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Maturity model of IoT technologies and applications in construction

Dong Wang[1]
1. PhD Student, Department of Building and Real Estate, The Hong Kong Polytechnic University, 11 Yuk Choi Rd, Hung Hom, Kowloon, Hong Kong
(E-mail: dongcq.wang@connect.polyu.hk)
Ming-Fung Francis Siu[2*]
2*. Assistant Professor, Corresponding author, Department of Building and Real Estate, The Hong Kong Polytechnic University, 11 Yuk Choi Rd, Hung Hom, Kowloon, Hong Kong
(E-mail: francis.siu@polyu.edu.hk)
Ping-Chuen Albert Chan[3]
3. Chair Professor, Head of Department, Department of Building and Real Estate, The Hong Kong Polytechnic University, 11 Yuk Choi Rd, Hung Hom, Kowloon, Hong Kong
(E-mail: albert.chan@polyu.edu.hk)

Abstract

Internet of Things (IoT) is the interconnection of sensing and actuating devices providing the ability to share information across platforms. Recently, some scholars have begun to explore the IoT technologies and applications in construction. Yet, there is no research work has been undertaken to examine the evolution statue of IoT technologies and applications in construction for identifying the opportunities of IoT research in construction management. As such, this research study conducted a thorough literature review in relation to IoT technologies and applications in construction using Scopus. Word frequency and clustering analysis were then developed to analyse and visualise the status quo of IoT in construction. A maturity model of IoT in construction is proposed. The results show that the IoT technologies of the RFID, BIM, and GPS; and the IoT applications of improving productivity, monitoring safety, and monitoring environment, are the hot research topics. The future development of IoT platforms for monitoring environment driven by GIS technologies, improving productivity driven by IoT technologies, improving safety driven by IoT technologies, were highlighted.

Keywords: Maturity model, internet of things, construction management, literature review, text mining, cluster analysis.

1. Introduction

Construction, as one of the oldest engineering industries, has been challenged for improving, but not limited to, construction productivity, safety, and environment through construction management research. For example, the main challenges are the low productivity of worker-oriented operations, low sustainability due to pollutant emission, unsafe work conditions because of dynamic site condition and operation. With the aim of improving construction performance, technical innovations are proposed, developed, and applied. Recently, "Internet of Things (IoT)" has drawn significant attention in research fields.

The phrase "Internet of Things (IoT)" was first reported in 1999, following the advent of internet-based techniques in 1990s (Ashton, 2009). Definitions of IoT are proposed by researchers. For instance, Gubbi et al. (2013) defined IoT as the interconnection of sensing and actuating devices for providing the ability to share information across platforms through a unified framework, such that communication channels can be established for combining the use of devices. Al-Fuqaha et al. (2015) described IoT as a technology that enables physical objects to see, to hear, to think, to share, to decide, and to perform. Although the IoT definitions are not standardised, the fundamental features of IoT denoted by Telecommunication Standardization Sector (ITU-T, 2015) and Vermesan and Friess (2014) are widely accepted. The features are (i) interconnectivity: anything can be interconnected with the global information and communication infrastructure; (ii) things-related services: thing-related services can be provided by IoT such as privacy protection and semantic consistency between physical things and their associated virtual things; (iii) heterogeneity: the devices in IoT are heterogeneous regardless of its hardware platforms and networks; (iv) dynamic changes: the dynamic changes in the device states; (v) enormous scale: the number of devices that need to be managed and communicated with each other will be at least an order of magnitude larger than the devices connected to the current internet.

The nature of IoT is the communication between "Things". It is reported that the IoT technology shows huge potential of the development as the number of IoT-connected devices is estimated to reach to 75.44 million by the end of 2025 while it was 15.41 billion in 2015 (Statista, 2018). The IoT technologies have been extensively used in many disciplines due to its notable benefits such as the improvement of productivity, cost, and safety. For instance, it is proven that the IoT is capable of saving cost and energy consumption in a smart home (Darianian and Michael, 2008) and realising real time noise monitoring and traffic congestion in a smart city (Zanella et al., 2014).

In construction, research endeavours have begun to explore the IoT technologies and applications for improving project performance. A construction project is a complex dynamic system featuring massive workflows of activities and resources, supported by information flows between project stakeholders. To improve construction effectiveness, the development and application of IoT philosophy in construction would be of huge potential. Despite there has been research exploring the IoT evolution for elevating construction performance in past years, no research work has examined the maturity of IoT technologies and applications in construction industry so as to identify the IoT research opportunities in construction management. In the following sections, literature review is first given to provide the methodologies of evaluating the construction IoT research trend from the angles of IoT applications and technologies, a new 3-stage method is then proposed for determining the maturity of IoT research, the results of the maturity model are given, and the opportunities of IoT-enabled future research are concluded at the end.

2. Literature review

The IoT research directions are mainly focused on "IoT technologies" and "IoT applications" (Al-Fuqaha et al., 2015; Alavi et al., 2018). In "IoT technologies" domain, the researchers investigated the IoT technical issues and systems in context of layers. The layers are defined as object, network, middleware, application (Čolaković and Hadžialić, 2018); or device, communication, cloud service, application (Hossain et al., 2016); or sensing, network, service, interface (Li et al., 2015). The layers contributed to mutual functions: (i) Sensing: collect data from relevant objects using sensors and store data to a database or cloud (Al-Fuqaha et al., 2015); (ii) Communication: connect objects and heterogeneous information to deliver specific smart services; (iii) Computation: run processing units to acquire computational ability; (iv) Service: provide identity-related service, information aggregation service, collaborative-aware service, and ubiquitous service. Notably, ubiquitous service is the ultimate goal for IoT applications which collect data and make decision realise in real time, such that the needs for anyone at anytime and anywhere can be met. Technical challenges must be overcome, for example, sensor energy scarcity, security, scalability, standardisation, and data storage and process (Čolaković and Hadžialić, 2018).

In "IoT application" domain, research studies were attempted to create smart cities (Zanella et al., 2014), smart home (Stojkoska and Trivodaliev, 2017), smart agriculture (TongKe, 2013), smart health (Muhammad et al., 2017), and smart manufacturing (Zhang et al., 2015, Davis et al., 2012). For example, in smart city, IoT was applied to develop cyberville, digital city, electronic city, flexicity, information city, and wired city, in order to enhance the safety, livability, and comfort of citizens. In smart home, IoT enables the installation of smart meters, smart power outlets, and sensing devices. This helps in saving energy, elderly care, and providing living comfort (Alavi et al., 2018). In smart manufacturing, the machines and computers will be connected through internet protocols (Löffler and Tschiesner, 2013) to enable the integration of manufacturing information in real time (Zhang et al., 2015).

In general, the above scholars reviewed the IoT from the perspectives of both "IoT technologies" and "IoT application". Any promising IoT research directions are explored by brainstorming and piloting IoT technologies or applications in construction. Yet, no research work has been conducted to examine the maturity of IoT research in connection with both "IoT technologies" and "IoT applications" based on the publications in construction management.

3. Research methodology for exploring the maturity of IoT research in construction management

Figure 1 shows an overview of the new three-stage approach for exploring the maturity of existing IoT technologies and applications in the research field of construction management so as to identify future research opportunities. The first step is to search relevant research studies reported in construction management. The second step is to identify the hot research areas of IoT technologies and applications using word frequency analysis and clustering analysis. The last step is to characterise the relationships between IoT technologies and applications by maturity matrix. This enables the exploration of future trends and opportunities of researching IoT in construction field.

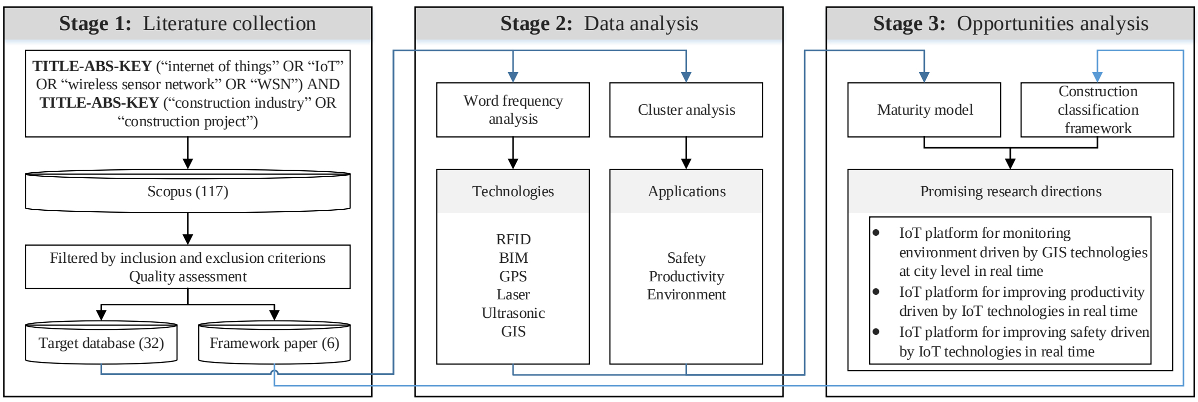

Figure 1: Proposed methods for exploring IoT research opportunities in construction management

3.1 Literature selection strategy for filtering the articles relevant to IoT

technologies and IoT applications

To select the research articles, this research study adopted the selection protocol inspired by SLR (systematic literature reviews) guidelines (Kitchenham, 2004). The protocol includes (i) search strategy, (ii) inclusion and exclusion criteria, (iii) quality assessment, and (iv) data extraction.

Search strategy: To search the literatures, “Scopus” database was used. This database includes relevant journals in construction management (e.g., Automation in Construction (AIC), Journal of Construction Engineering and Management (JCEM), Journal of Architectural Engineering (JAE), Construction Innovation (CI), Energy and Building (EB). The search keyword is “Internet of Things/IoT” and “construction project/industry”. Also, we considered “wireless sensor network/WSN”, which is the main technology for IoT development. The query string for retrieving the documents in Scopus was thus set as TITLE-ABS-KEY (“internet of things” OR “IoT” OR “wireless sensor network” OR “WSN”) AND TITLE-ABS-KEY (“construction industry” OR “construction project”). The reference types are journals, conferences, workshops, and symposiums.

Inclusion and exclusion criterions: To shortlist the targeted papers, a set of inclusion and exclusion criterions are proposed. The inclusion criterions are: (i) The article must be published in English language; (ii) The reported study described a specific IoT technology or IoT application in construction management research area; (iii) The application can be classified in the seven research areas, namely, planning, scheduling, monitoring and control, quality control/assurance, human resources, material and equipment, and safety and environmental protection; (iv) The research study purely reviewed the IoT literatures or applied the IoT concepts; (v) The reported technologies or applications demonstrated the fundamental characteristics of IoT: interconnectivity, things-related services, heterogeneity, dynamic changes, and enormous scale (Vermesan and Friess, 2014).

Quality assessment: To satisfy the publication quality in terms of the rigorousness and credibility, the assessment criterions are given. Criteria 1 (problem statement): Is the research objective clearly given? Criteria 2 (research design): Have the content covered the IoT technologies or the IoT applications in construction? Criteria 3 (data collection): Is the data collection method clearly given? Criteria 4 (data analysis): Is the data analysis clearly given? Criteria 5 (conclusion): Is the finding clearly given?

Data extraction: To import the initial literature search results, “Endnote” software platform is used. Once the document is recognised as relevant article, the document will be stored in a database (i.e., a folder established in Endnote). The database is used for further analysis.

3.2 Identification and classification of IoT technologies and applications using word frequency analysis and cluster analysis

To explore the “hot” IoT technologies and applications in construction management, the methods of word frequency analysis and cluster analysis were used. Word frequency analysis is used to study the occurrences of words given in a source text or document. The frequently-occurred words reflect and identify the greatest concerns of the main themes and concepts (Pina et al., 2019). The terms with high-frequency are searched in literatures to identify the focuses of reported IoT technologies and IoT applications. The words with general meaning (e.g., construction, project, and engineering) were excluded. The technical terms related to IoT technologies (e.g., RFID, GPS, and BIM) and IoT applications (e.g., time, safety, and location) were extracted. Cluster analysis is used to group the IoT applications into clusters based on similarity metrics (Wilks, 2011). For instance, a cluster containing terms “green” and “energy” should belong to “sustainability”.

3.3 Development of IoT maturity model by characterising the relationships between the IoT technologies and IoT applications

Although some researchers attempted to promote IoT, its development is still in an infant stage (Reda et al., 2018). The trend of future IoT development in construction was examined. A maturity model was proposed to evaluate the research maturity in connection with both IoT technologies and IoT applications. Maturity factor could be characterised by word frequencies in articles (Equation 1). Future opportunities on particular topics were indicated by those with low maturity.

$$y_{ij} = \frac{x_{ij} - wf_{\min}}{wf_{\max} - wf_{\min}} \tag{1}$$

where y_{ij} is the maturity factor of IoT technology i in IoT application cluster j. x_{ij} is the total word frequency of IoT technology i in all papers being clustered into Group j. $wf_{\max}$ and $wf_{\min}$ are the maximum and minimum word frequency amongst all x_{ij}.

4. RESULTS

4.1 Results of retrieving IoT-related articles in construction management research area

A total number of 116 papers were published according to the query string (Section 3.1). 32 of those papers were found to satisfy the screening criteria (Section 3.1). The journal of AIC (Automation in Construction) published the highest number of IoT-related article, accounting for over half of the journal papers. China is the largest contributor to IoT research area, followed by United States and Hong Kong.

4.2 Hot topics of IoT technologies and IoT applications

4.2.1 Development of IoT technologies

In general, an IoT architecture consists of several layers/domains, such as object domain, network domain, middleware domain, and application domain (Čolaković and Hadžialić, 2018); or IaaS (Infrastructure as a Service), PaaS (Platform as a Service), SaaS (Software as a Service) (Zhong et al., 2017). This research employed the IoT paradigm from Čolaković and Hadžialić (2018) to identify the research advancement in IoT technologies of such domains: object domain presents endpoint layer that includes physical things and virtual things, which have the capabilities of sensing, actuation, identifying, data storage, and processing; network domain includes hardware, software, technologies, and protocols that enable connectivity between IoT objects, and between IoT objects and global infrastructure (e.g., Internet); middleware domain is the intermediary between IoT objects and application layer; application domain manages application services that are provided through the IoT middleware layer (Čolaković and Hadžialić, 2018). To reveal the popularity of IoT technologies for capturing data for research, the words and its frequencies were extracted: **RFID (500), BIM (117), GPS (93), Laser (74), Ultrasonic (48),** and **GIS (31)**. These IoT technologies characterised IoT layer framework. Their advancement with respect to particular domains is shown in Table 1.

Table 1: IoT research for advancing IoT-related technologies

IoT technologies	Article identifier	Year	Domain	Advancement
RFID (500 times)	(1)	2007	Object domain	Integrated RFID readers, RFID tags, RFID antenna, and Zigbee sink nodes for tracking objects.
	(4)	2009	Object domain	Developed 3D RFID location algorithm for passive RFID labels.
	(5)	2009	Object domain	Tested effectiveness of using RFID tags with sensing distance of 100m using handheld RFID readers.
	(7)	2011	Object domain	Integrated RFID-based mover, trailer, gate and hoist for tracking objects.
	(9)	2012	Object domain	N/A
	(10)	2012	Object domain	N/A
	(25)	2017	Object domain	N/A
	(26)	2018	Object domain	N/A
	(28)	2018	Object domain	N/A

	(29)	2018	Object domain	N/A
	(30)	2018	Object domain	Developed small round NFC (near field communication)-enabled RFID tags for installation.
	(31)	2018	Object domain	N/A
BIM (117 times)	(15)	2014	Application domain	N/A
	(20)	2017	Object domain	Developed methods for transferring the data from TLS (terrestrial laser scanning) survey to BIM models.
	(24)	2017	Application domain	Developed n-dimensional BIM model for planning topology.
	(25)	2017	Object domain Application domain	N/A
	(30)	2018	Application domain	Developed BIM-based vitalisation service.
	(31)	2018	Application domain	Developed n-dimensional BIM model.
	(32)	2019	Application domain	N/A
GPS (93 times)	(8)	2011	Object domain	N/A
	(9)	2012	Object domain	N/A
	(17)	2017	Object domain	N/A
	(28)	2018	Object domain	N/A
	(30)	2018	Object domain	N/A
	(31)	2018	Object domain	N/A
Laser (74 times)	(20)	2017	Object domain	Developed method for assembling laser scanner data to generate BIM models.
	(28)	2018	Object domain	Developed method for assembling laser scanner data to determine production time.
	(29)	2018	Object domain	Developed method to detect signal change when the laser emitted was interrupted.
	(32)	2019	Object domain	N/A
Ultrasonic (48 times)	(16)	2014	Object domain	Lengthened measuring distance of ultrasonic.
	(19)	2015	Object domain	N/A
	(32)	2019	Object domain	N/A
GIS (31 times)	(9)	2012	Application domain	N/A

4.2.2 Development of IoT applications

To analysis the IoT applications in construction industry, word frequency analysis and clustering analysis (Section 3.2) were carried out. The IoT application studies could be clustered into themes using a software platform named as NVivo. Based on the frequently appeared words, the context of IoT applications were clustered into themes. To reveal the popularity of the researched IoT applications, the words and its frequency were extracted: **time (694), safety (479), location (350), crane (337), transportation (257), emission (235), tower (205), energy (163),** and **prefabrication (154)**. Then, a cluster analysis was conducted to group the IoT applications into **safety (12)**, **productivity (12)**, and **environment (8)**. Table 2 and Figure 2 present the clustering results.

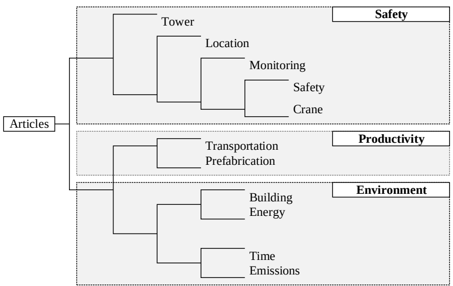

Figure 2: Cluster analysis of the object words

Table 2: Clusters of IoT applications

Clusters	Article identifier	IoT Applications	Article identifier	IoT Applications
Safety (12)	(5)	Site safety management	(16)	Crane safety monitoring
	(8)	Bridge disaster monitoring	(17)	Crane groups safety management
	(10)	Proactive accident prevention	(19)	Crane safety monitoring
	(11)	Data error improvement for safety monitoring	(21)	Safety management for visitors
	(13)	Data error improvement for safety monitoring	(27)	Safety monitoring for scaffolding structure
	(14)	Crane collision avoiding	(32)	Metro construction safety monitoring

Productivity (12)	(1)	Material tracking	(24)	Lean construction management
	(4)	Material positioning	(23)	Construction activities monitoring
	(7)	Construction supply chain management	(25)	Lean prefabricated construction management
	(9)	Construction site dynamics tracking	(26)	Inventory tracking
	(15)	Digital construction platform for precast components	(30)	Lean prefabricated construction
	(20)	Lean construction	(31)	Prefabrication transportation
Environment (8)	(2)	Building environmental monitoring	(18)	Building energy monitoring
	(3)	Environmental monitoring	(22)	Green building simulation
	(6)	Dynamic life cycle assessment of buildings	(28)	Carbon emission monitoring
	(12)	Environmental monitoring on construction site	(29)	Carbon emission monitoring

4.3 Identification of research trend and opportunities

Figure 3 maps the relationships between the IoT technologies and the applied articles. The weight of the relationships is given as the word frequency in the articles. These articles were clustered into three groups of IoT applications. A maturity matrix is proposed for indicating the maturity of IoT technologies in IoT applications (Equation 2).

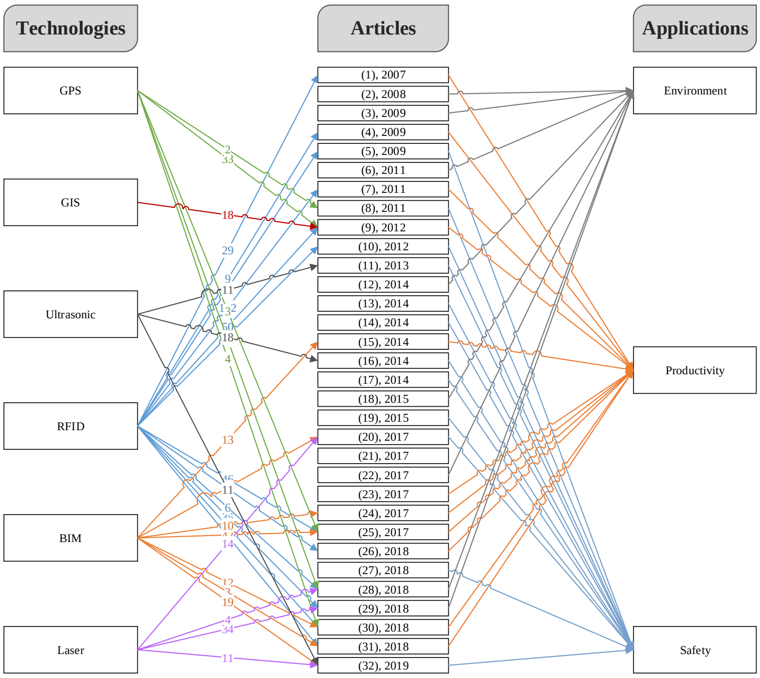

Figure 3: Maturity model of IoT in construction research

$$X_{ij} = \begin{pmatrix} 1.00 & 0.40 & 0.14 \\ 0.27 & 0.10 & 0 \\ 0.13 & 0.01 & 0.02 \\ 0 & 0.08 & 0.13 \\ 0 & 0.13 & 0.02 \\ 0.06 & 0 & 0 \end{pmatrix} \qquad (2)$$

where X_{1j}=RFID, X_{2j}=BIM, X_{3j}=GPS, X_{4j}=Laser, X_{5j}=Ultrasonic, X_{6j}=GIS; X_{i1}=Productivity, X_{i2}=Safety, X_{i3}=Environment

5. Discussion

5.1 IoT technology development in construction

5.1.1 Object domain development

Sensing is the main IoT object domain in IoT architecture. RFID is found to be the hottest IoT technologies. Due to its simplicity and low cost, the researchers used RFID to collect data (i.e., object ID, location, and distance). Other sensing technologies, such as GPS, laser, ultrasonic and GIS, were also utilised for sensing data. Besides, combinations of sensing methods may enable data collection with better coverage of site area. For instance, location tracking of moving objects (e.g., material, worker) can be realised by integrating RFID and GPS with reduced errors inherent by GPS on site.

5.1.2 Network domain development

The IoT network domain involves the communication technologies such as Cellular, Wi-Fi, LPWAN, Bluetooth, and ZigBee. These technologies not only can receive data from sensing "Things", but also share data with other connected "Things". Notably, there is very limited development of IoT network in research studies. Most of the IoT researchers utilised the existing communication technologies on site.

5.1.3 Middleware domain development

The IoT middleware domain is essential for connecting the IoT objects and application layer. It helps to aggregate and filter the received data from IoT devices. The researchers focused on managing the heterogeneous physical assets to share information. Since the information with different properties is flowed for different purposes of a construction project, researchers investigated on the unification of IoT data.

5.1.4 Application domain development

The IoT application domain was developed for realising IoT applications. BIM technology is found to be integrated in IoT architecture. This technology offers an integrated platform for sharing and visualising the information with project stakeholders. As such, the researchers proposed n-dimensional BIM model for sharing and analysing the information such as design, time, and cost.

5.2 IoT applications in construction

The dominant IoT application areas in construction mapped using clustering analysis (Section 4.2.3) are found as: safety, productivity, and environment.

5.2.1 Safety application development

In "safety" category, "monitoring" and "location" are the two main clusters. The safety research took advantages of IoT architecture featuring real time data collection. For example, the potential use of IoT in the construction projects related to scaffolding, building, bridge, tunnel, and tower crane was researched. The researchers found that safety can be monitored by IoT architecture and location data is the essential information for safety monitoring in IoT architecture. Although this concept was prototyped and proved feasible by researchers, limitations still exist in terms of the insufficient power supply of sensors and the low accuracy of captured data in practical settings.

5.2.2 Productivity application development

In "productivity" category, "prefabrication" and "transportation" are the two main clusters. The building components are prefabricated in factories off-site and transported to construction site for installation, such that the productivity can be improved. These articles are all related to component prefabrication, supply chain, and tracking objects. Thanks to IoT technologies, heterogeneous data sources can be captured, integrated, and processed within the IoT platform. However, intelligent approach for making decision using IoT platform does not exist yet.

5.2.3 Environment application development

In "environment" category, "building", "energy", "emission", and "time" are the four main clusters. The words "building", "energy", and "emission" are highly relevant to building environment. The word "time" refers "real-time" monitoring for energies. Generally, the researchers used IoT architecture for life cycle assessment, monitoring dust, simulating building energy, and monitoring greenhouse gas emission.

5.3 Future opportunities for IoT in construction

The future IoT development opportunities were identified based on the results of maturity model (Section 4.3). Notably, the maturity factors with low values do not certainly lead to the huge potential for further research development in that referred research area. For instance, the text-string "BIM-Environment" may not be feasible due to the inapplicability of BIM technologies for environmental applications, while text-string "Laser-Safety" may also not be feasible due to the high cost of laser devices for safety applications.

5.3.1 IoT platform for monitoring environment driven by GIS technologies at city level in real time

The maturity index of "GIS-Environment" is 0. This indicated that IoT research opportunity may exist. The researchers developed building energy software platforms aiming to evaluate and improve building energy performance over the past decades (Crawley et al., 2008). Energy simulation approaches and tools were proposed accordingly, including ECOTECT, EnerWin, EnergyPlus, eQUEST, PowerDomus (Fasi and Budaiwi, 2015). Not much research studies were reported to smartly visualise energy distribution of any locations in any cities. The GIS-enabled IoT technology should be able to integrate, analyse, and visualise the environmental information of a city. Therefore, GIS-based IoT platform can be materialised by developing and deploying sensors to capture and record the energy data in real time, transferring the data into a database, integrating the data by unifying mechanism, quantifying energy performance by analysing the data, and visualising the energy performance information on dashboard.

5.3.2 IoT platform for improving productivity driven by IoT technologies in real time

The maturity indexes of "BIM-Productivity", "GPS-Productivity", "Laser-Productivity", "Ultrasonic-Productivity", and "GIS-Productivity" are all less than 0.3. This indicated that IoT research opportunities may exist. The researchers developed simulation techniques for enhancing project productivity in construction. To control project productivity, on site data should be captured by developing IoT technologies for conducting simulation analysis in short time. In this case, the IoT technologies can be developed or modified based on BIM, GPS, Laser, Ultrasonic, and GIS. The IoT architecture should be developed for enabling real time data collection. The data will be used as input modelling for updating the simulation models. As such, project performance (e.g., time, cost) can be simulated in short time for helping the planners to forecast the project performance and suggest any rectifications for productivity improvement.

5.3.3 IoT platform for improving safety driven by on IoT technologies in real time

The maturity indexes of "GPS-Safety", "Laser-Safety", and "Ultrasonic-Safety", are all less than 0.2. The researchers developed safety monitoring systems to track the location of workers and the operation status of "things" (e.g., equipment, vehicles) in real time. This helps the workers to change their risky behaviours such that the accidents on site can be avoided. Also, the researchers investigated the accuracy of location tracking technologies (e.g., GPS: from 2.1m to 4.4m, Ultrasonic: less than 0.2m). To control and improve site safety in real time, the data detection (e.g., worker trails, equipment status) must be accurate. As such, sensing technologies, such as GPS, laser, ultrasonic should be developed and integrated. This not only can increase the precision of location data, but also increase the cost-effectiveness and time efficiency of collecting data. Therefore, the IoT platform can be used to gather, assemble, and analyse the big data in real time for generating safety reports, guidelines, and policies. To that end, the safety management performance can be improved.

6. Conclusions

This research provides new insights of quantifying "maturity" of IoT technologies and IoT application in construction research. The contributions of this research study are in two-fold. From academic perspective, a new three-step method is proposed for determining the maturity of IoT research. Word frequency analysis and cluster analysis were used to identify any hot topics in IoT technologies and IoT applications. To certain extent, compared to personal judgement, this new method provides a relatively objective means for searching research opportunities. From practical perspective, we discovered that the IoT paradigm was widely studied in relation to safety, environment, and productivity. In addition, future opportunities for IoT development in construction management are highlighted as per the text-strings GIS-environment, BIM-productivity, GPS-productivity, laser-productivity, ultrasonic-productivity, GIS-productivity, GPS-safety, laser-safety, and ultrasonic-safety. Future research can be done based on proposed method. For instance, the proposed method can be validated by applying the method to other research disciplines, and the database for the method can be expanded by including the documents in Scopus and any other databases for identifying more IoT research opportunities.

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