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BIM and IoT for the AEC Industry: A systematic literature mapping

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Abstract

The AEC industry has been facing a digital transformation for improving services involved in buildings lifecycle, fostered by two disruptive technologies: Building Information Modelling (BIM) and Internet of Things (IoT). However, the literature lacks discussions regarding applications and challenges of BIM and IoT systems in the AEC. This Systematic Literature Mapping addresses this gap through search, analysis, and classification of 75 journal article abstracts published between 2015 and 2019. An increase of articles over the period is observed, predominantly with technical and processual solutions for Construction and Operation and Maintenance. The interoperability of data is a key challenge to organizations.

Keywords: Building Information Modelling; Internet of Things; Integration; Network; Smart Cities

INTRODUCTION

The Architecture and Engineering Construction (AEC) industry has been facing a digital transformation for improving the efficiency of services involved in designing, building and operating assets, and the users' well-being in the built environment and urban spaces. Such a transformation towards sustainable smart cities has been fostered by two disruptive Information and Communication Technologies (ICTs), namely Building Information Modelling (BIM) and Internet of Things (IoT).

Defined as "the 'current expression of digital innovation' across the construction industry" (BIME Initiative, 2016), BIM integrates the information of a building and its objects in a centralized digital database. It enables the collaboration among stakeholders through the building life cycle (Eastman, Teicholz, Sacks, & Liston, 2014) and changes in the design process development and management (Emmitt, 2016), thus increasing the accuracy and availability of information and the final building quality.

Based on a network that connects physical objects to the Internet (Madakan, Ramaswamy, & Tripathi, 2015), IoT is also considered a key component of the smart cities concept, since it converges "physical, digital and human systems in the built environment to deliver a sustainable, prosperous and inclusive future for its citizens" (BSI, 2014, p. 3). IoT enables a real-time understanding of every aspect and component of a building and its operation, increasing the accuracy and availability of information (Gunduz, Isikdag, & Basaraner, 2017; Pishdad-Bozorgi, 2017; Wong, Ge, & He, 2018). Moreover, IoT supports constructors and managers to overcome one of BIM limitations, i.e. the static building information, raising the efficiency of services to a higher level.

Although a variety of technological solutions have been recently developed, understanding their benefits for the AEC activities is still a challenge, in special for the Facilities Management (FM) sector (Codinhoto, Fialho, Pinti, &

Fabricio, 2020). BIM and IoT-based systems offer the opportunity to automatize processes and support changes in the industry from a reactive to a predictive approach. The novelty and importance of the field justify the development of academic and technical investigations.

Previous studies have focused on the identification of BIM and IoT technologies applicable to FM industry processes, describing suitable devices, tools and software for data collection, storage and sharing (Fialho, Codinhoto, & Fabricio, 2019; Ye, Yin, Tang, & Jiang, 2018), as well as fields of application of their combined solutions (e.g. Construction, Operations and Maintenance) (Kensek & Kahn, 2013; Pärn & Edwards, 2017; Ramprasad et al., 2018; Vandecasteele, Mercier, & Verstockt, 2017). Nevertheless, the literature still lacks discussions regarding the broad implementation BIM and IoT-based systems in the AEC industry. This study focuses on the establishment of contextual knowledge concerning the applications and challenges of BIM and IoT systems integration through search, analysis, and classification of journal article abstracts published between 2015 and 2019.

MATERIAL AND METHODS

A Systematic Literature Mapping (SLM) was conducted to develop a broad perspective of the subject and a structured classification of publications, supporting future studies (Gough, Oliver, & Thomas, 2012; Petersen, Feldt, Mujtaba, & Mattsson, 2008). A research protocol synthesized the structure and criteria for the work (Table 1).

The Science Direct (Elsevier) database was considered appropriate for this study, providing relevant publications on the topic. Keywords and Boolean operators were defined for addressing both individual BIM and IoT concepts and the context for BIM and IoT integration. Filters for selecting innovative works include peer-reviewed journal articles published in Portuguese and English from 2015 to 2019. The five-year term was defined due to the

constant evolution of the area, in which technological solutions rapidly become obsolete. From 146 identified entries, 75 abstracts were chosen for further analysis after applying the filters and selection criteria.

Table 1: Research protocol.

Item	Content
Research questions	What are the applications and challenges of BIM and IoT systems integration in the AEC industry?
Key objectives	To develop contextual knowledge concerning the applications and challenges of BIM and IoT systems integration through search, analysis, and classification of journal article abstracts published between 2015 and 2019. Science Direct (Elsevier)
Database Keywords	("building information modelling" OR "building information modeling" OR "bim") and ("IoT" OR "IoT system" OR "IoT platform") AND ("integration" OR "connection") AND ("Computer Networks and Communications" OR "network") AND "Smart cities"
Filters	Year of publication: 2015 to 2019. Type of publication: peer-reviewed journal articles. Language: English and Portuguese
Selection criteria	Inclusion criteria: articles on BIM and IoT systems. Exclusion criteria: Publications neither correlated to BIM and IoT systems, nor written in the aforementioned languages.

RESEARCH FINDINGS

BIBLIOMETRIC ANALYSIS

Table 2 shows the distribution of articles published in Journals over time. An increase in submissions over the five past years is verified, particularly in 2018 (21) and 2019 (35). *Automation in Construction* concentrates 38% of the articles (29), followed by *Advanced Engineering Informatics* (6), *Procedia Engineering* account (6), and the *Journal of Cleaner Production* (5).

The distribution of authors country per article is illustrated in Figure 1. The authors are predominantly from the UK, USA, and China. 30% of the total number of publications comprehend more than one country, evidencing the partnership among nations. Together, Europe and Asia concentrate 80% of the whole publications. South America accounts for only one article, which demonstrates research opportunities on the topic in the region.

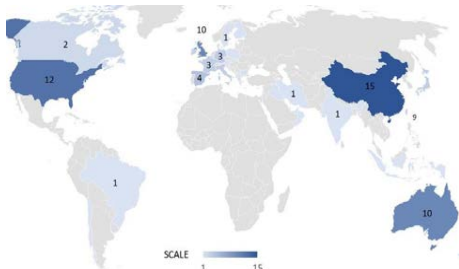


Figure 1: Distribution of authors country per article.

The distribution of articles per overall research method is shown in Figure 2. Literature Review was adopted in 24 articles, followed by Case Study (19) and Experimental

methods (14). Other methods include Interviews and questionnaires (4), Simulation (2), and Axiomatic design (1). The methods applied were not clearly identified in 11 articles, and, in most cases, the aim was to demonstrate the application of BIM- and IoT-based solutions in AEC processes and activities.

Table 2: Distribution of articles published in Journals per year.

Journal	2015	2016	2017	2018	2019	Sub
Automation in Construction	1	1	3	10	14	29
Advanced Engineering Informatics		1		1	4	6
Procedia Engineering	2		4			6
Journal of Cleaner Production		1	1	1	2	5
Procedia Computer Science				2	2	4
Future Generation Computer Systems				1	2	3
Computers in Industry				1	1	2
Journal of Building Engineering					2	2
Procedia Manufacturing			1	1		2
Sustainable Cities and Society				2		2
Technological Forecasting and Social Change				2		2
Building and Environment					1	1
Cities					1	1
Computer Networks					1	1
Computers & Industrial Engineering					1	1
Energy Procedia					1	1
Habitat International		1				1
IFAC-PapersOnLine	1					1
Journal of Urban Management				1	1	1
Neurocomputing					1	1
Renewable and Sustainable Energy Reviews			1			1
Resources, Conservation and Recycling			1			1
Safety Science					1	1
Total	4	4	11	21	35	75

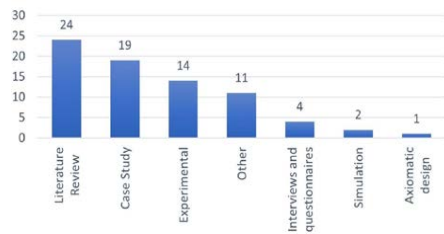


Figure 2: Distribution of articles per overall research method.

The distribution of articles per research focus on the AEC stages is shown in Figure 3. Construction and Operation & Maintenance (O&M) stages are the focus of 44 articles. 24 publications discuss BIM and IoT integration in a broad view and with no relation to specific AEC stages. Manufacturing is described in 4 articles, regarding building components production, while Design, Renovation, and Demolition are addressed in 3 articles.

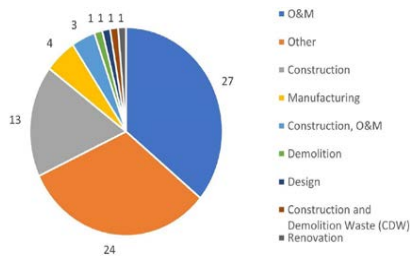


Figure 3: Distribution of articles per research focus on the AEC stages.

Table 4 presents the distribution of articles per year according to the research focus on three categories, namely 1. *Theory*, which includes Literature Review and conceptual propositions; 2. *Information Technology (IT)*, related to the development of interfaces, platforms, systems, and ontologies for BIM and IoT integration; and 3. *Process*, regarding approaches, frameworks, methods, and models for BIM and IoT integration. Focus on Process was identified in most publications (29), followed by IT, in 24, and Theory, in 22 articles.

Table 4: Distribution of articles per year according to the research focus – Theory, IT and Process.

Research Focus and Example	2015	2016	2017	2018	2019	Sub
Theory: "A concept for securing distributed applications and services in data infrastructures for Smart Cities" (CHATURVEDI et al., 2019)	1	0	4	4	13	22
Information Technology (IT): "Internet of Things-enabled BIM platform (IBIMP) for the Modular Integrated Construction (MiC) project" (ZHAI et al., 2019)	1	2	6	7	8	24
Process: "Smart Sewer Asset Information Model (SSAIM) for an existing sewerage network" (ZHONG et al., 2015)	2	2	1	10	14	29
Total	4	4	11	21	35	75

ABSTRACT ANALYSIS

The 75 selected abstracts were analysed for the identification of propositions for BIM and IoT integration and challenges and problems faced on this procedure. To do so, the articles were grouped according to the research focus (i.e. Theory, Process, and IT), emphasizing common scopes of the categories.

In the *Theory* group, 20 literature review articles discuss the role of emerging ICTs in AEC industry digital transformation. Tang et al. (2019) identified the application of BIM tools' APIs and semantic web technologies to the Construction and O&M. Wong, Ge and He (2018) explored digital technological developments into FM, including BIM and IoT. IoT has been explored as a disruptive technology in distinct perspectives, i.e. fostering the development of business models in Smart Cities scenario (Alcayaga, Wiener, & Hansen, 2019); supporting the evolution of AEC (Woodhead, Stephenson, & Morrey, 2018) and the smart building industry (Magruk, 2015), specifically over construction and O&M (Jia, Komeily, Wang, & Srinivasan, 2019); contributing to the remanufacturing sector in

combination with Virtual Reality (VR) and Augmented Reality (AR) (Kerin & Pham, 2019); and supporting intrusion detection in computer networks (Kelton, Papa, Lisboa, Munoz, & De, 2019). Improvements in the integration of concepts for supporting performance economy and between cyber-physical systems (CPS) and IoT are described as important challenges. IoT supports the development of new concepts. Chaturvedi et al. (2019) proposed the "Smart District Data Infrastructure (SDDI) concept" integrating sensors, simulation tools, and 3D models of cities. Yan and Sakairi (2019) discussed IoT and CPS in the context of urban management, supporting the "Geo CPS" proposed concept.

BIM has been approached as a central concept for the AEC evolution in some reviews. Gao and Pishdad-Bozorgi (2019) and Araszkievicz (2017) discussed its application in O&M, highlighting the integration of building lifecycle data and decision-making support as benefits. Energy management is one of the key areas (Araszkievicz, 2017) fostered by Building Energy Modeling methodologies and BIM database (Pezeshki, Soleimani, & Darabi, 2019). The use of BIM in urban infrastructure was explored by Costin et al. (2018) and Rice and Martin (2018). Other BIM applications involve off-site construction (OSC) (Yin, Liu, Chen, & Al-hussein, 2019), network security and data management (Nawari & Ravindran, 2019), and data integration, building energy management and urban governance (Wang, Pan, & Luo, 2019), promoted by BIM, GIS and complementary technologies (Ma & Ren, 2017; Pauwels, Zhang, & Lee, 2017).

With regards to the *Information Technology (IT)* group, some articles address the development of platforms, systems, interfaces and ontologies integrating BIM and IoT for various purposes in the built environment. Dave et al. (2018) proposed the Otaniemi3D web-based platform, associating BIM models with built environment data from IoT sensors. Lokshina, Greguš and Thomas (2019) developed a system design for improvements in data security, exchange, and sharing among stakeholders.

Prefabricated construction is the focus of some studies. Zhai et al. (2019) has developed an "Internet of Things-enabled BIM platform (IBIMP) for Modular Integrated Construction (MiC) project" to support data collection and automatic decision support. Zhengdao et al. (2016b) generate an IoT-enabled platform to streamline offshore prefabricated construction processes, while Zhengdao et al. (2017) develop a "RFID-enabled BIM platform" to manage critical schedule factors. Zhengdao et al. (2018) design an IoT-enabled platform by integrating BIM, RFID and VR technologies for facilitating the on-site assembly services (OAS) and Zhong et al. (2017) propose a "Multi-dimensional Internet of Things (IoT)-enabled BIM platform (MITBIMP)" for real-time traceability and visibility of components. The potential benefits of the presented solutions include availability of real-time cost information, remote supervision of construction progress, and information sharing among participants. BIM- and IoT-based solutions have also been proposed for O&M, i.e. a system to recognize unsafe worker behaviours in building environments (Arslan, Cruz, & Ginhas, 2019b); a "BIM-based visualization and warning system for fire rescue" (Chen, Liu, & Wu, 2018); a "semantic knowledge management service and domain ontology" combining BIM and smart water field systems for improvements in systems

performance (Howell, Rezgui, & Beach, 2017), and the Real-Time Replay System (RTRS) for building users managing energy consumption and conservation (Chiang, Chu, & Chou, 2015).

The development of IoT-based platforms for distinct lifecycle stages is the scope of some articles. In construction, a virtual experimental platform was proposed for simulating the use of an IoT-enabled control for an earthmoving work (Louis & Dunston, 2018), as well as a cloud-based IoT platform for managing physical assets (G. Xu, Li, Chen, & Wei, 2018), and an "IoT-enabled Smart Factory Visibility and Traceability Platform" for smart factory production (Zhong, Xu, & Wang, 2017). The propositions for O&M include the "IoT Energy Platform (IoT-EP)" for management, processing, and analysis of building energy data (Terroso-saenz, González-vidal, Ramallo-gonzález, & Skarmeta, 2019); a sensor management system for energy efficiency of smart buildings (Plageras, Psannis, Stergiou, Wang, & Gupta, 2018); and an integration citizen's suggestion system for user's communication (Ham, Teng, Wijaya, & Wikopratama, 2018). Addressing Health and Safety, a framework for information integration and a prototype system for safety monitoring over the AEC industry were introduced (Q. Xu, Chong, & Liao, 2019), as well as a "cyber-physical-system-based safety monitoring system" for hoisting in underground constructions (Zhou, Luo, Fang, Wei, & Ding, 2019).

BIM-based systems and interfaces were proposed for distinct applications, i.e. a BIM-based interface to support customers in exploring design solutions in mass-customized housing sector (Bianconi, Filippucci, & Buffi, 2019); a BIM-based prototype CPS for structural health monitoring (SHM) (Fitz, Theiler, & Smarsly, 2019); a GIS-BIM based system for urban energy planning optimization (Yamamura, Fan, & Suzuki, 2017); an "interactive Augmented Reality system for Temporal and Spatial analysis of power consumption data integrated with building information models (iARTS)" (Chou, Chiang, Wu, Chu, & Lin, 2017).

Regarding the *Process* group, frameworks, approaches, models, and methods for the integration of BIM and IoT have aimed streamlining AEC processes. Heaton and Parlikad (2019) developed a "smart asset alignment framework" integrating infrastructure asset information and citizen necessities; Love, Matthews and Gates (2019) proposed a generic business dependency network (BDN) for analysis of multiple relationships of digital technologies implementation; and Motamedi et al. (2016) introduced a method for setting RFID technology components in BIM. Focusing on anticipating building users' needs, Ciribini et al. (2017) developed a workflow to populate BIM models with sensors' data. Arslan, Cruz and Ginhas (2019b) designed the "Occupant Behaviors in Dynamic Environments (OBIDE) framework" incorporating the environment information. Zhengdao et al. (2016a) provide a BIM-IoT based method that analyses risk factors and effects for stakeholders in prefabrication construction.

O&M-oriented solutions are addressed by Rashid, Louis and Fiawoyife (2019), who introduced a framework for electrical fixtures control in smart built environments, integrating an ultra-wideband-based indoor positioning system with a BIM-based virtual environment, and

Edmondson et al. (2018), through a "Smart Sewer Asset Information Model (SSAIM)" for managing operations. In the Health and Safety domain, Liu et al. (2019) developed a method for safety inspection integrating BIM and unmanned aerial vehicle (UAV) camera for supplying industrial and residential water, and Peng, Li and Hu (2019) proposed a neural networks-based approach for evacuation planning in grand public buildings.

IoT-centred solutions are also developed, i.e. a framework for safety management and monitoring in complex environments (Haddad, Bouyahia, & Chaudhry, 2019); "a big data analytics for IoT-enabled manufacturing shop floor" (Kho et al., 2018); "a Physical Internet-enabled decision support system (DSS)" for tracking components and mapping real-time interactions among stakeholders of prefabricated housing construction (Zhong et al., 2015); and a semantic knowledge model for smart buildings using the IndoorGML standard (Rubio et al., 2018).

Difficulties related to BIM embracement by AEC industry have fostered some propositions, i.e. a "Unified BIM Adoption Taxonomy (UBAT)" for classification and integration of drivers and factors for BIM adoption (Louay & Kassem, 2018); models, matrices and charts for macro-BIM adoption assessment and BIM diffusion policies information (Succar & Kassem, 2015, p. 64); a recommendation for building geometry representation (McGlinn et al., 2019); and the DALTON (DAta Linked Through Occurrences Network) conceptual model, that provides checking components for business rules (Fortineau, Paviot, & Lamouri, 2019).

BIM-based solutions have been proposed for construction and demolition stages. Among such solutions are the "smart work packaging (SWP)" for constraints management (X. Li, Qiping, et al., 2019) and the conceptual framework for BIM integration in prefabrication housing production (X. Li, Wu, & Yue, 2019); a group of BIM expectations for construction and demolition waste management (Akinade et al., 2018); a conceptual "Reverse logistics supply chain (RLSC)" model to support demolition and reprocessing of salvaged materials (Chileshe, Jayasinghe, & Rameezdeen, 2019). Processual solutions have also been proposed for O&M, i.e. a "Diagnosis-Aided Historic Building Information Modelling and Management framework" (Bruno, Fino, & Fatiguso, 2018), an "Integrated Knowledge-based Building Management System" for detecting and diagnosing operational faults (Gha et al., 2019), and "an object-oriented city design model" for building energy performance assessment (Zachary et al., 2019).

Additional approaches and technologies were addressed, i.e. Good, Ellis and Mancarella (2017) discussed barriers and enablers involved in the demand response of electric systems, Novais, Manuel and Ortiz-Bas (2019) investigated the integration between Cloud Computing and Supply Chain, (J. Li, Greenwood, & Kassem, 2019) and Marsal-Llacuna (2018) proposed Blockchain-based frameworks supporting the built environment and construction sector, David, Aubry and Derigent (2018) and Yang et al. (2018) introduced integrated frameworks for multisector infrastructure asset management, whereas Hu et al. (2016) developed a "Resource Description Framework (RDF) syntax structure" for representing existing database information.

DISCUSSION AND CONCLUSIONS

This systematic literature mapping analyzed relevant abstract articles published in the past five years. Publications on ICT implementation (i.e. BIM and IoT) in the AEC industry has significantly increased over the period, from 4 in 2015 to 35 in 2019, evidencing an expansion of investigations on the topic, particularly in Europe and Asia (Figure 1). The collaboration among several countries was identified, which enables the research development through distinct approaches.

The predominance of journals in construction and engineering domains (Table 2) demonstrates the applicative bias of the studies, concerned with the AEC demands. Most publications are driven to Construction and O&M, which evidences the potential advantages of BIM and IoT integration for building and managing assets. Regarding the research method (Figure 2), most articles have adopted literature reviews, still required to state a knowledge field, followed by Case Study and experimental methods, demonstrating an orientation to the development of technical and processual solutions for building lifecycle.

Table 4 shows a predominance of articles regarding IT propositions (47%) in the first three years (2015-2017) in comparison to theoretical and processual approaches. Mostly, the IT solutions address BIM models and IoT devices integration issues for key areas, i.e. prefabrication construction, building and infrastructure operation and maintenance, energy management, and health and safety. However, this scenario was altered in 2018 and 2019, with a significant increase on processes improvement solutions (42%), evidencing the required transformations imposed by BIM and IoT to organizations for adapting traditional activities to a digital environment, thus setting a trend for investigations.

Challenges and problems faced in the BIM and IoT integration are described by few articles (Aguiar et al., 2017; Gao & Pishdad-bozorgi, 2019; Tang et al., 2019; Wong et al., 2018) in a broad perspective of ICT implementation and can be summarized in one main issue, i.e. interoperability throughout information exchange standards over the building lifecycle. Defined as the "ability of diverse systems (and organizations) to work together seamlessly without data loss and without a special effort" (BIMe Initiative, 2019), the interoperability among AEC processes and systems is crucial for improving the integration among ICT's. Although BIM platforms and IoT devices have individually achieved a high level of development, the generation of effective integrated systems driven to practical problems is required. Governments, professional bodies, and universities around the world has been addressing this gap (Pezeshki et al., 2019) through the definition of mandates, handbooks, and technical standards. Once again, a global effort is needed to establish a common approach for organizations managing BIM and IoT-based systems.

The novelty of the subject and the overall predominance of processes propositions might explain the scarcity of challenge and problems description, commonly identified in practical applications of BIM- and IoT-based systems. Besides, articles usually tend to prioritize positive aspects of the research rather than the negative ones. This is more evident in the abstracts of AEC area, that draw in a few

words a synthesis of the research structure and results lacking, in some cases, important information on problems and challenges.

In fact, the potential of BIM and IoT-based systems for the evolution of AEC service provision is unlimited and still few explored. Understanding the real problems faced by organizations is imperative for the efficacy of BIM and IoT implementation. Opportunities for improvements in the FM sector are described by (Codinhoto et al., 2020), through the analysis of approximately 80.000 work requests of two educational organization in Italy and the UK. Previous results show the relationship between the severity and recurrence of problems as an important metric for identifying critical problems in building facilities. In this sense, the characterization of problems in each context through empirical data is essential to define the most appropriate BIM and IoT solutions for specific processes, supporting the implementation of a predictive strategy for problems solving.

Given the embryonic phase of BIM and IoT combined areas in the AEC industry, the authors have been working on developing a baseline through theoretical and practical investigations. This study contributes to knowledge by mapping and discussing relevant articles through a systematic method, providing a reference for future literature reviews. In addition, the study establishes a contextual knowledge from the past five years, identifying the proposed solutions, scenarios of development (i.e. country, lifecycle stage, research method) and trends on the topic advancement.

Some limitations and opportunities were identified in this study. Difficulties were found in tracking publications from a multidisciplinary subject within the database. The selection of keywords and filters was repeatedly tested to get entries addressing the study questions and key objectives. Also, the assessment of abstract articles as a methodological approach has limited deepening the critical analysis. In this respect, a full-text reading is recommended. Finally, empirical investigations are recommended aiming to explore opportunities and strategies for BIM and IoT-based systems implementation as disruptive solutions for AEC industry.

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