies (e.g. Babalola et al., 2019). The rating was chosen based on the extent of the empirical evidence in each article, where “1”, “2” and “3” denoted low, medium and high relevance, respectively. Only those articles that demonstrated implementation case studies/practices of one or several technologies in construction would receive “3” and were included.

Second, the article type was limited to papers published in journals and conference proceedings. Only peer-refereed journal articles and conference papers were included in this study to ensure the authenticity and credibility of the publications (Saunders, 2011).

Third, the currency of articles was considered. Only articles published between 2001 and 2020 were included. In the initial search stage, no currency criteria were set. The results showed that the majority of publications regarding technology in construction were published within the past 20 years. The article eligibility check resulted in 278 articles.

2.4 Step 4: inclusion of selected articles and synthesis
At this step a quality check of publication sources was undertaken. Only articles published in Q1 and Q2 quartile-ranked journals were included. These two rankings represent the top 50% of studies widely cited and have high methodological strength in accordance with the SCImago Journal Ranking metric (Royle et al., 2013). This resulted in a total of 175 articles. From the 175 articles, information such as: (1) article title; (2) publication source; (3) year published; (4) country or region (referring to the affiliation of the corresponding author); (5) technology referred to; (6) implementation areas; and (7) associated benefits of implementation were extracted. In order to compile and code results with the aforesaid aspects, an in-depth content analysis was then carried out using descriptive and thematic analyses. Knowledge gaps regarding technology implementation and key areas for further research were also investigated.

3. Results
3.1 Summary of selected articles
Table 2 provides an overview of the selected articles and their publication sources. Of the 175 articles, the journal Automation in Construction published the highest number of selected articles (80 articles out of 175, 45.71%). The majority of selected articles (150 articles, 85.71%) were published in 19 journals, while 25 articles (14.29%) were from 25 journals and were classified as “Other journals”.

Figure 2 illustrates the chronological distribution of the 175 articles. As shown in Figure 2, there is gradual growing research interest from 2001 to 2010, with a slight drop in 2011. However, 2012 saw a sharp increase in the number of publications (16 articles) and this continued into 2013 (16 articles). The momentum of research on this topic seems to have slowed down from 2014 to 2017, with 2018 marked as a pivotal time with an increase to 25 articles and a slight decrease in the following year in 2019 (20 articles). It is worth noting that only one article was selected from 2020 as the reporting time of this systematic review was in early 2020.

Figure 3 shows the pattern of publications according to the geographical location of the first author’s institute. The 175 articles came from 26 countries/regions (the USA, China, Hong Kong, South Korea, Canada, the UK, Taiwan, Australia, Germany, Turkey, Brazil, Italy, Finland, India, the Netherlands, Norway, Singapore, the UAE, Egypt, Japan, Malaysia,
Portugal, South Africa, Spain, Sweden, and Switzerland) across five continents. Research institutes in the USA led research in this area (41 articles out of 175, 23.0%), followed by leading research institutes in China (25.0%), Hong Kong (20.0%) and South Korea (13.0%). Research institutes in Asia contributed the most articles (45.7%). Researchers from America and Europe made contributions of 32.0% and 16.6%, respectively. Oceania, which includes Australia and New Zealand, appears to lack research investigating technology implementation in construction, with only 4.6% of articles published from this region. The remainder of the articles was from research institutes in Africa.

3.2 Types of technologies and categorisation
Table A1 (see Appendix) lists the 26 technologies and their definitions that were identified from the 175 selected articles. Figure 4 shows the distribution of these articles according to the type of technology and their categorisation. The top five most researched technologies in the construction domain were BIM (52 articles, 30.0%), radio-frequency identification (RFID) (36 articles, 21.0%), immersive media (e.g. virtual reality, AR, mixed reality and gaming technology) (24 articles, 14.0%), multidimensional building modelling (nD) (18 articles, 10.0%) and web services (13 articles, 7.0%). Most of the selected articles researched the use of multiple technologies at different project phases. BIM appeared to be the most commonly used technology with which other technologies combined, such as nD-BIM (8 articles), BIM-GIS (6 articles), LiDAR-BIM (4 articles) and nD-BIM-GIS (1 article).

The 26 technologies can be categorised into five groups according to their functionality, namely: (1) technologies for data acquisition; (2) technologies for data analytics; (3) technologies for data visualisation; (4) technologies for communication and (5) technologies for design and construction automation. The functionality of these technologies depends on the application described in the reviewed papers and the specific technologies included in these five categories can be seen in Figure 4 and Table 3. As shown in Figure 4, more than half of the selected articles (89 out of 175, 51.0%) focused on research concerning construction.
data acquisition technologies, and another 47.0% of articles (83 out of 175) studied data visualisation technologies. Approximately 9% of articles (16 out of 175) looked at technologies that assisted communication among stakeholder and construction teams. Technologies for data analytics (13 out of 175 articles) and construction automation (12 out of 175 articles) seem to have received almost equal attention from scientific and research communities.

3.3 Technology implementation trend over time
The investigation period of this review was from 2001 to 2020. Figure 5 presents the general trend of the implementation of each technology category over time and Figure 6 presents the most implemented technology in each category. It can be seen that data acquisition and visualisation technologies have been extensively implemented in the construction industry since 2003–2004. The number of articles published regarding visualisation technologies
such as BIM and nD, has increased from only two articles between 2003 and 2004 to its peak of 20 articles between 2017 and 2018. The implementation of data acquisition technologies, such as UAV and LiDAR (light detection and ranging) seem to have followed a similar trend. This trend seems to have dropped between 2019 and 2020, perhaps due to the timing of this systematic review (October 2019–March 2020) as many articles were yet be published. Surprisingly, the implementation of data analytics technologies appears to have not gained momentum, despite “big data” being a ‘buzz word’ in the construction research domain. Similarly, the implementation of construction automation technologies has not taken up speed, with only seven articles as its highest number between 2017 and 2018.

Traditional manual data acquisition methods for progress tracking and monitoring of construction have long been accused of posing various problems including low accuracy and time delays. Due to the rapid development of wireless technologies, numerous automated and electronic data acquisition technologies have been implemented in the construction industry. For example, barcoding technology requires manual scanning and only one reading can be captured at a time, whereas with automatic identification technology (RFID), all tags within a certain frequency range can be captured by readers no matter the complexity of the environment. Articles regarding barcoding are found only in 2014 and 2017, while articles

![Geographical distribution of selected articles](image-url)
Regarding RFID have increased in popularity since 2007. As data acquisition technologies are implemented, their applicability and suitability to different projects can be determined according to their benefits and limitations. More recently, the integration of different data acquisition technologies, the hybrid approach, has shown obvious advantages in regard to mitigating individual technologies’ limitations and leveraging more benefits.

Technologies for data analytics have been gaining more attention since 2009. With the development of computer technologies, complex project problems involving a large amount of data and uncertainty can be solved by employing advanced data analytics approaches. For example, the predictive capability of artificial intelligence (AI) techniques can take into account more details of the construction project and provide solutions to overcome both existing and future problems. Implementation of data analytics technologies has focused on improvement in the accuracy and quality of outcomes, efficiency of the analysis process and its ability to deal with huge datasets.
<table>
<thead>
<tr>
<th>Category</th>
<th>Technology</th>
<th>Planning and design</th>
<th>Project management</th>
<th>Implementation/application area</th>
<th>Health and safety</th>
<th>Onsite operation</th>
<th>Construction methods</th>
<th>Building performance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data acquisition</td>
<td>WLANs</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>1</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>Barcoding</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>1</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>MC</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>3</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>Eye-tracking</td>
<td>–</td>
<td>–</td>
<td>4</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>Zigbee</td>
<td>–</td>
<td>–</td>
<td>5</td>
<td>1</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>Bluetooth</td>
<td>–</td>
<td>–</td>
<td>3</td>
<td>3</td>
<td>–</td>
<td>1</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>WSNs</td>
<td>–</td>
<td>–</td>
<td>4</td>
<td>1</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>IoTs</td>
<td>–</td>
<td>–</td>
<td>3</td>
<td>3</td>
<td>1</td>
<td>2</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>UAV/UAS/drones</td>
<td>2</td>
<td>–</td>
<td>3</td>
<td>1</td>
<td>–</td>
<td>–</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>UWB (Ultra-wideband)</td>
<td>–</td>
<td>–</td>
<td>3</td>
<td>4</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>GIS</td>
<td>5</td>
<td>–</td>
<td>–</td>
<td>3</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>LiDAR/LADAR</td>
<td>3</td>
<td>1</td>
<td>1</td>
<td>3</td>
<td>–</td>
<td>2</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>GPS</td>
<td>–</td>
<td>–</td>
<td>2</td>
<td>7</td>
<td>1</td>
<td>2</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>Photogrammetry</td>
<td>3</td>
<td>–</td>
<td>–</td>
<td>6</td>
<td>–</td>
<td>2</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>Sensors</td>
<td>–</td>
<td>–</td>
<td>7</td>
<td>1</td>
<td>–</td>
<td>–</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>RFID</td>
<td>4</td>
<td>–</td>
<td>9</td>
<td>24</td>
<td>2</td>
<td>10</td>
<td>–</td>
</tr>
<tr>
<td>Data analytics</td>
<td>Big data</td>
<td>2</td>
<td>–</td>
<td>1</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>AI/ML</td>
<td>1</td>
<td>4</td>
<td>5</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Data visualisation</td>
<td>VP</td>
<td>6</td>
<td>–</td>
<td>2</td>
<td>2</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>nD</td>
<td>11</td>
<td>3</td>
<td>2</td>
<td>12</td>
<td>–</td>
<td>1</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>IM</td>
<td>12</td>
<td>–</td>
<td>8</td>
<td>7</td>
<td>1</td>
<td>1</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>BIM</td>
<td>28</td>
<td>4</td>
<td>6</td>
<td>19</td>
<td>3</td>
<td>8</td>
<td>–</td>
</tr>
<tr>
<td>Communication</td>
<td>Web services</td>
<td>6</td>
<td>1</td>
<td>1</td>
<td>5</td>
<td>–</td>
<td>2</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>MC</td>
<td>–</td>
<td>–</td>
<td>1</td>
<td>3</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Construction automation</td>
<td>AM/3D printing</td>
<td>1</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>4</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>Robotics</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>4</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>DFab</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>1</td>
<td>4</td>
<td>2</td>
<td>–</td>
</tr>
</tbody>
</table>

Table 3. Technologies used in construction
Visualisation technologies that have seen a steady growth in implementation similar to data acquisition technologies have become a solution to numerous construction problems in recent years. The visualisation of construction data in an interactive/virtual environment can provide a more comprehensive construction process and help communication between different project participants. Visualisation technologies have also been increasingly integrated with each other or with data acquisition technologies to achieve a more efficient and effective planning, designing and monitoring process. As shown in Figure 6, BIM technology, which has fundamentally changed the traditional manner in which construction designing and planning is undertaken, has been increasingly implemented in the construction industry since 2011. With the help of advances in computer technology, BIM has become a standard technology in the construction industry and a support which has been extensively integrated with other technologies such as nD and IM.

Communication technologies have been implemented in the construction industry over the entire investigated period. Due to the multi-party nature of the sector, timely and accurate
transfer of information among participants has become one of the key factors influencing the overall performance of construction projects. Internet-related or web service technologies have been reported to be very useful and could provide an open platform for project participants to share files, systems, data and other information efficiently. Communication technologies in recent years have been frequently integrated with other technologies (e.g. BIM, IM and AI) to help users access and alter designs and processing systems through the Internet. The implementation of advanced communication technologies enables participants to achieve efficient collaboration in terms of management.

Construction automation is recognised as an advanced technology which may in the future result in the autonomous production of buildings. Compared with other technologies, the real-world utilisation of construction automation technologies is still in its infancy. The increased implementation of construction automation technologies in recent years, especially in 2018, may be due to the growing demand for sustainability, economy and productivity in construction and the built environment. The advantages of utilising construction automation technologies in terms of the environment, economy and sustainability have been addressed frequently in recent years.

3.4 Construction activities in which technologies are implemented

Figure 7 and Table 3 illustrate the distribution of technologies according to their application/implementation areas. These areas span a variety of construction activities and fall into the following six categories:

1. Project planning and design (e.g. site layout, material estimation, design standardisation/automation and preparation for project commencement).
2. Project management (e.g. monitoring and assessment of cost, risk, time, progress, profit and quality).
3. Health and safety (e.g. health and safety planning, monitoring, assessment and training).
4. Onsite operation, logistics and supply chains (e.g. material tracking, logistics monitoring and controlling and supply chain management).
5. Construction methods (e.g. 3D printing, robots and prefabrication).
6. Building performance/structural health assessment (e.g. defects detection, building structural checks and performance monitoring).

BIM (53 articles, 16.00%), immersive media (AR/VR/MR/Gaming) (12 articles, 6.86%) and nD (9 articles, 5.14%) were the most commonly used technologies for project planning and design. For example, BIM was used to enable an automated schedule generation process that included creating construction tasks, calculating activity durations and applying sequencing rules (Kim et al., 2013). Hilfert and König (2016) proposed a VR-BIM methodology to generate a low-cost VR environment from the detailed modelling of BIM, which also enabled interaction between a user and the model within a virtual space. Kang and Miranda (2006) integrated VR technology to visualise the erection processes of multiple cranes and design the schedule before the commencement of construction. By using nD technology, Dawood and Mallasi (2006) presented a space-time analysis approach to modelling and quantifying workspace congestion for planners.

BIM (4 articles, 2.29%), AI (4 articles, 2.29%) and nD (3 articles, 1.71%) seem to be the most popular technologies for managing construction projects. For example, Jin et al. (2019) proposed a 4D-BIM method for risk assessment that enabled designers and contractors to effectively collaborate to identify undiscovered hazards, recognise design and schedule
errors, select design alternatives concerning safety in the early design phase and visualise the results of the 4D model for site safety planning. Hartmann et al. (2012) also adopted 4D-BIM tools to combine 3D representations with construction schedules and enable project managers to visualise, assess and mitigate project risks throughout the life cycle of a
A construction project. Based on AI techniques (i.e. artificial neural networks and support vector machines), Wang et al. (2012) proposed an AI model using the status of early planning to predict project cost and schedules.

In regard to improving the health and safety of construction workers, RFID (9 articles, 5.14%), immersive media (IM) (AR/VR/MR/Gaming) (8 articles, 5.00%) and BIM (6 articles, 3.43%) technologies were the most frequently investigated. Lee et al. (2012) provided two case studies that employed an RFID-based real-time location system to monitor workers and equipment in a dynamic and complex construction site environment. Such a system can warn anyone who might be in immediate danger. Chae and Yoshida (2010) also adopted an RFID-based system to prevent collision accidents between heavy equipment such as hydraulic excavators and cranes by analysing data received from RFID tags attached to the equipment. Guo et al. (2012) applied game technology to simulate construction hazards and human behaviour in the safety training of workers on a construction site. By combining location tracking, BIM, AR and game technologies, a safety management and visualisation system can identify field safety risks and enhance real-time communication between managers/site engineers and workers (Park and Kim, 2013).

The implementation of RFID (24 articles, 13.71%), BIM (19 articles, 10.86%) and nD (12 articles, 6.86%) technologies were frequently investigated for onsite operations, logistics and supply chain management. Song et al. (2006) found that by using RFID technology in pipe fabrication, the amount of cement/concrete materials used could be accurately identified and work progress could be tracked in near-real time. This could then enable just-in-time cement production and delivery. Demiralp et al. (2012) simulated the implementation of RFID technology in tracking components in the supply chain of prefabricated concrete wall panels and observed significant cost savings. Similarly, BIM was often used together with GIS models to simulate the flow of materials, track supply chain status and send warning signals to site teams to plan and prepare for material delivery (Irizarry et al., 2013). Kim et al. (2018a, b) developed an AR-based 4D-BIM system that connected 4D, 5D and AR objects to monitor the construction schedule and enable better cooperation and decision making between project managers and site engineers.

As for new construction methods, robotics, AM/3D printing and digital fabrication technologies (4 articles each, 2.29%) were the most researched in the literature. For instance, Jung et al. (2013) investigated a high-rise building project which adopted a robot-based construction automation system to conduct the fabrication of steel beams, including a rail sliding mechanism and a cross-wired lift for transporting robotic bolting devices. Bos et al. (2016) introduced the 3D printing of concrete and discussed the characteristics and practical applications of 3D concrete printing technology. While most studies focused on concrete construction, future research is inclined towards lighter materials such as steel for the purposes of better structural efficiency, reduction in material consumption and wastage, streamlining and expedition of the design-build process, enhanced customisation, greater architectural freedom and improved accuracy and safety on site. There is also the possibility to utilise AM for hybrid construction, structural strengthening and repairs. The current digital-led prefabrication field, however, has largely focused on investigating the integration of robotic systems in the automation process (Garcia de Soto et al., 2018).

For building quality and performance monitoring, studies tended to focus on the application of RFID (10 articles, 5.71%) and BIM (8 articles, 4.57%) as both tools provide a large amount of data about a structure or a building. The field tests conducted by Ergen et al. (2007) suggested “intelligent components” embedded with RFID tags could store and retrieve maintenance information during the service life of a facility. Costin and Teizer (2015) integrated passive RFID and BIM technologies to enable real-time localisation and visualisation within an indoor environment and helped workers to efficiently locate required equipment in facilities for proper maintenance. Compared with conventional 2D
models or drawings, BIM can also be used for effective time/cost analysis when retrofitting a building, as both designers and construction workers can easily identify items in a 3D model and recognise workflows between activities (Cha and Lee, 2015).

3.5 Benefits exhibited by implementing technologies in construction

Most of the reviewed work highlighted the benefits of using technologies in construction (see Table 4 and 5). Table 4 illustrates that the benefits cited in the literature fall into five groups, namely, improvement in:

1. Work efficiency (145 articles, 82.86%).
2. Health and safety (92 articles, 52.57%).
3. Productivity (86 articles, 49.14%).
4. Quality (58 articles, 33.14%).
5. Sustainability (20 articles, 11.43%).

It can be seen that the most frequently cited benefit as a result of implementing technology is an improvement in work efficiency (82.86%), followed by health and safety (52.57%), productivity (49.14%), quality (33.14%) and finally sustainability (11.43%). Two technologies, BIM (46 articles, 26.29%) and RFID (33 articles, 18.86%) were recognised as having the potential to provide benefits in all five categories. These were followed by IM (e.g. AR/VR/MR/Gaming) (21 articles, 12.00%), nD (17 articles, 9.71%) and web services:

<table>
<thead>
<tr>
<th>Benefit category</th>
<th>Detailed benefits</th>
<th>Selected sources</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sustainability</td>
<td>Application of sustainable design</td>
<td>Jalaei and Jrade (2014), Wong and Kuan (2014)</td>
<td>11.43</td>
</tr>
<tr>
<td></td>
<td>Adoption of sustainable construction materials and methods</td>
<td>Bos et al. (2016), García de Soto et al. (2018)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Enhancement of project delivery schedule</td>
<td>Deng et al. (2019), Rwamamara et al. (2010)</td>
<td></td>
</tr>
<tr>
<td>Quality</td>
<td>Reduction of construction waste</td>
<td>Liu et al. (2019), Pan et al. (2018)</td>
<td>33.14</td>
</tr>
<tr>
<td></td>
<td>Improvement in quality management and control</td>
<td>Golparvar-Fard et al. (2009), Irizarry et al. (2013), Lu et al. (2007), Pan et al. (2018)</td>
<td></td>
</tr>
<tr>
<td>Productivity</td>
<td>Improvement in communication and collaboration</td>
<td>Cha and Lee (2015), Costin and Teizer (2015), García de Soto et al. (2018), Khanzode et al. (2008), Pan et al. (2018), Song et al. (2006)</td>
<td>49.14</td>
</tr>
<tr>
<td></td>
<td>Reduction of project cost and time</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Health and safety</td>
<td>Reduction of high risk work</td>
<td>Pan et al. (2018), Rwamamara et al. (2010)</td>
<td>52.57</td>
</tr>
<tr>
<td></td>
<td>Improvement of safety training</td>
<td>Hasanzadeh et al. (2017), Le et al. (2015), Teizer et al. (2013)</td>
<td></td>
</tr>
<tr>
<td>Efficiency</td>
<td>Improvement of management and control</td>
<td>Dawood and Mallasi (2006), Deng et al. (2019), Irizarry et al. (2013), Lee et al. (2013)</td>
<td>82.86</td>
</tr>
<tr>
<td></td>
<td>Reduction of construction conflicts and project delays</td>
<td>Khanzode et al. (2008), Lee and Kim (2017), Lu et al. (2007)</td>
<td></td>
</tr>
</tbody>
</table>

Table 4. Implementation of technologies and benefits
The VR-BIM methodology proposed by Hilfert and König (2016), for example, could enable interaction between users and the model, which would provide effective collaboration and understanding between the design team and the construction team and enhance the efficiency of project planning and design. The RFID-BIM indoor localisation technology integrated by Costin and Teizer (2015) provided an economic and effective way to assist construction workers in real-time with indoor location tracking and visualisation, saving time and money.

As for addressing health and safety issues, RFID (20 articles, 11.43%), BIM (19 articles, 10.86%), IM (12 articles, 6.86%), nD (9 articles, 5.14%) and sensor technologies (8 articles, 4.57%) were frequently implemented. For example, the 4D-BIM risk assessment framework proposed by Jin et al. (2019) could help planners identify undiscovered hazards and select design-safe alternatives in early design phases. This would in turn achieve better site safety planning before construction. The AR-BIM-RFID framework proposed by Park and Kim (2013) could identify field safety risks by collecting information from construction sites, visually display hazard information and improve safety knowledge and effective decision making among safety managers and workers.

In terms of productivity, technologies such as BIM (35 articles, 20.00%), RFID (19 articles, 10.86%), IM (12 articles, 6.86%) and nD (10 articles, 5.71%) were most commonly suggested.
in the literature. For instance, the implementation of nD-BIM tools in a healthcare construction project investigated by Khanzode et al. (2008) could help optimise the coordination process of mechanical, electrical and plumbing systems with significant time and cost savings. A BIM/RFID enriched VR simulation could acquire the construction data of a steel structure through RFID in real time, accomplish data integration through BIM and improve VR representations (Xie et al., 2011).

For the purpose of improving project quality, the implementation of BIM (18 articles, 10.29%) and RFID (16 articles, 9.14%) was highly recommended. For instance, application of BIM resulted in better quality control and, if combined with RFID tagging technology, could enhance the accuracy of BIM models and achieve a higher quality project at the end of the construction process.

The importance of quality control and improvement was also investigated frequently in the reviewed articles. Implementation of technologies such as BIM (18 articles, 10.29%), RFID (16 articles, 9.14%), photogrammetry, nD and web services (6 articles, 3.43% each) were most frequently implemented in the literature. For example, the BIM-based AR application proposed by Ratajczak et al. (2019) could provide context-specific information on the construction site, link quality checklists to each construction task and streamline the information flow by displaying tailored information through 3D models. Abundant information on construction sites could reduce the likelihood of errors and increase building quality. As indicated by Lu et al. (2007), data or information collection through the use of GPS, RFID and Bluetooth technologies could help eliminate the temporal and spatial gaps between the construction site and the management office, achieve a real-time quality control process of construction operations and improve the quality of both the components and operations.

As for sustainability, related articles were comparatively limited, with the most cited technologies including BIM (9 articles, 5.14%) and nD (4 articles, 2.29%). Lee and Kim (2017) suggested that BIM-based 4D simulation could minimise product manufacturing errors and the necessity for rework. This could lead to further reductions in construction delays, waste and cost overruns and could be used for modular construction with the goals of waste reduction and enhancing sustainability during project lifecycles.

The five categories of benefits also coincide with the requirements in engineering practice. The construction industry has long been challenged by several key issues, including low efficiency, poor safety management and low productivity. According to Zhang et al. (2018), the main reason for poor efficiency lies in the interface between design and construction and the delays and cost overruns as a result of design errors and construction variations from the design. As for health and safety, the construction industry has even been known as “one of the most dangerous industries” due to its poor safety record (Zhou et al., 2013). This review reveals that stakeholders are increasingly considering the implementation of new technologies that could make the construction industry eco-friendly while achieving higher quality (Babalola et al., 2019). Dealing with these challenges will also benefit the project in various aspects.

Figure 8 illustrates the benefits associated with the various technology categories. The implementation of data acquisition and visualisation technologies shows advantages in all five categories of benefits. For example, automatic data acquisition technologies, such as RFID, could enable efficient management of the construction site (Ergen et al., 2007), identify potential hazards (Chae and Yoshida, 2010; Teizer, 2015), improve project quality (Wang, 2008), increase workforce productivity (Teizer et al., 2013) and improve the sustainability of materials (Lee et al., 2013). The visualisation of construction information and schedules could improve efficiency, quality and safety by enabling interaction and optimisation of construction scheduling and design (Liu et al., 2015), enhance labour productivity and
sustainability by saving design and planning time and reduce human errors (Lee and Kim, 2017).

4. Discussion
This systematic review shows that data acquisition technologies have been implemented intensively for onsite operations, logistics and management of supply chains, health and safety management and the assessment of the health of a structure. Among these implementation areas, the data acquired from construction sites or workers can be used for various proposes, including progress tracking and controlling, equipment and material tracking, safety planning and monitoring, productivity monitoring for individual workers and construction maintenance management. Specifically, for onsite operations, various data acquisition technologies (i.e. RFID, GPS, photogrammetry and UWB) were used to gather information from a construction site with often complex and dynamic activities. Such information was used to enhance communication between onsite workers and staff in the office and can significantly help a project management office to have a better understanding and control of the construction process.

Instead of manual approaches to progress tracking and monitoring that often lack sufficient accuracy, the implementation of digital data acquisition technologies has provided an automatic methodology to achieve timely detection, eliminate potential construction discrepancies and provide direct support for better decision making. As for logistics and management of supply chains, data acquisition technologies (i.e. RFID, GPS, GIS and UWB) were adopted for equipment and material tracking and location information in harsh construction environments. These technologies in turn helped streamline information flow in construction supply chain systems and achieved an effective and convenient materials management system by reducing lead time, operational errors and costs.

Our review reveals that technologies for data visualisation seem to be largely used for project planning and design, onsite operations and managing health and safety. By visualising details of the construction project, the following goals could be achieved: virtual designing and planning of the construction project at an early preconstruction phase
(Kim et al., 2018a, b; Liu et al., 2018), real-time construction process visualisation and control (Golparvar-Fard et al., 2009) and safety training (Teizer et al., 2013). Virtual designing and planning were the main focus in terms of the implementation of visualisation technologies. As indicated by Li et al. (2003), increased competition among contractors encourages them to optimise and validate their construction operations planning and design through a virtual environment. The visualisation technologies (i.e. BIM, IM, nD and VP) could generate a virtual model containing objects with real-world properties and integrate 3D models, construction schedules, resources and site spaces together. These capabilities provide a good way to help designers and planners demonstrate, validate and optimise their model and planning virtually. In this way, design-related errors could be reduced during the earliest stage of the project, and better communication and collaboration among project participants could be achieved (Kim et al., 2018a, b). In combination with data acquisition technologies, visualisation technologies could provide a visual representation of the construction site, thus enhancing communication between project participants. Efficiency could also be enhanced with respect to the detection of problems, enhancing communication between project participants and assisting with timely problem solving (Deng et al., 2019; Irizarry et al., 2013).

The reviewed articles have provided extensive practical examples of how to implement technologies to achieve desired goals. Goodrum et al. (2009) and Goodrum and Haas (2004) suggested that a substantial shift to technology-led systems could have a significant impact on the construction workforce. As we see construction companies globally are increasingly looking at how to embrace new ideas and engage with new approaches to do things better, it is crucial to pinpoint both the drivers and barriers to technology implementation in technological, cultural, organisational and institutional contexts. Blanco et al. (2016) advocated that to reap the full potential technologies can offer the construction sector; it requires a new business model that supports the implementation of new technologies. Additionally, it requires a corresponding change in the construction sector’s operating systems in regard to building regulation, education and training, as well as contracting and procurement. In particular, establishing supportive guidance and guidelines in building regulations can be a key factor in the successful implementation of technology (Mao et al., 2015). As the adoption of technologies generally require upskilling of the current workforce, sufficient education and training at all levels is also crucial. This may require close cooperation between the technology providers and construction organisations (Mazurkiewicz and Poteralska, 2017). Requiring the use of new technologies or innovative methods in design and construction might be a very good lever in procurement and contracting to encourage engineering and construction companies to take the leap of faith into technology adoption.

5. Research contribution and future research directions

There are a limited number of reviews that addressed the new technologies implemented in the construction sector. Most of these studies only focused on a particular technology, identifying the trend of its application and the general challenges and opportunities that exist to date (e.g. Bilal et al., 2016; Cai et al., 2019; Guo et al., 2017; Tay et al., 2017). The most important difference between this study and existing reviews is that this is the first attempt internationally to provide a holistic picture of technologies that have been studied and implemented at construction project level. In addition to identifying the types of new technologies that have been implemented in construction, it also defined the categories for their application areas throughout the life cycle of a construction project and categories of perceived benefits. This is critical as such categorisations facilitate understanding and devising appropriate strategies and action plans to uplift the overall outcomes of a construction project from project planning and design to building maintenance.
In examining the level of technology adoption in the construction sector, questions that should be asked are, if there are new ways of doing things, have they been beneficial for the sectors adopted, if not, how can they ensure that the sector is capable to take on? (Duncan et al., 2018). The findings of this systematic review therefore have answered the first part of this question. To address the second part of the question, future research is needed to develop a benchmarking tool for technology adoption at both levels of construction organisations and projects. This review has also provided additional insights into the myriad of benefits of using proven technologies in construction projects and will help us understand how different technologies can be deployed by incorporating the associated benefits from a technology diffusion process using Tornatzky and Fleisher’s (1990) technology-organization-environment framework. The research trend of the reviewed technologies as revealed in this paper provide a general direction of where innovation interests lies and where further research can focus on how to translate such interests into real success in the construction sector. Further studies may also be required for investigations into the drivers and barriers of implementation of different technologies in a systematic manner to ensure successful adoption.

Practically, the review findings provide the global construction sector with a full picture of the types of new and emerging technologies that have attracted attention from academia and practitioners. Based on the benefits and application areas of the investigated technologies, construction companies could make informed decisions to prioritise their investments in these new technologies. Implementation will also require changes in building regulation, education and training, as well as contracting and procurement. Therefore, further cross-disciplinary studies to address the barriers to technology implementation that are within and outside construction organisations are needed.

6. Conclusions and research limitations
With the rapid development of various modern construction methods and technologies, efforts are being made to solve frequently mentioned construction issues such as low productivity and efficiency. During the writing of this article, the COVID-19 crisis has had a significant impact on the construction sector which is vulnerable to economic cycles. This crisis may however accelerate the industry transformation that started well before the pandemic. In times such as these, it is more important than ever for AEC businesses to look to the future to see what their industries may look like in the aftermath and make strategic decisions to manage disruptions and thrive through crises.

The search process was conducted in October 2019 and a total of 175 articles were included. Based on a comprehensive investigation of the reviewed articles, 26 technologies were identified and categorised into five groups according to their functionality, namely: data acquisition, analytics, visualisation, communication, and design and construction automation. Digital technologies collectively appear to underpin and enable innovation in many aspects of construction. With improved understandings of these technologies, a variety of corresponding implementation areas were categorised into six aspects and the main benefits associated with those technologies were also highlighted. Improvements in work efficiency, health and safety, productivity, quality and sustainability have been cited as being primary benefits of using these technologies.

The findings of this research indicate that digital technologies, especially those for data acquisition and visualisation, dominate the global technological implementation in the construction sector. BIM and RFID technologies were identified as the most implemented technologies. More significantly, BIM was frequently integrated with other technologies to achieve multiple benefits, and RFID was found to be the most common automatic tracking and monitoring technology on construction sites. It seems that extended use of data
acquisition and visualisation technologies can bring numerous benefits in terms of enhancing work efficiency, labour productivity, health and safety, project quality and sustainability.

The findings from this systematic review provide construction organisations with an improved understanding of global trends in technology implementation. Construction companies can draw on this list of technologies and their associated benefits and areas in which they have been implemented to make better decisions regarding investment in new technologies. However, the existing literature provides limited information on the conditions that are required for successful implementation of these technologies. As the majority of technologies identified in this paper are data-oriented and involve construction data, therefore, if any data that contain information on construction workers and employees, there might be a set of ethical and legal concerns due to privacy and data security issues. In addition to the technical complexities of certain technologies, it is important that government agencies work alongside the construction sector for an optimal configuration of policies and decisions that will enable construction companies to become technology competent. The authors hope this systematic review of technologies can spur further discussions around how technology can address not only the construction sector's productivity issues, but how it may also be able to resolve other economic, environmental and social problems facing our communities.

References


# Technology Definition

<table>
<thead>
<tr>
<th>Technology</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wireless local area networks (WLANs)</td>
<td>WLANs are radio-signal-based positioning systems, supported by underlying radio frequency (RF) and infrared (IR) transmission technologies</td>
</tr>
<tr>
<td>Barcoding</td>
<td>Barcoding technology tags materials with symbols that can be scanned electronically using laser or camera</td>
</tr>
<tr>
<td>Mobile computing (MC)</td>
<td>MC allows the user to access data and information by using a computer without a fixed physical link</td>
</tr>
<tr>
<td>Eye-tracking</td>
<td>Eye-tracking technology can track the rapid movements of the eye between fixation points followed by an eye-movement data analysis</td>
</tr>
<tr>
<td>Zigbee</td>
<td>Zigbee is a short wireless network protocol based on IEEE 802.15.4</td>
</tr>
<tr>
<td>Bluetooth</td>
<td>Bluetooth is a wireless technology capable of exchanging data and communicating over short distances</td>
</tr>
<tr>
<td>Wireless sensor networks (WSNs)</td>
<td>A WSN is a self-organised wireless network consisting of a large number of sensor nodes that interact with the physical world</td>
</tr>
<tr>
<td>Internet of things (IoTs)</td>
<td>IoT enables real-time monitoring of devices dynamically achieved by multiple types of available sensors and the interconnection of these smart objects into a global network</td>
</tr>
<tr>
<td>Unmanned aerial vehicles/systems or drones (UAVs/UASs/drones)</td>
<td>Aircraft that work without a human pilot onboard. Primarily used to acquire information</td>
</tr>
<tr>
<td>Ultra-wide band (UWB)</td>
<td>UWB is applied as a network of receivers and tags that communicate with one another</td>
</tr>
<tr>
<td>Geographical information system (GIS)</td>
<td>GIS is a computer-based system to collect, store, integrate, manipulate, analyse and display data in a spatially referenced environment</td>
</tr>
<tr>
<td>Light/laser detection and ranging or 3D scanning (LiDAR/LADAR)</td>
<td>An optical remote sensing technology that can determine distance between a sensor and an object or a surface</td>
</tr>
<tr>
<td>Global positioning systems (GPS)</td>
<td>GPS is a satellite-based navigation system made up of a network of satellites</td>
</tr>
<tr>
<td>Photogrammetry (photogrammetry or image processing or video-grammetry)</td>
<td>This technology acquires point cloud data by re-organising 2D images or videos that have overlapping intervals into 3D point clouds</td>
</tr>
<tr>
<td>Sensor technology</td>
<td>Sensor technology enables smart sensors, such as FBG (Fiber Bragg grating) sensors and/or piezoelectric sensors to monitor people or buildings</td>
</tr>
<tr>
<td>Radio-frequency identification (RFID)</td>
<td>RFID is a location system characterised with superior predispositions, including the recognition of multiple markers, communication ranges from five to six metres and a storage database for thousands of data files</td>
</tr>
<tr>
<td>Big data</td>
<td>Big data is capable of transforming the way in which organisations can visualise, function and perform routines and practices which deal with large amounts of data</td>
</tr>
</tbody>
</table>

Table A1. List of technologies and their definition (continued)
<table>
<thead>
<tr>
<th>Technology</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Artificial intelligence (AI)</td>
<td>AI techniques include latent class clustering analysis (LCCA), hybrid models of case-based reasoning (CBR), analytic hierarchy processes (AHP), artificial neural networks (ANN), fuzzy logic (FL), genetic algorithms (GAs) and their derivatives</td>
</tr>
<tr>
<td>Virtual prototyping (VP)</td>
<td>VP is a computer-aided design and manufacturing process concerned with the construction of virtual prototypes and realistic graphical simulations that address the broad issues of physical layout, operational concepts, functional specifications and dynamic analysis under various operating environments</td>
</tr>
<tr>
<td>nD (3D/4D/5D modelling)</td>
<td>nD models contain 3D geometric information and enable users to visualise the progress of a project when added to a time factor</td>
</tr>
<tr>
<td>Immersive media (IM) including augmented reality (AR), virtual reality (VR), mixed reality (MR) and gaming technology</td>
<td>IM technologies enable users to visualise large amounts of complex data through free navigation in real time within a 3D environment</td>
</tr>
<tr>
<td>Building information modelling (BIM)</td>
<td>BIM combines design and visualisation capabilities with rich parametric objects and the maximum level of detail in geometry</td>
</tr>
<tr>
<td>Web services</td>
<td>Web services allow collaborative management under conditions of decentralised coordination and enable users to access, modify and update projects in accordance with a user’s level of authority</td>
</tr>
<tr>
<td>Additive manufacturing or 3D printing (AM)</td>
<td>AM is a manufacturing procedure that produces layers to create solid 3D objects from digital models, allowing engineers, architects and designers to create customised designs in one-step</td>
</tr>
<tr>
<td>Digital prefabrication (DFab)</td>
<td>DFab is based on a combination of computational design methods and automated construction processes, which are typically categorised as subtractive, formative or additive</td>
</tr>
<tr>
<td>Robotics</td>
<td>Robotic technology covers systems from manually manipulated mechanical machinery, remote controlled semi-automated or automated devices, to more sensible and intelligent autonomous robots</td>
</tr>
</tbody>
</table>

Table A1.