ITcon
www.itcon.org - Journal of Information Technology in Construction - ISSN 1874-4753

CONSTRUCTION 4.0: A COMPARATIVE ANALYSIS OF RESEARCH AND PRACTICE

SUBMITTED: April 2022
REVISED: January 2024
PUBLISHED: February 2024
EDITOR: Bimal Kumar
DOI: 10.36680/j.itcon.2024.002

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SUMMARY*: This paper presents an overview of the existing literature on Construction 4.0 technologies over the past decade and their most common applications in both research and practice, aimed at achieving three objectives. First, the search for the most relevant articles on Construction 4.0, published in the scientific literature, and small firms that are developing and delivering 4.0 technologies in the construction industry allows to identify the numerous applications associated with Construction 4.0. Second, the applications found in the scientific literature and those identified in practice are classified and compared based on a framework consisting of three distinct axes. Third, the classification framework highlights current research trends and potential areas for future research, which can be summarized as follows: (i) development of hybrid digital solutions; (ii) alignment with effective collection of more structured data, smart interactive web technologies, robotics, autonomous systems, and intelligent built assets; and (iii) strengthen the capacities of artificial intelligence and machine learning.*

KEYWORDS*: Construction industry; Industry 4.0; Construction 4.0; Digital technologies.*

REFERENCE*: Nathalie Perrier, Aristide Bled First, Mario Bourgault, Nolwenn Cousin, Christophe Danjou, Robert Pellerin, Thibaut Roland (2024). Construction 4.0: A comparative analysis of research and practice. Journal of Information Technology in Construction (ITcon), Vol. 29, pg. 16-39, DOI: 10.36680/j.itcon.2024.002*

1. INTRODUCTION

After the advent of mechanization, electrification, and automation, the fourth Industrial Revolution, also known as Industry 4.0, can be seen as a digital revolution merging and interplaying the digital and the physical to enable new technologies, new smart products, new services, new kinds of value chains, new processes, and new business models to create more value (Dallasega et al., 2018; Underwood and Isikdag, 2011; Turk, 2019; Woodhead et al., 2018). Digitalisation is gradually changing the construction industry, thus giving rise to what can be called "Construction 4.0" (Turk, 2019). Whether at the level of project management, manufacturing, execution, monitoring, construction techniques or the tools used, digitalisation is gradually transforming the traditional ways of doing things in the construction industry. New forms of work are emerging thanks to the introduction of technologies such as: Building Information Modeling (BIM), virtual and augmented reality, prefabrication, smart objects, additive manufacturing, wearable technologies, automation, robotization, etc. These new technologies have great potential not only for improving productivity, collaboration and information management, but also for reducing project deadlines, increasing the quality of built deliverables, improving health and safety on site, and promoting the achievement of environmental targets.

While these technologies are not specific to the 4.0 revolution, some are more frequently mentioned when it comes to Construction 4.0. Examples include the use of Radio Frequency Identification (RFID) tags to identify and locate materials on site, and the use of augmented, virtual and mixed reality to visualize a building design idea in three-dimensional (3D). Another major technological concept in the field of construction is robotization, which includes work automation and collaborative robotics to guide workers' gestures or to perform repetitive manual tasks on construction sites (e.g., masonry robots), drones and Unmanned Aerial Vehicles or UAVs to continuously analyze data that can help monitor sites, track work progress, quality and safety of operations, 3D printing or additive manufacturing to manufacture components for modular construction, and 3D laser scanning to reproduce the shape of a site by capturing the necessary data in the field to create a point cloud image that will then be integrated into a BIM software (Oesterreich and Teuteberg, 2016).

Despite its importance, the construction sector still suffers from difficulties preventing it from reaching performance and productivity levels in terms of using the technologies. This discrepancy can be explained by a number of characteristics specific to the construction sector. In particular, the construction industry is struggling to modernise its practices. The field is subject to strong resistance to change and many of its processes are still very manual. For example, research and development expenditures in the construction sector are significantly lower than in other industries. In construction, about 1% of revenues are dedicated to research and development, while the automotive and aerospace industries devote between 3.5% and 4.5% of their revenues to research (Agarwal, Chandrasekaran, & Sridhar, 2016). This gap can be explained in part by the size of construction firms, often very small, which have a lower capacity to invest in new technologies (Oesterreich & Teuteberg, 2016). The value chain is fragmented and the completion of projects usually relies on numerous subcontractors. This fragmentation requires collaboration between several actors of different sizes who generally do not have the same level of technological development as the big actors in the sector. Also, in highly engineered and complex projects, many challenges arise from difficult access to project information to support critical decision-making, resulting in considerable time spent on accessing and retrieving relevant information (Tezel and Aziz, 2017). In this context, the value of Construction 4.0 is in its ability to allow rapid and convenient access to relevant and accurate construction project information-

To meet the challenges facing the construction industry, the development and adoption of digital technologies in the construction sector – and in all stages of project's life cycle (i.e., from design to renovation) – has mainly focused in recent years on the integration and use of Building Information Modeling (BIM). BIM refers to both the digital information sharing model and the information management methodology. Building information models are files which reliably represent the planning, design, construction and operation of a building facility (Cheng et al., 2013). BIM also refers to a collaborative working methodology characterized by the use of up-to-date accessible information about a building project by architects, engineers, builders, and owners to support design and construction tasks and make informed decisions faster (Rocha et al., 2017).

BIM technology has been increasingly adopted in the architectural, engineering and construction industry in the last two decades (Cheng et al., 2013). Thoughtful use of BIM can improve building quality by allowing timely discovery of potential problems through increased detail and information in the design phase (Dallasega et al., 2018). As a result, BIM has become a construction standard in some form in several countries (McAuley et al., 2017). In countries such as the United States and the United Kingdom, governments are promoting, even requiring, BIM-supported project completion (Cheng et al., 2013). At German Railways, an internal vision of the introduction of BIM has been developed since 2015 to design and control with BIM all new and complex projects that are suitable for standardisation by the end of 2020 (Ehrbar, 2016). To stimulate the adoption of technologies, the construction sector needs to develop standardized policies or procedures, like BIM.

The development and use of technological applications represent both a major challenge and an opportunity for the construction industry. In the end, the ability to capture, analyze and integrate massive meaningful data will contribute to enhancing the added value of the design, management and execution of worksites, with the ultimate goal of increasing the productivity of businesses, the quality of built structures and the health and safety of workers (Oesterreich & Teuteberg, 2016).

Over the recent years, developments in Construction 4.0 have attracted increasing interest from researchers. Various surveys relating to these developments have thus been published. For example, the use of BIM in the field of construction has been reviewed (Azhar, 2011) as well as its evolution throughout the construction life cycle phases (Megahed, 2015; Chowdhury et al., 2019). Surveys on the combination of BIM with other technologies, such as cloud computing (Wong et al., 2018b), Internet of Things (Shahinmoghadam and Motamedi, 2019), Geographic Information System or GIS (Basir et al., 2018, Wang et al., 2019), and virtual reality (Sidani, 2019) have also been proposed to report on the deployment and application of BIM. Some key 4.0 technologies in construction, including additive manufacturing (Paolini et al., 2019) and mixed reality (Cheng et al., 2020), have been the subject of state-of-the-art reviews, while more global literature reviews related to the current state of Construction 4.0 have appeared in the scientific literature (Boton et al., 2020; Zabidin et al., 2020).

Moreover, a large part of the surveys focused on the development of analytical frameworks to classify key 4.0 technologies for construction into several main categories, all in an effort to help reach the goals of Construction 4.0. Such frameworks were described, for example, by Son et al. (2010), Oesterreich and Teuteberg (2016), Qin et al. (2016), Dallasega et al. (2018), Hossain and Nadeem (2019), and Perrier et al. (2020). It is worth mentioning that, in addition to survey the state-of-the-art research in the context of Construction 4.0, Oesterreich and Teuteberg (2016) have explored the state of practice of Industry 4.0 relating technologies in the construction industry.

Most of these surveys focused either on BIM applications or on the grouping of 4.0 technologies; a very few papers took a construction life cycle perspective, i.e., according to the phases of the project – design and engineering, construction, operation and maintenance, etc. – where these technologies are mostly used (De Groote and Lefever, 2016; Firdaus Razali et al., 2019; Gerbert et al., 2016; Panteli et al., 2020; Perrier et al., 2020; Wong et al., 2018a) or the point of view of a project management process, e.g., risk management, safety management, etc. (Perrier et al., 2020; Štefanič and Stankovski, 2018; Zhou et al., 2012; Zou et al., 2017).

This paper focuses on both perspectives, taking into account all phases of a project life cycle as well as key project management processes. To our knowledge, 4.0 technologies and their applications have not yet been reviewed and classified from both perspectives, comparing what has been done in both research and practice. More precisely, this review is intended to fulfill three ambitions.

Our first ambition is to review the technologies and concepts at the heart of Construction 4.0 in the scientific literature over the past decade. Second, relevant research and practice on Construction 4.0 technologies and their most common applications will be classified from a project management perspective, according to a framework consisting of three axes: 1) the phases of a construction project's life cycle in which these technologies are used (e.g., design, engineering, construction, operation, maintenance, renovation); 2) the various underlying project management processes (e.g., communications, health and safety, human resources, procurement, etc.) that are facilitated by using these 4.0 technologies; and 3) the level of development or maturity of the applications of technologies in practice, i.e., in start-up firms. The third and final objective of this paper is to compare existing 4.0 technological applications researched in the scientific literature and technological solutions developed in the construction industry and to identify the main gaps between research and practice. These gaps should motivate and guide researchers to make contributions to the future development of the construction sector as technological-rich systems totally different from conventional construction production systems.

The remainder of this article is organized as follows. First, Section 2 outlines research background on Construction 4.0 and presents key Construction 4.0 technologies and concepts studied in the scientific literature. Section 3 will elaborate on the research methodology that resulted in the classification framework provided in Section 4 and the research trends and areas for future research that will be discussed in Section 5. Conclusions and direction for future research are presented in Section 6.

2. RESEARCH BACKGROUND

Section 2 presents a brief discussion of the major trends – Construction 4.0, BIM, and other key technologies – actually driving the gradual movement towards the development and adoption of technologies in the construction sector. For each of these streams, we provide a definition and summarize the main opportunities it can offer in the construction sector.

2.1 Construction 4.0: the state of the art in construction

Construction 4.0 is based on the concepts of Industry 4.0 and digitalisation related to this industrial revolution in the construction industry. The term "Industry 4.0" was first used in 2011 at the Hannover Fair in Germany to describe a new type of industrialization aimed at improving energy efficiency and responding to the country's changing demographics (Drath and Horch, 2014). Since then, several concepts, such as smart manufacturing – the term 'smart' highlights the importance of information and communication technologies in enhancing manufacturing – smart production, and advanced manufacturing, have been used to describe the phenomenon of Industry 4.0. The concept of smart factory, which is specific to the manufacturing sector, has also been used to refer to the interconnection of different production points and the automation of their information exchange (Halaška & Šperka, 2018). More specifically, Industry 4.0 in manufacturing focuses on cyberphysical systems (CPS) and the Internet of Things (IoT), i.e., the association of the physical world with the virtual world (Kagermann et al., 2013). The IoT and CPS are in fact a way of managing systems and technologies that can be used in real time across the entire value chain and enable process improvement (Brettel, Friederischen, Keller, & Rosenberg, 2014). Industry 4.0 is therefore at the origin of integrated environments, based on the all-digital and the all-connected between the different objects (processes, products, services) automated throughout the value chain for real-time decision-making (Danjou et al., 2017; Halaška & Šperka, 2018). For example, the integration of sensors in products enables them to be geolocated, performance in-use to be measured and monitored.

While Industry 4.0 is expanding in the manufacturing sector, its potential for transformation is gradually reaching that of construction. Several authors have already begun this movement by focusing on what is known as "Construction 4.0", i.e., the application of concepts and technologies related to Industry 4.0 to the field of construction. Like Industry 4.0, Construction 4.0 implies a notion of data exploitation and sharing to support real-time decision making. These decisions will be mostly decentralized and some of them may even be made automatically by systems, without human intervention. The scientific literature offers several reviews of technological applications that can be related to Construction 4.0 (Dallasega, Rauch, & Linder, 2018; Oesterreich & Teuteberg, 2016; Zabidin et al., 2020). However, these applications are not necessarily based on new technologies, since they include both emerging technologies, such as augmented reality, as well as technologies that have existed for decades, such as RFID, which, through data management provided by Industry 4.0, is now used to locate raw material inventories on a construction site. Certainly, many authors agree that so-called '4.0 technologies' are built around one main tool in the construction industry: the Building Information Modeling.

2.2 Building Information Modeling

BIM is more broadly part of the "digital building" trend, which can be considered as the set of information that defines the building with the possibility of a virtual representation reflecting its life cycle (Watson, 2011). BIM is now part of the digital transformation in construction (Zhao et al., 2017). As mentioned in the introduction, the term BIM defines both a numerical modelling tool and a working methodology based on information sharing.

Indeed, besides providing a data-rich, object-oriented, intelligent and parametric digital representation of the building, thus facilitating the exchange and interoperability of information in digital format, BIM can also support collaboration between all stakeholders in construction projects through a range of tasks, such as design, decision-making, fabrication, high-quality construction, document production, construction planning, performance predictions, and cost estimates (Cheng et al., 2013; Petri et al., 2017).

BIM therefore enables direct, real-time collaboration between all stakeholders involved in a construction project. BIM can thus be seen as the cornerstone of the construction industry and its emergence has facilitated the introduction of Construction 4.0. The quantitative analysis by Oesterreich and Teuteberg (2016) shows that indeed BIM is the most cited technology in the scientific literature. However, it is not the only element. The adoption of BIM represents the beginning of a new paradigm towards the digital revolution in the construction sector (Turk, 2019; Underwood and Isikdag, 2011).

In fact, the intensive and collaborative use of BIM, combined with the development and adoption of various emerging 4.0 technologies and approaches, will facilitate the development of many applications to enable an integrated environment – instead of a model providing data about a building in a standardised way, like BIM alone – where information is constantly updated, shared in real time among all stakeholders and subsequently exploited for real-time decision-making. For example, the combined application of BIM and genetic algorithms can be used to address the difficulties of decision-making on building sustainability in the early design process (Lim et al., 2018). Also, combining the data models of BIM and GIS enables the identification of feasible locations for defined tower cranes (Izarry and Karan, 2012). An emerging approach, called 5D BIM, even integrates 3D model, time and cost, starting from the initial design to the final construction stage (Lee et al., 2016).

BIM thus seems to be a subset of a more general group of related technological tools that would be keystones of Construction 4.0 as well.

2.3 Other key technologies in the construction sector

As highlighted in the introduction, one important issue for the construction industry is rapid access to information. In this context, for many authors, the technologies associated with real-time data capture for monitoring the progress of construction projects are at the heart of Construction 4.0 (Pučko et al., 2018). These technologies include, but are not limited to, laser scanning, radio frequency techniques, ultra-wideband applications, Global Positioning System (GPS), and Wireless Sensor Networks (WSNs).

Over the last decade, several examples of these 4.0 technologies associated with data capture have been raised in the scientific literature. Table 1 provides an overview of these main technologies and their areas of application that allow for project data acquisition. In what follows, these areas of application and their associated technologies are briefly discussed.

Table 1: Construction 4.0 technologies for project data acquisition.

Project data			**Technologies**	**Authors**
Weather conditions	Current and future conditions		Web-based systems	Park et Cai (2017)
Productivity	Actual estimate	Monitoring the progress of construction	Laser scanning and UAV	Adan et al. (2015), Dallasega et al. (2018), Pärn & Edwards (2017), Woodhead et al. (2018)
		Location and movement to capture productivity (human and resource)	RFID / barcode	Pärn & Edwards (2017)
	Productivity measurement (inspections)		Drones associated with laser scanning	Woodhead et al. (2018)
Safety	Safety rules (checklist)	Safety rules on the construction site	Artificial intelligence (chatbot)	Li (2019)
		Smart contracts / proofs of delivery	Blockchain	Woodhead et al. (2018)
	Actual position	Location of workers in relation to equipment	RFID + Ultra High Frequency (UHF)	Woodhead et al. (2018)
		Location of connections per room	Mobile devices + WSN	Araszkiewicz (2017)
		Location	GPS, smartphones, connected objects	Dallasega et al. (2018), Tezel & Aziz (2017)
		Access control	RFID	Oesterreich & Teuteberg (2016)
	Worker's suit	Equipment control	RFID	Oesterreich & Teuteberg (2016), Pärn & Edwards (2017)
	Safety performance		RFID	Pärn et Edwards (2017)
	Real-time monitoring of accidents		RFID	Wu et al. (2010)
	Safety monitoring		Drones	Oesterreich et Teuteberg (2016)

Project data			Technologies	Authors
Staff on site	Number and location		RFID	Oesterreich et Teuteberg (2016)
Availability of equipment and materials	Actual quantity	Plan of the elements on site	UAV/Photogrammetry /Mobile devices	Laine & Ikonen (2011)
		Volume measurement	Laser scanning	Woodhead et al. (2018)
		Access to the site	RFID	Dallasega et al. (2018), Wang (2013)
	Actual position	Location of equipment	RFID + UHF	Woodhead et al. (2018)
		Location of connections per room	Mobile devices + WSN	Araszkiewicz (2017)
		Location	GPS, smartphones, connected objects	Dallasega et al. (2018), Tezel & Aziz (2017)
		Access control	RFID	Oesterreich & Teuteberg (2016)
	Date of application	Customer/supplier relations	Artificial intelligence (chatbot)	Spohrer et al. (2008)
		Access to information	Mobile devices	Araszkiewicz (2017), Dallasega et al. (2018)
		Smart contracts / proofs of delivery	Blockchain	Woodhead et al. (2018)
	Application status	Access to and monitoring of information	Mobile devices	Santos et al. (2017)
		Supply chain monitoring	Advanced sensors / RFID	Dallasega et al. (2018)
Use and condition of equipment	Condition	Embedded systems on equipment	Mobile devices and advanced sensors	Dallasega et al. (2018), Whyte & Hartmann (2017), Woodhead et al. (2018)
		Predictive maintenance	Advanced sensors and machine learning	Truong (2018)
	Duration of activity	Access to history	Mobile devices	Hu et al. (2018), Laine & Ikonen (2011)
	Equipment maintenance performed	Data logging	RFID / barcode	Hu et al. (2018)
	Location		RFID coupled with GPS	Dallasega et al. (2018), Sardroud (2012)
	Equipment condition and diagnosis		Augmented reality	Woodhead et al. (2018)
Quality of materials	Real quality	Recording of verification data	RFID / barcode	Hu et al. (2018)
		Smart contracts	Blockchain	Woodhead et al. (2018)
	Quality inspections		PDA	Kim et al. (2008)
Delivery of materials	Allocation of delivered resources		RFID	Sardroud (2012)
Communication and coordination	Checklist, transmission date, reading/decision status	Customer/supplier relations	Artificial intelligence (chatbot)	Spohrer et al. (2008)
		Access to information	Mobile devices	Araszkiewicz (2017), Dallasega et al. (2018)
		Smart contracts / proofs of delivery	Blockchain	Woodhead et al. (2018)
Monitoring and control of activities	Validation of work	Customer/supplier relations	Artificial intelligence (chatbot)	Spohrer et al. (2008)
		Access to information	Mobile devices	Araszkiewicz (2017), Dallasega et al. (2018)
		Smart contracts / proofs of delivery	Blockchain	Woodhead et al. (2018)
		Testing and verification of dynamic solutions	UAV + laser scanning	Getuli et al. (2017), Moum (2010)

Project data			Technologies	Authors
	Progress	Monitoring the progress of construction	Laser scanning and UAV	Adan et al. (2015), Dallasega et al. (2018), Pärn & Edwards (2017), Woodhead et al. (2018)
		Analysis of job site data in real time	Artificial intelligence (Machine learning)	Whyte & Hartmann (2017)
		Real-time progress and percentage of completion	Drones coupled with GIS	Dallasega et al. (2018)
	Completed activities		Light Detection and Ranging (LiDAR), Laser Detection and Ranging (LaDAR)	Randall (2011)
Document and authorization	Dispatch date, status, document release	Customer/supplier relations	Artificial intelligence (chatbot)	Spohrer et al. (2008)
		Access to information	Mobile devices	Araszkiewicz (2017), Dallasega et al. (2018)

Weather conditions. In addition to more traditional means such as the Internet and meteorological sensors, the weather conditions (weather forecast or current conditions) required to perform each task can be obtained using Web-based systems (Park and Cai, 2017).

Productivity. New processes today are changing workflows by creating more value through information flows. For example, emerging trends include the use of drones and laser scanners to measure production volumes and detect productivity problems in the execution of a task (Adan et al., 2015; Dallasega et al., 2018; Pärn & Edwards, 2017; Woodhead et al., 2018).

Safety. In terms of security, UAVs are already used to monitor construction sites and RFID tags allow performance monitoring, for example by tracking the location of workers and machines (Oesterreich and Teuteberg, 2016; Pärn and Edwards, 2017). In addition, accidents can be tracked in real time on construction sites using stand-alone systems that use RFID for access control and storage of safety data (workers, materials, equipment and materials) combined with a wireless network for transmission, the whole being integrated into a Zigbee RFID sensor network architecture (Wu et al., 2010).

Staff on site. There are a few interesting approaches and technologies to automate the construction process and to create a "smart factory" for the construction environment. Among these technologies, RFID tags are being used to track the number and identities of workers on "smart construction sites" (Oesterreich and Teuteberg, 2016).

Equipment and materials. Combining technologies reduces tasks related to localization of items on construction sites. Such technologies involve, for example, integrating RFID with GPS to locate equipment on construction sites (Dallasega et al., 2018). The RFID chip is used to identify the equipment while its location is determined by GPS. Solutions that use augmented reality have also been experienced to help field operatives fix equipment by using their mobile phones to overlay real-time diagnostics (Woodhead et al., 2018). PDA can be used to collect real-time information on defects (types of defects via an electronic checklist displayed on the PDA) and the current quality inspection status, which will then be transmitted via wireless internet (Kim et al., 2008). Finally, RFID tags to collect real-time data automatically improve the tracking, delivery, receipt and location of materials and components on the construction site (Sardroud, 2012).

Monitoring and control of activities. New integrated technological applications allow quality control and real-time monitoring of the progress of the construction site. For example, drones equipped with GIS technology are used to gather data for quality control purposes and to measure construction site progress in real-time (Dallasega et al., 2018). Also, LaDAR flash allows real-time data capture on a dynamic scene such as a construction site to see how it is progressing (Randall, 2011). It is worth mentioning that laser scanning applications have been strongly influenced by the increasing adoption of BIM in the construction sector in recent years. In fact, besides laser scanning, several of the technologies shown in Table 1, such as photogrammetry, barcode and RFID tagging, can be used to capture the data required for BIM models. These data capturing approaches have been used to facilitate automated construction progress monitoring with relatively high accuracy (Tezel and Aziz, 2017).

Communication and coordination. Good communication is crucial as several stakeholders need to share information during the execution of a construction project. Improvements in communication can be made by also using BIM, not only during the execution phase, but also at a more advanced stage, e,g, during the transfer to the operation in order to transfer information from past construction projects to future projects to improve the quality of future work (Dubas and Pasławski, 2017).

3. RESEARCH METHODOLOGY

The research methodology involved a bibliographical search on Construction 4.0 using the Scopus database. The search terms consisted of combinations of the following keywords: 'construction industry' or 'building industry' or 'innovation construction' or 'innovation building' or 'construction site' or 'building system' or 'construction sector' or 'BIM' or 'building information model', and '4.0' or 'digital'. The term 'BIM' is included in the search because of its importance in the emergence of digitalisation in the construction sector. The whole search was limited to articles published during the last decade (between 2009 and 2020). This search has generated nearly 200 documents, mostly journal articles and conference papers. We then retained only the publications dealing with applications of Construction 4.0 technologies, which led to a total of almost 50 documents. We note that we are interested in applications of Industry 4.0 technologies that have been either tested in a laboratory, or in real situations. The collected documents were classified according to a framework consisting of two main axes: (1) the phases of a construction project's life cycle in which the technologies studied in the document are used; and (2) the project management processes that are renewed by using the technologies.

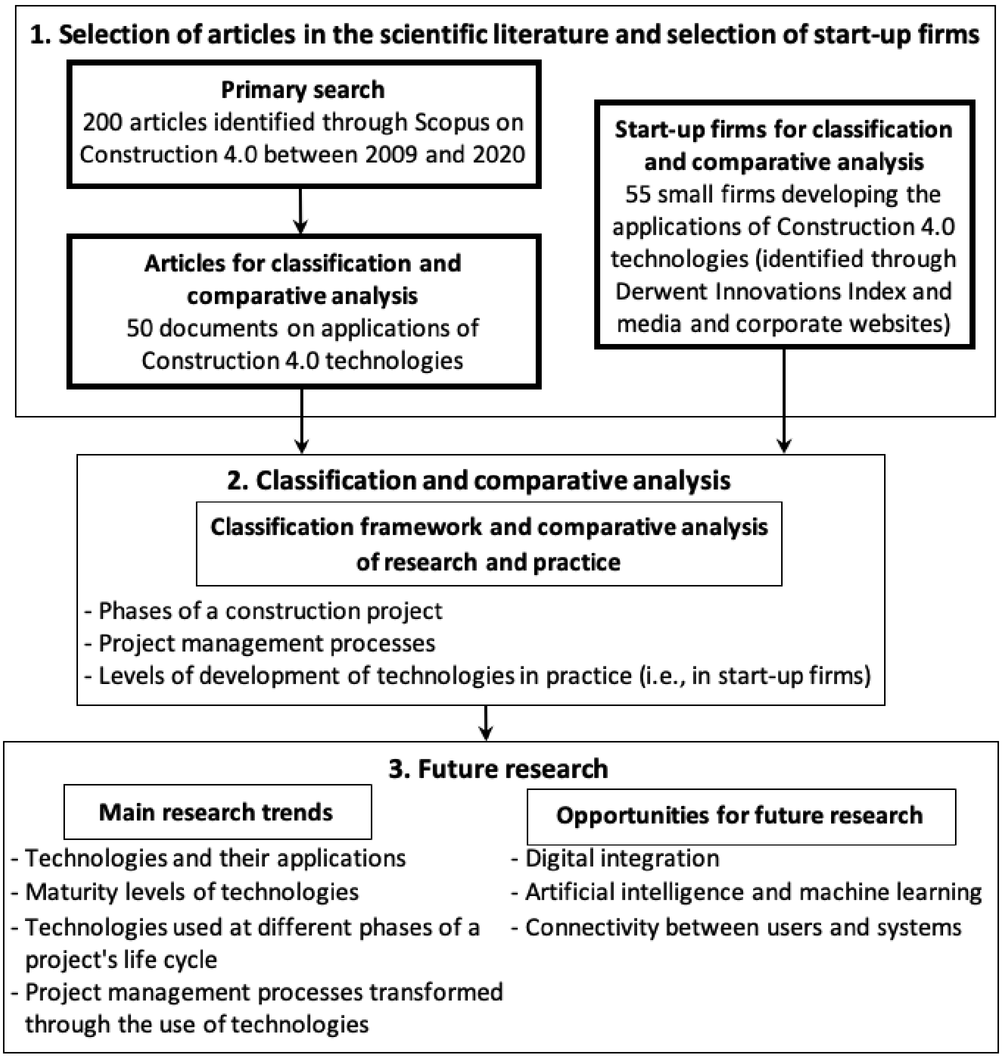

Figure 1: Representation of the research methodology.

The research methodology also implied looking for small companies that are developing – or are in the process of developing – the applications of Construction 4.0 technologies. To this end, we searched for practical applications of technologies in the Derwent Innovations Index (a database of industrial patents) as well as in articles provided on media and corporate websites. However, it should be mentioned that some companies may not disclose information on applications of specific technologies since these constitute their intellectual property. As a result of this search, we found 55 small firms or start-ups that develop and deliver 4.0 technologies in the construction industry. In addition to being classified according to a project management perspective, each of the technology applications developed by these start-ups was classified along its level of development or maturity in start-up firms.

Finally, the research methodology included a comparative analysis of existing 4.0 technological applications researched in the scientific literature and technological solutions developed by start-up firms to allow identifying the main knowledge gaps between research and practice and possible research ideas for the future.

Figure 1 presents an overview of the research methodology that resulted in the classification matrix and the comparative analysis presented in Section 4, and the main trends and opportunities for future research discussed in Section 5.

4. CLASSIFICATION OF 4.0 TECHNOLOGIES AND THEIR APPLICATIONS IN RESEARCH AD PRACTICE

Section 2 presented an overview of the main technologies that are at the heart of Construction 4.0 in the scientific literature. Section 4 now presents a classification framework and a comparative analysis between these technologies, i.e., those that have been described in the scientific literature, and the applications of technologies that have been developed – or with a strong potential to be developed – by newly founded innovative companies in the construction industry. We are interested here in classifying and comparing a series of technological applications related to Construction 4.0 in the scientific literature to the level of development of these applications in practice, i.e., in start-up firms since these small firms are often the ones that invent or promote a technology (contrary to large firms that adopt and use the technologies).

Table 2 presents the classification of technologies and their applications, including the results of both the scientific literature and professional practice, i.e., start-up firms. In the first column of Table 2, the technology applications identified are classified into three categories determined by their level of development in start-up firms:

1) *no development*: the technological application described in the scientific literature has not yet been developed by a start-up firm;
2) *strong level development*: the technological application has been developed by at least one start-up firm;
3) *promising development*: the technological application is closely related to the main activity of the start-up firm. However, although it would be relatively easy to develop, it has not yet been developed by the start-up firm.

For each of the applications identified, Table 2 shows:

- the technologies associated with the application (second column);
- the phases of the construction project's life cycle that are currently being facilitated, transformed or even renewed using the technologies associated with the application (third column); and
- the project management processes that are currently being transformed using the associated technologies (fourth column).

For each technology application, the last two columns list the author(s) describing the technology in the scientific literature and the start-up firm(s) having developed the technology (or having not yet done so, but having the potential to do so), respectively. Note that empty cells mean that no paper or start-up have addressed the specified technology application.

In Section 5, this classification framework will be used to extract trends in current research and to make recommendations for future research.

Table 2: Classification of technologies and their applications.

Applications	Technologies	Phases	Processes	Authors	Start-up firms
Level 1: No development					
Cost estimation according to the size of building elements	n-dimensional (nD) modeling, drone, point cloud	Design & engineering	Cost	Lee et al. (2016)	–
Facilitation of mass production	Parametric design	Design & engineering	Cost	Monizza et al. (2016, 2018)	–
Tag reading	Mobiles devices, RFID	Construction	Procurement	Dallasega et al. (2018)	–
Waste location	Drone	Construction	Cost	Castro-Lacouture et al. (2014)	–
Data securement for proof delivery	Blockchain	Construction	Health and safety, risk	Woodhead et al. (2018)	–
Waste disposal	Robots	Operation & maintenance	Quality	Oesterreich and Teuteberg (2016)	–
Energy management	Laser scanning, infrared camera	Operation & maintenance	Cost	Santos et al. (2017)	–
Evacuation of occupants in case of fire	3D modeling, WSN, smartphone bluetooth-based technologies	Operation & maintenance	Health and safety, risk	Wong et al. (2018a)	–
Monitoring of structural deformations	RFID, advanced sensors	Operation & maintenance	Health and safety, quality, risk	Santos et al. (2017)	–
Thermal 3D point clouds	3D laser, RGB camera, thermal camera	Renovation	Quality	Adán et al. (2017)	–
Making of a 3D point cloud	Two cameras	Renovation	Quality	Wong et al. (2018a)	–
Level 2: Strong level development					
Design & engineering	nD modeling	Design & engineering	Human resources, time	Abolghasemzadeh(2013), Cheng and Ma (2013), Dubas and Pasławski (2017), Ehrbar (2016), Getuli et al. (2017), Hilfert and König (2016), Jian (2017), Lee et al. (2016), Lin et al. (2013), Moum (2010), Oreni et al. (2012), Pocobelli et al. (2018), Santos et al. (2017), Shuo (2013), Tezel and Aziz (2017), Underwood and Isikdag (2011), Wang (2013)	Betterview (2020), Bridgit (2020), Buildertrend (n.d.), Buildup (2020), BulldozAIR (2019), Delair (2020), DroneDeploy (n.d.), EIDA Software Solutions (2020), eSUB Inc. (2020), Finalcad SARL (2020), Propeller Aerobotics Pty Ltd. (2010), SiteAware Inc. (2020), Skycatch Inc. (2020), Strayos Inc. (2020), Unearth Labs. (2020), 3DR (2020)
Testing and verification of dynamic design solutions	UAV, laser scanning	Design & engineering	Quality	Getuli et al. (2017), Moum (2010)	Betterview (2020), Delair (2020), DroneDeploy (n.d.), Propeller Aerobotics Pty Ltd. (2010), SiteAware Inc. (2020), Skycatch Inc. (2020), Strayos Inc.

Applications	Technologies	Phases	Processes	Authors	Start-up firms
					(2020), Unearth Labs. (2020), 3DR (2020)
Detection of drilling areas	Laser	Design & engineering	Scope	Santos et al. (2017)	Propeller Aerobotics Pty Ltd. (2010), Strayos Inc. (2020)
3D topography	Photogrammetry, drone , laser scan	Design & engineering, renovation	Scope, quality	Pärn and Edwards (2017), Yeniceli and Ozcelik (2015), Živec and Žibert (2016)	Betterview (2020), Delair (2020), DroneDeploy (n.d.), Propeller Aerobotics Pty Ltd. (2010), SiteAware Inc. (2020), Skycatch Inc. (2020), Strayos Inc. (2020), Unearth Labs. (2020), 3DR (2020)
Field study	Drone	Design & engineering	Scope	Živec and Žibert (2016)	Betterview (2020), Delair (2020), DroneDeploy (n.d.), Propeller Aerobotics Pty Ltd. (2010), SiteAware Inc. (2020), Skycatch Inc. (2020), Strayos Inc. (2020), Unearth Labs. (2020), 3DR (2020)
Automatic design of the building envelope according to existing projects and constraints	Parametric design	Design & engineering	Scope	Lim et al. (2018)	Building SP Inc. (2017)
Smart contracts	Blockchain	Design & engineering	Scope	Woodhead et al. (2018)	Crunchbase Inc. (2020)
3D presentation of digital models and texture	Augmented and virtual reality, nD modeling	Design & engineering, construction	Communications	Oreni et al. (2012)	AR Pandora Augmented and Virtual Reality Technologies (2015), HoloBuilder Inc. (2020), IrisVR Inc. (2019), Melzo (n.d.), Vrban Inc. (2020)
3D presentation of building information	Virtual reality	Design & engineering	Communications	Shuo (2013)	IrisVR Inc. (2019), Vrban Inc. (2020)
Improvement of customer understanding in the design phase	Virtual reality	Design & engineering	Communications	Dallasega et al. (2018)	IrisVR Inc. (2019), Vrban Inc. (2020)
Communication standard, program, programming language, standard file, standard design, syntax standard, visualization standard	Industry Foundation Classes	Design & engineering	Communications, quality, risk	Alves et al. (2017), Araszkiewicz (2017), Dallasega et al. (2018), Hilfert and König (2016), Hjelseth (2017), Isikdag (2015), Pocobelli et al. (2018), Rocha et al. (2017), Santos et al. (2017), Scully et al. (2015), Shen et al. (2013), Shuo (2013), Steel et al. (2010)	BuildingConnected (2020)
Estimation of future energy consumption	WSN, advanced sensors	Design & engineering	Cost	Petri et al. (2017)	Invento (2020)
Heuristic methods for project planning	Neural networks, artificial intelligence	Design & engineering, construction	Quality, time, cost	Zhao et al. (2017)	ALICE Technologies Inc. (2020)

Applications	Technologies	Phases	Processes	Authors	Start-up firms
3D modeling	Drone	Construction	Quality, time	Oesterreich and Teuteberg (2016)	Betterview (2020), Delair (2020), DroneDeploy (n.d.), Propeller Aerobotics Pty Ltd. (2010), SiteAware Inc. (2020), Skycatch Inc. (2020), Strayos Inc. (2020), Unearth Labs. (2020), 3DR (2020)
Reading	Mobiles devices	Construction	Communications	Dallasega et al. (2018)	Bridgit (2020), Buildertrend (n.d.), Buildup (2020), BulldozAIR (2019), EIDA Software Solutions (2020), eSUB Inc. (2020), Finalcad SARL (2020), Rhumbix (2019)
Location and movement of machines and workers	RFID	Construction	Health and safety, human resources, quality, risk, time	Pärn and Edwards (2017)	Busybusy (2020), CB Information Services Inc. (2020), Pillar Technologies (2020), SignOnSite (n.d.)
Wifi connections as a proxy for human occupancy	Mobile devices, WSN	Construction	Health and safety, risk	Araszkiewicz (2017)	SignOnSite (n.d.)
Detection of human movements	Camera, webcam	Construction	Human resources	Hilfert and König (2016)	Busybusy (2020), Vrban Inc. (2020)
Mapping of elements or groups of elements on site	Drone, UAV, photogrammetry, mobiles devices, nD modeling	Construction	Cost, procurement	Laine et Ikonen (2011)	Delair (2020), DroneDeploy (n.d.), Skycatch Inc. (2020), Unearth Labs. (2020), 3DR (2020)
Assembly automation	Mobile robots on-site	Construction	Cost	Oesterreich and Teuteberg (2016)	Batra (2018)
Worker replacement (e.g., assembling bricks)	Mobile robots on-site	Construction	Cost	Oesterreich and Teuteberg (2016)	Construction Robotics (2019)
Cost reduction	Prefabrication	Construction	Cost	Dallasega et al. (2018)	Katerra (2020)
Delay reduction	Prefabrication	Construction	Quality, time	Monizza et al. (2018)	Katerra (2020)
Structure analysis	Advanced sensors	Construction	Health and safety, risk	Oreni et al. (2012)	Skycatch Inc. (2020)
Safety check	Drones	Construction	Health and safety, risk	Oesterreich and Teuteberg (2016), Tezel and Aziz (2017)	DroneDeploy (2017)
Security training	Augmented and virtual reality	Construction, design & engineering	Health and safety, risk	Oesterreich and Teuteberg (2016)	Wood (2016)
Modeling for safety and building exit means in case of fire	WSN, mobile devices, nD modeling	Design & engineering	Health and safety, risk	Abolghasemzadeh (2013)	CB Information Services Inc. (2020), Pillar Technologies (2020),
Collision detection	RFID, bluetooth, ultra sound	Construction	Health and safety, procurement, risk	Ehrbar (2016), Irizarry and Karan (2012)	Busybusy (2020), CB Information Services Inc. (2020), Invento (2020)
Access to information	Mobiles devices	Construction	Communications	Santos et al. (2017)	Bridgit (2020), Buildertrend (n.d.),

Applications	Technologies	Phases	Processes	Authors	Start-up firms
					Buildup (2020), BulldozAIR (2019), EIDA Software Solutions (2020), eSUB Inc. (2020), Finalcad SARL (2020), Rhumbix (2019)
Real-time data collection	Mobiles devices	Construction	Health and safety, risk	Dubas and Pasławski(2017), Hu et al. (2018), Laine et Ikonen (2011), Whyte, T. Hartmann (2017)	Bridgit (2020), Buildertrend (n.d.), Buildup (2020), BulldozAIR (2019), EIDA Software Solutions (2020), eSUB Inc. (2020), Finalcad SARL (2020), Rhumbix (2019)
Real-time data analysis	Machine learning	Construction	Quality, time	Whyte, T. Hartmann (2017)	Uptake Technologies Inc. (2020)
Human control access on site	RFID	Construction	Health and safety, human resources	Oesterreich and Teuteberg (2016)	Biosite Systems Ltd. (2020), SignOnSite (n.d.)
Accessibility of trucks on site	RFID	Construction	Health and safety, procurement	Lin et al. (2013)	Busybusy (2020), Invento (2020)
Improvement of material resources allocation on site	WSN, RFID	Construction	Health and safety, procurement	Wang (2013)	Bridgit (2020), Buildertrend (n.d.), Buildup (2020), BulldozAIR (2019), EIDA Software Solutions (2020), eSUB Inc. (2020), Finalcad SARL (2020), Rhumbix (2019)
Flow optimisation	nD modeling, neural networks	Construction	Health and safety, procurement	Irizarry and Karan (2012)	Bridgit (2020), Buildertrend (n.d.), Buildup (2020), BulldozAIR (2019), EIDA Software Solutions (2020), eSUB Inc. (2020), Finalcad SARL (2020), Rhumbix (2019)
Location of workers on site	GPS	Construction	Human resources	Tezel and Aziz (2017)	Busybusy (2020), CB Information Services Inc. (2020), Pillar Technologies (2020), SignOnSite (n.d.)
Controllability of access of materials on site	RFID	Construction	Procurement	Dallasega et al. (2018)	Busybusy (2020), Invento (2020)
Tracking items in the supply chain	Advanced sensors, RFID	Construction	Procurement	Dallasega et al. (2018)	BuildingConnected (2020), Katerra (2020), Viloc (n.d.)
Project progress in real-time	Drone, laser scanning	Construction	Quality, time	Dallasega et al. (2018)	Delair (2020), DroneDeploy (n.d.), Skycatch Inc. (2020), Unearth Labs. (2020), 3DR (2020)
Production volume and productivity measurement	Drone, laser	Construction	Quality	Woodhead et al. (2018)	Strayos Inc. (2020)
Process efficiency improvement	Parametric design	Construction	Quality, time	Monizza and Benedetti (2018)	Bridgit (2020), Buildertrend (n.d.),

Applications	Technologies	Phases	Processes	Authors	Start-up firms
					Buildup (2020), BulldozAIR (2019), EIDA Software Solutions (2020), eSUB Inc. (2020), Finalcad SARL (2020), Rhumbix (2019)
Location of occupants and fire sources in the event of a fire	GPS	Operation & maintenance	Health and safety, risk	Wong et al. (2018a)	CB Information Services Inc. (2020), Pillar Technologies (2020)
Emergency response operations	3D modeling	Operation & maintenance	Health and safety, risk	Isikdag et al. (2011)	Pillar Technologies (2020)
Building fire safety reviews	GPS-enabled tools	Operation & maintenance	Health and safety, risk	Wong et al. (2018a)	CB Information Services Inc. (2020)
Safety and guidance in case of evacuation	Mobile devices, smartphone	Operation & maintenance	Health and safety, risk	Wong et al. (2018a)	SignOnSite (n.d.)
Monitoring the condition of building elements	RFID, advanced sensors	Operation & maintenance	Quality	Hu et al. (2018), Wong et al. (2018a)	Delair (2020), DroneDeploy (n.d.), Skycatch Inc. (2020), Unearth Labs. (2020), 3DR (2020)
Building mapping to facilitate operations and maintenance	Drone, laser scanning	Operation & maintenance	Quality	Hu et al. (2018)	Bridgit (2020), Buildertrend (n.d.), Buildup (2020), BulldozAIR (2019), EIDA Software Solutions (2020), eSUB Inc. (2020), Finalcad SARL (2020), Rhumbix (2019)
Follow-up of maintenance actions	RFID	Operation & maintenance	Quality	Wong et al. (2018a)	Invento (2020)
Reshaping of the building's functions and layout by redesigning modules	Robotic cranes (crabots)	Operation & maintenance	Scope	–	Perry (2015)
Modeling of old buildings, geometry, texture	point cloud, nD modeling	Renovation	Quality	Cheng and Ma (2013), Pocobelli et al. (2018), Scott et al. (2013)	FARO Technologies Inc. (2020)
Integration between 2D and 3D images	nD modeling	Renovation	Quality	Wong et al. (2018a)	FARO Technologies Inc. (2020)
Modeling/Building reconstruction, point cloud, historical building	laser scanning	Renovation	Quality	–	FARO Technologies Inc. (2020)
Modeling accuracy and 3D model creation to reconstruct an existing building	laser scanning, photogrammetry, LiDAR	Renovation	Quality	Pocobelli et al. (2018)	FARO Technologies Inc. (2020)
Level 3: Promising development					
Workers safety (location // materials)	RFID, UHF	Construction	Health and safety, risk	Woodhead et al. (2018)	CB Information Services Inc. (2020)
Image analysis of the site to detect security problems	Neural networks	Construction	Health and safety, risk	–	Uptake Technologies Inc. 2020

Applications	Technologies	Phases	Processes	Authors	Start-up firms
Prevention of tower cranes collisions	Neural networks, GIS	Construction, design & engineering	Health and safety, procurement, risk	Araszkiewicz (2017), Irizarry and Karan (2012)	Biosite Systems Ltd. (2020), Busybusy (2020), Uptake Technologies Inc. (2020)
Optimisation of tower cranes location on site	Neural networks	Construction, design & engineering	Health and safety, procurement	Irizarry and Karan (2012)	Busybusy (2020), Uptake Technologies Inc. (2020)

5. RESEARCH TRENDS AND OPPORTUNITIES FOR FUTURE RESEARCH

The third and last objective of this literature review is to identify current research trends and possible gaps that could shape future research in the promising field of Construction 4.0 technologies.

First, based on the classification framework developed in Section 4 (see Table 2), the following trends in current research can be identified:

(i) a single technology can have a wide range of potential applications;
(ii) most technologies and their applications have reached a high level of maturity in terms of development in the professional world;
(iii) 4.0 technologies are now applied at different phases of a construction project's life cycle, especially during the execution phase; and
(iv) many project management processes are being facilitated through the use of 4.0 technologies.

Similarly, based also on Table 2, three recommendations can be made with respect to the design of future research:

(i) develop hybrid digital solutions;
(ii) continue to build upon artificial intelligence and machine learning; and
(iii) align with effective collection of more structured data, smart interactive web technologies, robotics, autonomous systems, and intelligent built assets.

These findings will be discussed in detail in Sections 5.1, 5.2, 5.3, and 5.4.

5.1 Technologies and their applications

As shown in Table 2, a given technology can have several applications. For example, drones can be used for photogrammetry to map batches of materials (Tezel and Aziz, 2017) or to guide equipment on a site (Oesterreich and Teuteberg, 2016). Laser scanning technology is now used to capture data for numerous built environment applications, including construction progress monitoring, quality control assessment, structural health monitoring, site activity monitoring, safety assessment, and resource and material tracking (Pärn and Edwards, 2017). Developments into the potential applications of nD modeling (e.g., BIM) have also been steadily increasing over the years. Researchers have explored the use of rich digital building models derived from BIM for various applications, such as emergency response operations and fire simulations (Isikdag et al., 2011). Emergency response operations require an enormous amount of information related to the building. Models used just over ten years ago for evacuation operations were based primarily on 2D floor plans. Today, the high amount of information related to the building can be transferred from BIM models into the geospatial environment.

5.2 Levels of development of technologies

With regard to the levels of development of technologies, Table 2 shows that while academics examined certain topics and applications theoretically, the industrial world is already either developing them (level 2, strong development) or with a view to doing so (level 3, promising development). Interest in strongly developing 4.0 technologies in the construction industry has indeed grown over the past few years. Based on Table 2, RFID development had the most applications in published papers and real-world practice, followed by drones, laser scanning, nD modeling and virtual reality. Concepts such as Artificial Intelligence (AI), machine learning, robotics, and prefabrication can also be considered as new trends. These results are somewhat consistent with other findings stipulating that studies on BIM adoption, RFID, laser scanning and augmented reality represent important research topics in the scientific and practical literature (Dallasega et al., 2018; Oesterreich and Teuteberg, 2016; Santos et al., 2017; Zabidin et al., 2020).

However, a few number of technological applications found in the scientific literature do not have counterparts in practice (level 1, no development). These applications include cost estimation (Lee et al., 2016), tag reading (Dallasega et al., 2018), waste location and disposal (Castro-Lacouture et al., 2014; Oesterreich and Teuteberg, 2016), data securement (Woodhead et al., 2018), energy management (Santos et al., 2017), fire escape (Wong et al., 2018a), monitoring of structural deformations (Santos et al., 2017), and 3D point clouds (Adán et al., 2017; Wong et al., 2018a). These technological applications have not yet been developed in construction practice due to several practical issues. From practitioners' point of view, the stage of development of an application may still be too early for a start-up firm, or a market analysis may not reveal sufficient potential for such development (Danjou et al., 2020). The requirements and costs of developing digital technologies as well as the investment needed to train personnel to acquire core competencies to operate advanced technologies effectively can also act as disincentives to technology development (Pärn, and Edwards, 2017; Wong et al., 2018a).

5.3 Technologies used at different phases of a construction project's life cycle and the project management processes transformed by these technologies

Table 2 reveals that Construction 4.0 involves a host of technologies at all phases of a project's life cycle. This is not surprising since, in the context of Construction 4.0, several construction companies have put the re-engineering of their project management processes (e.g., communications, cost, health and safety, etc.), linked to 4.0 technologies, at the heart of their strategy in order to create sustainable value within the enterprise (Oesterreich and Teuteberg, 2016). These companies have launched initiatives to collect richer data during the project execution phase, including, for example, the use of drones, cameras, telemetry tools, sensors and, RFID systems. These companies seek to undertake the re-engineering of their project management processes by redesigning the main activities underlying these processes and by developing data models that, based on 4.0 technologies, are able to capture and exploit relevant information for optimal decision-making at different phases of a project's life cycle.

As shown in Table 2, 4.0 technologies mainly cover the execution phase of construction projects. These technologies include but are not limited to the use of drones, mobile devices, RFID, sensors, cameras, mobile robots on sites, and laser scanning. Many project management processes, e.g., communications, cost, health and safety, human resources, procurement, quality, risk, and time, are also being facilitated through the use of 4.0 technologies during the construction phase.

Table 2 also reveals that the application of technologies in the design & engineering phase, as well as the construction phase, can be considered at an advanced state of maturity (strong development), meaning that feasible technological applications and tools are available to assist managers in their tasks at this phase. For example, BIM models (nD modeling) are mostly developed for the design stage. Technologies like laser scanning also make BIM model creation for existing buildings more convenient (Cheng et al., 2013).

However, less research has been performed on the application of digital technologies in the operation and maintenance phase. In particular, renovation is an important component of operations and maintenance, and there has been even less research and development in this area, compared to the design and construction phases. This finding is somewhat surprising given that the operation and maintenance phase accounts for the largest proportion of whole life costs of the building project (Wong et al., 2018a). The operation and maintenance management phase, which includes asset management, maintenance/repair management, running status monitoring, patrol inspection and emergency-response management, requires appropriate tools to facilitate rapid field inspection. In line with what has been raised in the literature by Hu et al. (2018), mobile devices, such as portable terminals (PDAs, smart phones and tablets) and laptops, are thus frequently employed to help quickly access the relevant information (see Table 2).

5.4 Future research avenues

To address these limitations, a promising future research direction is to develop hybrid technology solutions. For example, when coupled with BIM, laser scanning provides an enhanced solution to quickly create and update as-built BIM models (Pärn, and Edwards, 2017). Another example is the GIS-based integration of information provided by a BIM model and the IoT, which allows improving many fields of applications, ranging from emergency response, urban surveillance, and urban monitoring to smart buildings (Isikdag, 2015). As 4.0 technologies are combined, the management of built environment assets will become increasingly reliant upon machine learning algorithms and automated decision-making to fully exploit a plethora of data. In that sense, our analysis revealed that concepts such as artificial intelligence and machine learning still hold potential for strong development in the future.

In the coming decades, the construction industry should therefore line up towards digital integration, effective collection of more structured data, smart interactive web technologies, autonomous systems, and intelligent built assets (i.e., IoT, knowledge of location, condition, and availability of assets). These innovations, supported by mobile technologies, should improve connectivity between users and systems, resulting in new large-scale datasets (big data), adaptive and agile learned information embedded into artificial intelligence, and better-informed decisions (Philp et al., 2014). Robotics and autonomous systems, such as bricklaying robots, demolition robots, and survey drones, will become important technologies of this new era of the built environment.

Figure 2 depicts the state of technology development and implementation on a time horizon in the construction industry.

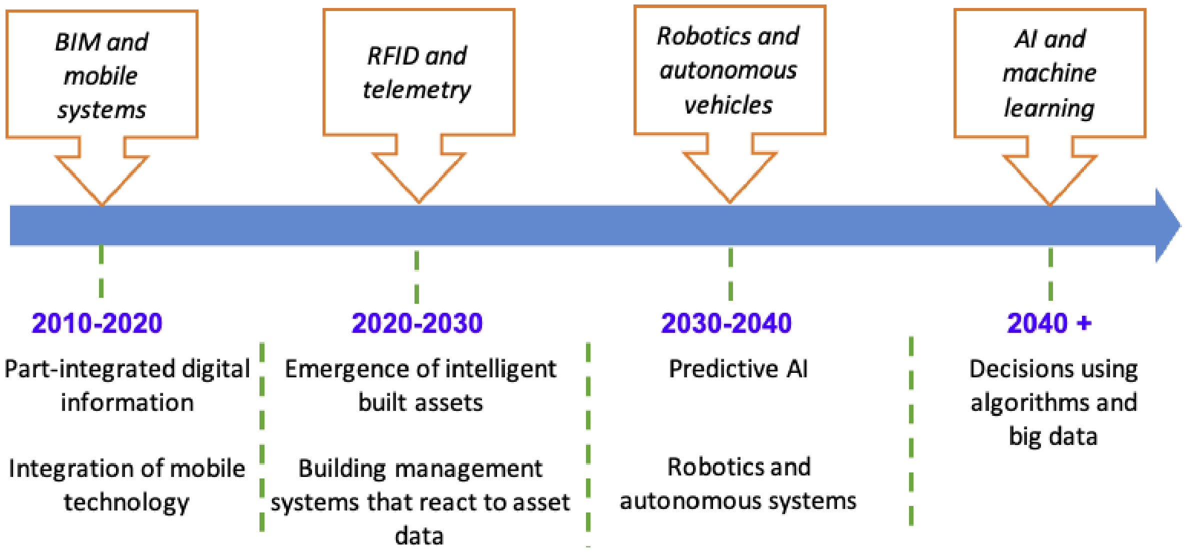

Figure 2: Current trends and future vision of Construction 4.0 (adapted from Philp et al., 2014).

6. CONCLUSION

This paper has presented a comparative analysis of the most recent technological applications identified in the scientific literature and the world of practice. The analysis shows that the development of technological applications associated with Construction 4.0 is now in progress and is changing management practices on construction sites.

In fact, Construction 4.0 technologies and their applications have reached different levels of maturity. During the last decade, standards for an integrated digital approach (e.g., 3D modelling) to design and construction have been developed in the construction industry (Philp et al., 2014). The BIM field is clearly reaching advanced levels of maturity, but the practical literature has also shown that several other technologies, such as RFID, laser scanning, drones, virtual reality, and mobile computing, have reached a high level of development and can thus be used in the construction industry. Mobile technologies, such as tablets and phones, now allow for the interaction with the virtual design to collect data and execute tasks. Many project management processes, e.g., communications, cost, health and safety, human resources, procurement, quality, risk, and time, are also being transformed through the use of these 4.0 technologies.

Summarizing, the main advancements addressed in this literature review aim at:

enhance exploration of the use of 4.0 technologies for various applications in the construction industry;

reaching high levels of maturity in the development of several 4.0 technological applications in the construction industry in the last decade;

assist managers in their tasks with feasible technological applications available at all phases of a project's life cycle, especially during the design and construction phases; and

facilitate the management of several project management processes through the use of 4.0 technologies.

However, a number of gaps between research and practice can be identified as well. Fields such as cost estimation, tag reading, waste location and disposal, data securement, energy management, fire escape, monitoring of structural deformations, and 3D point clouds do not appear to have found their way into practice. Full-integrated information containing all aspects of construction information is also still needed to facilitate decision-making.

To reduce these gaps, research and industry practices primarily advocate hybrid or integrated digital solutions to improve performance, i.e., increasing the capabilities of a technology by combining it with other technologies. Various concepts and technologies, including laser scanning, IoT, virtual and augmented reality, genetic algorithms, information and communication technologies, sensors, and GIS, are becoming important levers in the development of hybrid digital solutions combined with BIM. For example, BIM coupled with information and communication technologies can enable faster and more reliable design of decision-making and construction follow-up (Petri et al., 2017), while integration of BIM with sensor data allows real-time data processing (Alves et al., 2017). BIM has also been integrated with VR technology to develop a digital building/facility delivery system for construction and post-delivery operations and management (Shuo, 2013).

In addition to combining 4.0 technologies, future research should also focus on strongly developing concepts such as artificial intelligence and machine learning to optimally exploit the wealth of data, and on effective collection of more structured data, smart interactive web technologies, robotics, autonomous systems, and intelligent built assets to improve connectivity between users and systems.

ACKNOWLEDGEMENTS

This work has been supported by the Pomerleau Industrial Research Chair in Innovation and Construction Project Governance and the Jarislowsky / SNC-Lavalin Research Chair in the Management of International Projects. Their support is gratefully acknowledged.

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