SOLUTIONS INTEGRATING BIM AND INTERNET OF THINGS IN BUILDING LIFE CYCLE: A CRITICAL REVIEW

SOLUÇÕES INTEGRANDO BIM E INTERNET DAS COISAS NO CICLO DE VIDA DA EDIFICAÇÃO: UMA REVISÃO CRÍTICA

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Abstract

This article aims at identifying, analyzing, and classifying into classes of problems the components, models, and methods related to the integration of Building Information Modeling (BIM) and Internet of Things (IoT) found in the existing solutions reported in the literature. The guidelines of the Systematic Literature Review (SLR) methodology were used to map related studies, identify artifacts that have been produced addressing such integration, and configure classes of problems. The results show that artifacts are mostly concentrated in the Building Operation and Maintenance phase; there is an increasing interest in the Construction and Commissioning phase, and; models and instantiations are the most recurring artifacts in BIM/IoT integration, which addresses nine different classes of problems and is in full development. BIM model series and uses applied in each context, as well as the technologies associated, are presented. Moreover, the purposes of BIM and IoT in the integration, as well as the main agents involved, are pointed out. The authors indicate new research fields in a post-BIM stage, in which Building Information Modeling transcends for a multidisciplinary context, embracing Sensing Technology and Information and Communication Technology (ICT) specific solutions that should expand static or dynamic relations between physical and virtual environments.

Keywords: BIM. Internet of Things. BIM/IoT Interfacing. Systematic Literature Review.

Resumo

O objetivo deste artigo é identificar, analisar e estratificar em classes de problemas os componentes, modelos e métodos das soluções existentes na literatura que integram Modelagem da Informação da Construção (BIM) e Internet das Coisas (IoT). Foram adotados os procedimentos metodológicos da Revisão Sistemática da Literatura (RSL) para o mapeamento de estudos convergentes, a identificação de artefatos já produzidos inerentes à integração mencionada e a configuração de classes de problemas. Os resultados constatam artefatos concentrados majoritariamente na fase de Operação e Manutenção da edificação e interesse crescente na fase de Construção e Comissionamento; maior recorrência de modelos e instanciações na integração de BIM e IoT, que atende a nove classes de problemas distintos e apresenta-se em pleno desenvolvimento. São discriminados as séries e os usos do modelo BIM empregados em cada contexto, bem como as tecnologias utilizadas. Ademais, são evidenciados os propósitos do BIM e da IoT na integração e os principais agentes envolvidos no processo. Apontam-se novos campos de pesquisa em um estágio post-BIM, nos quais a modelagem da informação da construção transcende para um contexto multidisciplinar, abarcando soluções específicas de Tecnologias da Informação e Comunicação (TIC) e Sensoriamento que devem ampliar as relações estáticas ou dinâmicas entre os ambientes físico e virtual.

Palavras-chave: BIM. Internet das Coisas. Interface BIM/IoT. Revisão Sistemática da Literatura.

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Introduction

Building Information Modeling (BIM) is an innovative paradigm that consists of "a set of interacting policies, processes, and technologies" (SUCCAR, 2009) to produce methodologies for building production and information management throughout its life cycle (PENTTILA, 2006). The backbone of this set comprises semantically rich, digital 3D models that are capable of sharing and exchanging data (GSA, 2006; ISIKDAG, 2015). Its effectiveness in the Architecture, Engineering, Construction and Operation (AECO) industry can be measured by performance milestones that indicate organizational potentialities to meet the minimum requirements for each stage of implementation - object-based modeling, model-based collaboration, and network-based integration. The completion of these stages leads to a variable, continually evolving scenario called post-BIM. The post-BIM represents goals that aim at the use of tools and concepts virtually integrated into the building context (SUCCAR, 2010). This scenario tends to be assisted by Information and Communication Technologies (ICTs), capable of expanding the skills to manage the several phases of the building life cycle (UNDERWOOD; ISIKDAG, 2011; SABOL, 2013; ISIKDAG, 2015).

Succar, Saleeb, and Sher (2016) emphasize the context of BIM evolution with ICTs when it classifies the Model Uses (MUs) associated with the construction domain. The BIM/IoT Interfacing, subject of this study, is included in one of the Model Uses' extension series. The Internet of Things (IoT) is a paradigm that involves different technologies and consists of a global network infrastructure of interconnected objects. This infrastructure not only collects data from the physical environment and interacts with the real world, but also uses existing network protocols to provide information transfer, analysis, application and communication services, with or without human intervention (EUROPEAN COMISSION, 2010; VERMESAN et al., 2011; GUBBI et al., 2013). This interconnection can foster the creation of intelligent scenarios in various application domains, such as cities, environments, domotics and home automation, security and emergencies, logistics, industrial control, retail, and so forth (ASIN; GASCON, 2012).

Considering the application domains inherent to the built environment, the integration of BIM and IoT may consist of using the BIM model as an interface improved with data provided by a network of equipment, sensors and mobile devices. The results from this integration point to: (i) the use of BIM models in real time to display data collected by sensor networks; (ii) the use of BIM models in asset tracking to locate fixed or mobile assets using tracking and marking technologies; and (iii) the use of BIM models for building automation to monitor and control the building (SUCCAR; SALEEB; SHER, 2016; BIM DICTIONARY, 2017).

Considering this post-BIM perspective, this article presents a Systematic Literature Review (SLR), whose purpose is to identify, analyze and organize into classes of problems the components, models, and methods of the existing solutions reported in the literature that integrate BIM and IoT.

BIM/IoT Interfacing

The integration of information acquired through the IoT to the BIM objects[1] becomes fundamental to provide its representation, contextualization, and correlation with a particular building in real time (ISIKDAG, 2015). Underwood and Isikdag (2011) and Isikdag (2015) suggest a new characterization, in which the BIM model evolves into an integrated model - of distributed information - always up-to-date and open for addition of new information. Sabol (2013) points out that the potential offered by ICTs should position the BIM model as a 3D visual portal, capable of offering access to both static (e.g., installation date) and dynamic (e.g., current state) information about building objects - providing more intuitive feedbacks for analysis.

These imminent transformations of the BIM model demand new capabilities that must be incorporated by making use of enabling technologies such as: Wireless Sensor Networks (WSNs), Cloud Computing, Web Services and Semantic Web (UNDERWOOD; ISIKDAG, 2011); Radio Frequency Identification (RFID) and Augmented Reality (AR) Technologies (SABOL, 2013).

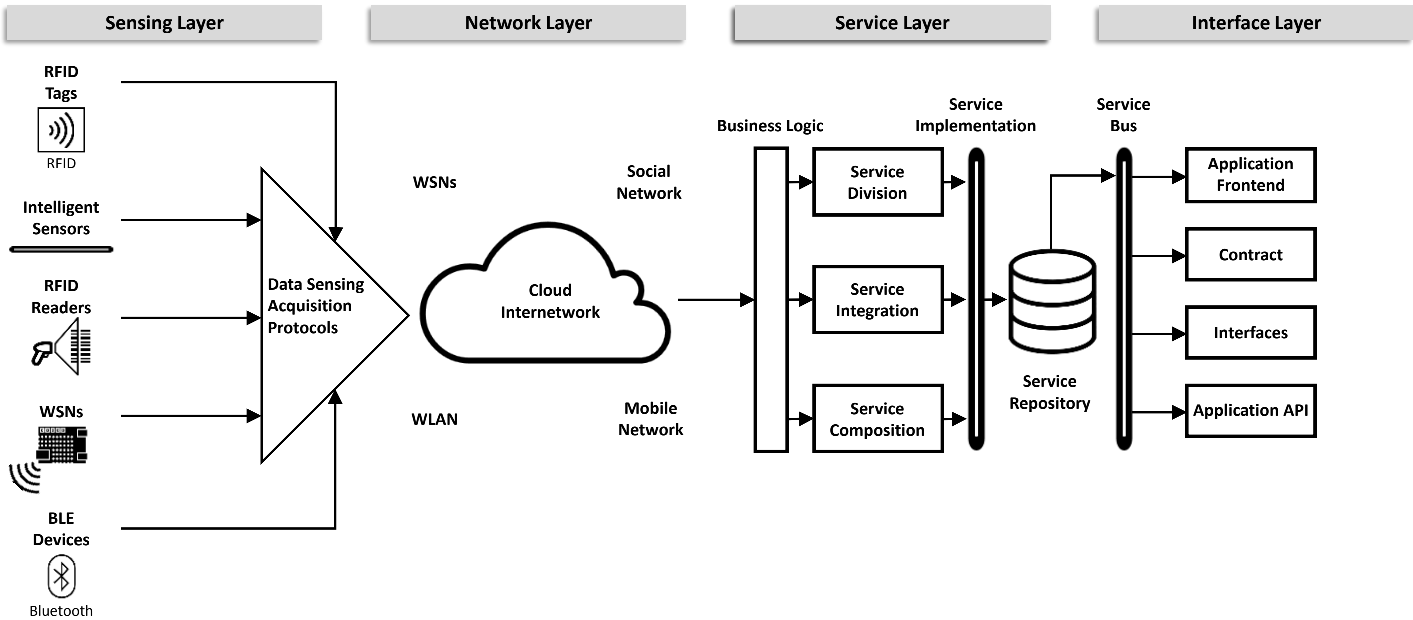
WSN can collect and produce large amounts of data, whose use can contribute to the allocation of information about the physical environment directly into the geometry of the building, using the BIM objects' properties (SABOL, 2013; SUCCAR; SALEEB; SHER, 2016). Similarly, identifiers inherent to RFID Technology can be associated with BIM objects to mediate activities linked to asset management (SABOL, 2013). We reiterate that RFID technology uses readers and markers to monitor objects in real time by means of remote processing (PERERA et al., 2013). In both cases, Sabol (2013) indicates the need to improve the methods for visualization, analysis, and evaluation of information.

Cloud Computing is a technology that involves virtualizing storage-intensive environments. Its use should allow the BIM model to reside in a data repository that can be accessed via web (UNDERWOOD; ISIKDAG, 2011; ISIKDAG, 2015). In addition, this technology may support intensive analysis by receiving real-time data and given its potential to integrate to mobile computing (SABOL, 2013). Still, within the web context, Service

Oriented Architectures (SOA) and Web Services provide opportunities to generate combinations and relationships between data and make building information dynamic – in real-time, accurate, and up-to-date. In this context, the Semantic Web[2] can allow queries about the new information to be answered, in case they are assisted by ontologies and comply with semantic web standards (UNDERWOOD; ISIKDAG, 2011; ISIKDAG, 2015). Finally, the association between AR and BIM Models can provide several user-extended experiences by overlapping virtual data with the real environment (WANG et al., 2012). Applications can enable the display of projected consumption information in the building, lists of asset records, infrastructure information, among other building Operation and Maintenance (O&M) activities (SABOL, 2013).

These enabling technologies, which can be integrated with the BIM model, are distributed into the four layers that form the structure of the IoT and its Service Oriented Architecture: sensing, network, service and interface (Figure 1) (LI; XU; ZHAO, 2014). The sensing layer consists of hardware and software components, which are capable of automatically capturing the environment and exchanging data between devices. The functions of this layer include detection, actuation, identification, interaction, and communication. The network layer consists of an infrastructure that connects all objects and makes them environmentally sensitive. Through this infrastructure the data is shared, managed, and processed. The service layer is based on middleware technology and includes both on-demand storage for users and applications as well as computational tools for data analysis. The interface layer, in turn, consists of methods of interaction with users and applications and involves visualization and interpretation tools (GUBBI et al., 2013; LI; XU; ZHAO, 2014).

Figure 1 – Service Oriented Architecture for Internet of Things



Source: Adapted from Li, Xu and Zhao (2014).

Systematic Literature Review (SLR)

The Systematic Literature Review (SLR) is a method to identify, evaluate and interpret all available research relevant to a particular research question, topic, or phenomenon of interest. The development of a SLR allow a robust view of the study area under analysis (DRESCH; LACERDA; ANTUNES JÚNIOR, 2015).

This review adopted the research method described by Kitchenham (2004), which procedures are detailed below and consist of: (i) Planning the Review, in which the Review Protocol and the Search Conduct Forms are developed; (ii) Conducting the Review, which involves the application of inclusion/exclusion criteria of the primary studies mapped, as well as the completion of Data Extraction Forms; and (iii) Analyzing the Results, dedicated to the summarization and explanation of the results obtained.

Planning the Review

We used the search protocol to structure the mapping of the primary studies, discriminating the aim, research questions, search strategies, defined databases, inclusion and exclusion criteria, data extraction strategies, and summarization of results.

The **aim** of the SLR was set to identify, analyze and classify in classes of problems the components, models, and methods of the existing solutions reported in the literature about the integration of BIM and IoT. Components, models, methods, and solutions are understood as artifacts, according to March and Smith (1995)'s classification. The components, referred to as constructs, are a concept used to describe the problems within a domain and to specify their respective solutions, so that the terms used in the description and the design of the tasks are defined. The models are a set of propositions or statements that express the relations between the constructs, visualized as a description or representation of a real configuration or structure. The methods are a set of steps used to perform tasks and are based on the constructs and models elaborated for a given solution. Finally, the instantiations represent the implemented solution, in order to produce results within a given context. They aggregate the operation of the other artifacts, demonstrating their feasibility and effectiveness.

The **research questions** included: what are the artifacts developed with an emphasis on the integration of BIM and IoT? In which phases of the building life cycle there is a higher recurrence of these artifacts? What are the BIM Model Uses applied to make these artifacts feasible? And what ICTs are deployed in this integration?

As for the **search strategies**, it was established that the sources should have been those published in peer-reviewed scientific journals, in English, between 2000 and 2016, and they should be fully available in electronic form. The time interval encompasses studies published between the first use of the term Internet of Things by Kevin Ashton in 1999 (ASHTON, 2009) and the publication of the book Building Product Models: Computer Environments, Supporting Design and Construction by Eastman (1999) and the present date. The search terms used were "Internet of Things" and "IoT"; "Building Information Model*" and "BIM"; "Real-time Data" and "Sensor"; "Radio-Frequency" and RFID; Bluetooth and BLE; "Near Field Communication" and NFC; "Ultra-Wide Band" and UWB. In addition, all possible combinations between "Building Information Model*" or BIM and the other terms were searched.

We carried out the searches in the SCOPUS, Compendex, ASCE Library and Web of Science databases. **Inclusion and exclusion criteria** for primary studies were prepared to support the selection of relevant studies that met the research questions. The inclusion criteria adopted were: (a) Studies that address the integration of BIM and IoT at any stage of the building life cycle; and (b) Studies that contain the search terms at least in the title, abstract, or keywords. The criteria for exclusion adopted were: (a) Repeated studies; (b) Studies that are not directed to the AECO area, and (c) Studies that do not address the IoT's sensing layer in the integration, as they do not ensure interaction with the physical environment.

The **strategies for extraction of data** upon selected studies during full analytical reading allowed the filling of a set of specific forms, considering the following identification and classification aspects: (i) types of artifact, according to March and Smith (1995); (ii) series and uses of the BIM model for the construction domain, both based on the taxonomy elaborated by Succar, Saleeb, and Sher (2016)[3]; (iii) BIM technology solutions (software, hardware, and network), according to Succar (2009); and (iv) IoT technology solutions, based on Li, Xu, and Zhao (2014). The definition of classes of problems is related to the topics covered by each study. **Summarizing the results** aided in identifying patterns and correlations between the studies.

Conducting the Review

Table 1 shows the sequence of events from the search of the sources to the application of the inclusion and exclusion filters to the studies, as established in the SLR planning. In the end, the sample for analysis added up to forty-five publications in journals.

Analyzing the Results

Initially, the publications in the sample were grouped according to their phase in the building life cycle based on NIST (2006), namely: Planning/Programming and Design; Construction and Commissioning; Operation and Maintenance; and Demolition or Disposal. Besides, a group for cases of timeless publications was created. The continuing studies carried out by the same group of authors were analyzed together.

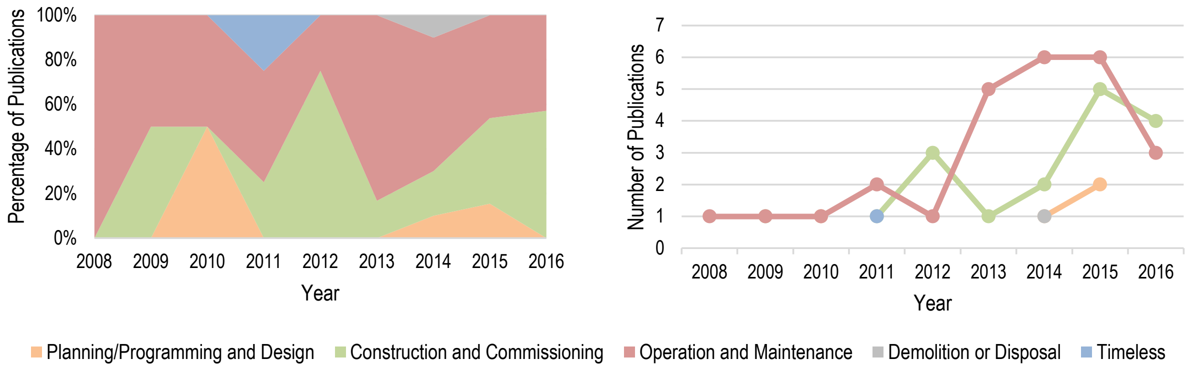
Considering the time interval established in this article, it is noted that the approaches about BIM-IoT integration started to be published in journals in 2008 (Figure 2). It is also noted that such integration is more prominent in the building O&M phase between 2013 and 2015. On the other hand, a growing interest in the integration in Construction and Commissioning is observed more recently, considering the prevalence of publications in this phase in 2016. In turn, the general survey of artifacts shows that the "model" and "instantiation" types are the most recurrent creations in this scope, considering all phases of the building life cycle (Figure 3). This scenario means greater scientific development in precise relationship structures (model) and, consequently, the need for proofs of concept and prototype testing (instantiation).

Table 1 – Conducting the review up to sample definition

Parameters	Search Applications			
Databases	COMPENDEX	ASCE LIBRARY	WEB OF SCIENCE	SCOPUS
Search Fields	Subject/Title/Abstract	Anywhere	Topic	Title/Abstract/Keywords
Publication Types	Journal Article	N/A	Article	Article
Results	77	7	79	107
Elimination by repetition in the same base	35	2	32	52
Total publications per base	42	5	47	55
Total Publications	149 publications			
Elimination by repetition between bases	87 publications			
Resulting Publications	62 publications			
Elimination by exclusion criteria	17 publications			
Total Sample	**45 publications**			

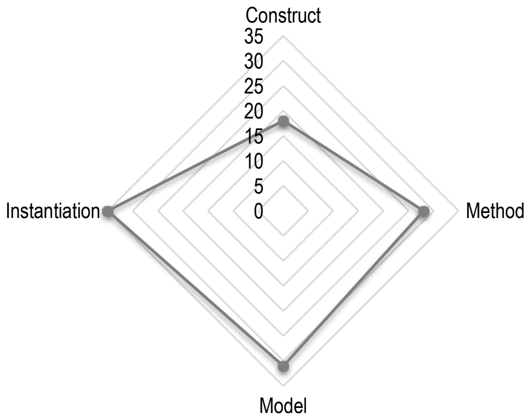
Source: The authors.

Figure 2 - Percentage and number of publications per year and phase of the building life cycle



Source: The authors.

Figure 3 - Radar of artifacts in the context of BIM and IoT integration



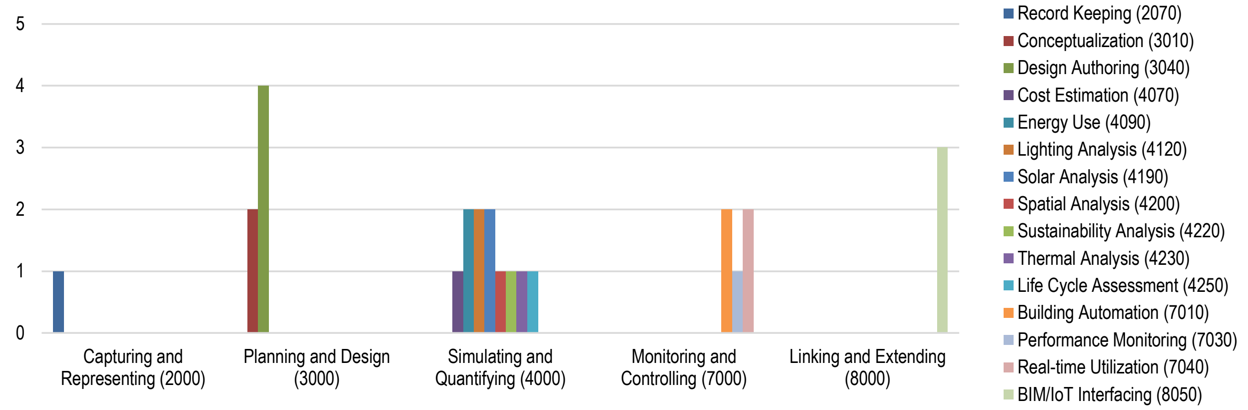
Source: The authors.

BIM and IoT in Planning/Programming and Design

The group of studies related to Planning/Programming and Design (Table 2) includes four publications, and the BIM and IoT integration addresses three classes of problems: Energy Efficiency Awareness, Intelligent Systems Planning, and Conceptualization and Design Authoring. The synthesis of the Model Use Series and Model Uses identified in this phase is presented in Figure 4, and involves five distinct series associated with seventeen uses of the model. The application of the model in Design Authoring is emphasized, associated with a range of uses of the Simulating and Quantifying Series. The use of the BIM/IoT Interfacing contributes to initial design stages and retrofit scenarios, relating to the Monitoring and Controlling Series.

The class of problems related to Energy Efficiency Awareness is addressed by Crosbie, Dawood, and Dean (2010). The authors developed a method to produce and use BIM models to identify design and/or operation strategies, based on performance. The potential applications of the study contemplate the same building throughout its life cycle and retrofit scenarios, since both make possible the comparison between the building's predictive (simulation) and real (monitoring) energy profiles for decision making (control) and optimization of consumption.

Figure 4 - Synthesis of Model Series and Uses: Planning/Programming and Design Phase Studies



Source: The authors.

Table 2 - BIM/IoT Interfacing: Planning/Programming and Design

Classes of Problems	Model Use Series	Model Uses	References
Energy Efficiency Awareness	Capturing and Representing (2000)	Record Keeping (2070)	Crosbie, Dawood, and Dean (2010)*
	Planning and Design (3000)	Design Authoring (3040)	
	Simulating and Quantifying (4000)	Cost Estimation (4070) Energy Use (4090) Sustainability Analysis (4220) Thermal Analysis (4230) Life Cycle Assessment (4250)	
	Monitoring and Controlling (7000)	Building Automation (7010) Performance Monitoring (7030)	
	Linking and Extending (8000)	BIM/IoT Interfacing (8050)	
Intelligent Systems Planning	Planning and Design (3000)	Design Authoring (3040)	Suh, Kim, and Chung (2015)
	Simulating and Quantifying (4000)	Spatial Analysis (4200)	
Conceptualization and Design Authoring	Planning and Design (3000)	Conceptualization (3010) Design Authoring (3040)	Kensek (2014) Kensek (2015)
	Simulating and Quantifying (4000)	Energy Use (4090) Lighting Analysis (4120) Solar Analysis (4190)	
	Monitoring and Controlling (7000)	Building Automation (7010) Real-time Utilization (7040)	
	Linking and Extending (8000)	BIM/IoT Interfacing (8050)	

Note: *Studies that address more than one phase of the building life cycle. Source: The authors.

The class of problems related to Intelligent Systems Planning is addressed by Suh, Kim, and Chung (2015). The authors present guidelines for the preparation of network-based sensor systems for intelligent housing for the elderly. The guidelines include the collaborative integration between architectural projects and IT systems using the BIM model (e.g., the inclusion of object libraries of sensor networks for modularization and convergence of technologies). The purpose of the study is to reduce spatial interference and increase the effectiveness of monitoring and control applied to the elderly's health, safety, convenience and consumption.

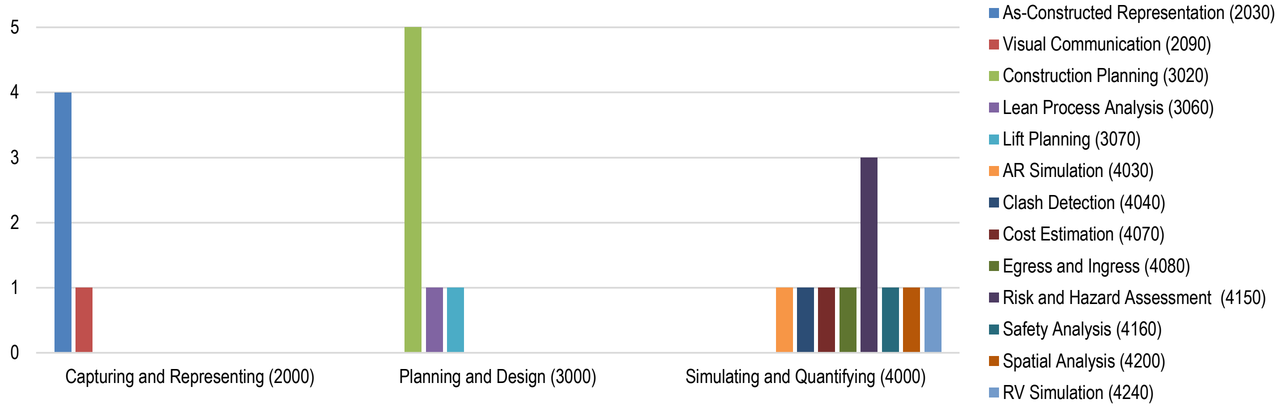
The class of problems related to Conceptualization and Design Authoring is addressed in Kensek (2014, 2015), which explores the concept of intelligent systems in sustainable building designs. The author presents two-way, real-time solutions for the interaction between physical prototypes and BIM models, using sensors and actuators mediated by micro-controlling boards. The interactions were enabled by using Visual Programming Language (VPL) environments (e.g., Grasshopper and Dynamo) and native language for the .NET platform, which can act as middleware upon access to the Application Programming Interface (API) of the authoring BIM tool (Autodesk Revit). The applications aim to consider, from the initial stages of design, the interactive behavior of facade components (brise-soleil, panels, and openings) in relation to the intensity of incident light.

BIM and IoT in Construction and Commissioning

The group of studies related to Construction and Commissioning (Table 3) includes seventeen publications, and the BIM and IoT integration addresses three classes of problems: Occupational Health and Safety Management, Smart Objects Detection and Tracking, and Visualization, Interaction and Communication between Agents in the workplace. The synthesis of the BIM Model's Series and Uses identified in this phase is presented in Figure 5 and Figure 6, and involves seven distinct series associated with twenty-six uses applied to the model. The emphasis of this phase is noted in the following series: Constructing and

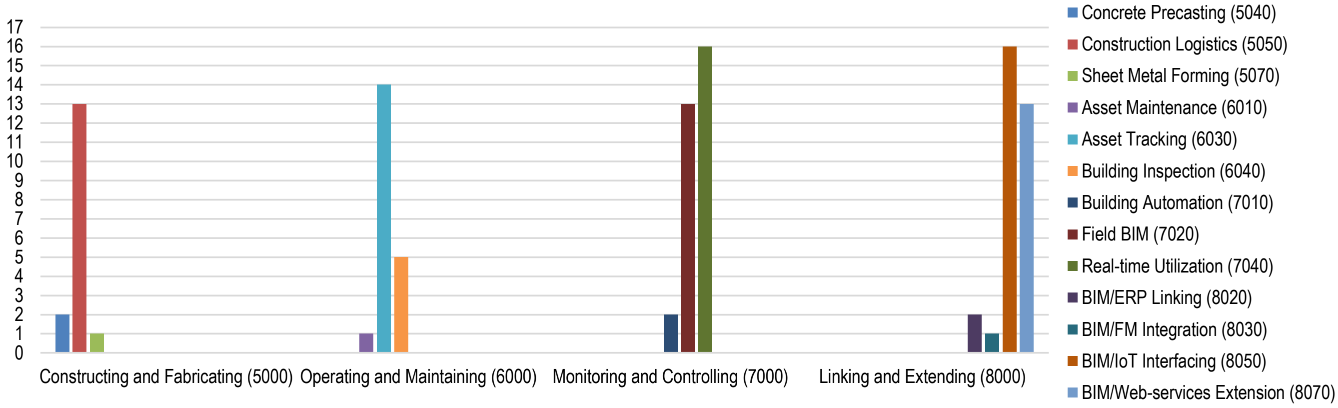
Fabricating, associated to the use in Construction Logistics; Operating and Maintaining, applied in Asset Tracking; and Monitoring and Controlling, for Field BIM and Real-time Utilization. These applications were recurrent at the construction site and in associated workplaces. Moreover, the distinctive uses are correlated to the Linking and Extending Series, by deploying the BIM/IoT Interfacing and the BIM/Web-services Extension.

Figure 5 - Synthesis of Model Series and Uses: Construction and Commissioning Phase Studies (Part 1)



Source: The authors.

Figure 6 - Synthesis of Model Series and Uses: Construction and Commissioning Phase Studies (Part 2)



Source: The authors.

Table 3 - BIM/IoT Interfacing: Construction and Commissioning

(Continues)

Classes of Problems	Model Use Series	Model Uses	References
Occupational Health and Safety Management	Planning and Design (3000)	Construction Planning (3020)	Arslan et al. (2014) Riaz et al. (2014) Costin, Teizer, and Schoner (2015) Fang et al. (2016) Park, Kim, and Cho (2016)
	Simulating and Quantifying (4000)	Egress and Ingress (4080) Risk and Hazard Assessment (4150) Safety Analysis (4160) Spatial Analysis (4200)	
	Constructing and Fabricating (5000)	Construction Logistics (5050)	
	Operating and Maintaining (6000)	Asset Tracking (6030) Building Inspection (6040)	
	Monitoring and Controlling (7000)	Building Automation (7010) Field BIM (7020) Real-time Utilization (7040)	
	Linking and Extending (8000)	BIM/IoT Interfacing (8050) BIM/Web-services Extension (8070)	

Table 3 - BIM/IoT Interfacing: Construction and Commissioning

(Conclusion)

Classes of Problems	Model Use Series	Model Uses	References
Smart Objects Detection and Tracking	Capturing and Representing (2000)	As-Constructed Representation (2030)	Akanmu, Anumba, and Messner (2012)* Niu et al. (2015)*
	Planning and Design (3000)	Construction Planning (3020)	
	Constructing and Fabricating (5000)	Concrete Precasting (5040) Construction Logistics (5050)	
	Operating and Maintaining (6000)	Asset Maintenance (6010) Asset Tracking (6030) Building Inspection (6040)	
	Monitoring and Controlling (7000)	Field BIM (7020) Real-time Utilization (7040)	
	Linking and Extending (8000)	BIM/FM Integration (8030) BIM/IoT Interfacing (8050) BIM/Web-services Extension (8070)	
Visualization, Interaction and Communication between Agents in the workplace	Capturing and Representing (2000)	As-Constructed Representation (2030) Visual Communication (2090)	Motamedi and Hammad (2009)* Xie, Shi, and Issa (2011) Lee et al. (2012) Wang et al. (2012) Ikonen et al. (2013) Feng et al. (2015) Akanmu et al. (2015) Dave et al. (2015) Li et al. (2016a) Li et al. (2016b)
	Planning and Design (3000)	Construction Planning (3020) Lean Process Analysis (3060) Lift Planning (3070)	
	Simulating and Quantifying (4000)	AR Simulation (4030) Clash Detection (4040) Cost Estimation (4070) RV Simulation (4240)	
	Constructing and Fabricating (5000)	Concrete Precasting (5040) Construction Logistics (5050) Sheet Metal Forming (5070)	
	Operating and Maintaining (6000)	Asset Tracking (6030) Building Inspection (6040)	
	Monitoring and Controlling (7000)	Field BIM (7020) Real-time Utilization (7040)	
	Linking and Extending (8000)	BIM/ERP Linking (8020) BIM/IoT Interfacing (8050) BIM/Web-services Extension (8070)	

Note: *Studies that address more than one phase of the building life cycle. Source: The authors.

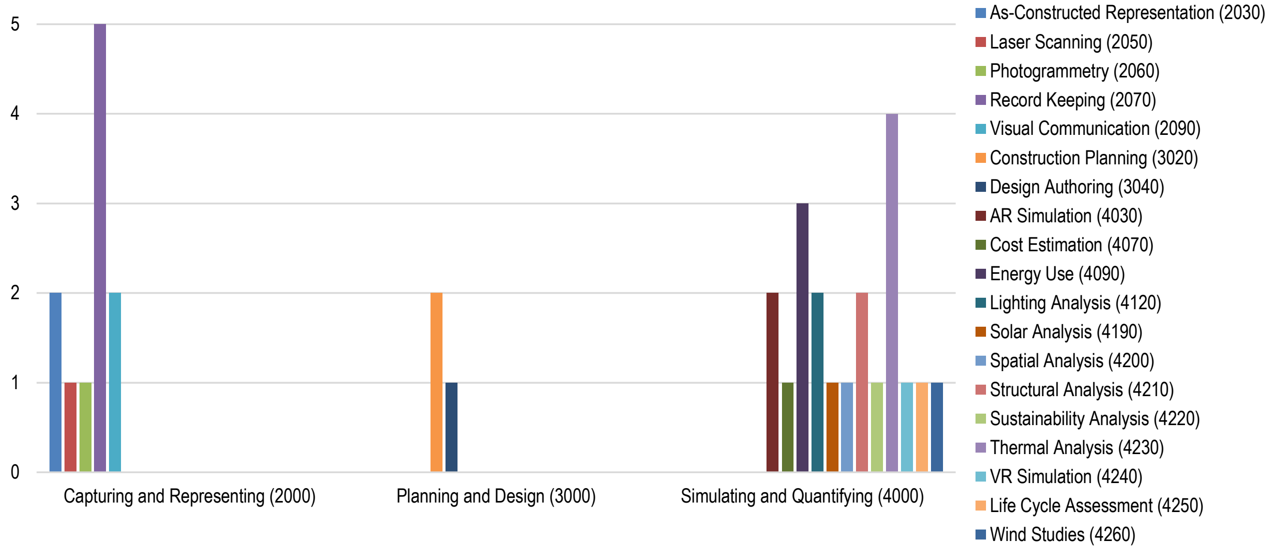
The class of problems related to the Smart Objects Detection and Tracking is presented in two studies. Akanmu, Anumba, and Messner (2012) develop an RFID-BIM solution to track the position/status of objects at the construction site, store this information, and integrate them for contextual view in the model, in an integration BIM tool (Autodesk Navisworks). The objective is to monitor the production progress in real time and verify consistencies related to planning, so to assist with the logistical control and decision making. Niu et al. (2015) define the concepts and properties of Smart Construction Objects (SCO) - autonomy, awareness and the ability to interact with the surroundings. Virtually represented in the BIM model, the potential applications of SCOs include logistics and supply chain management; security management; guidance of workflow procedures (e.g., pre-fabrication); and facility management.

The class of problems related to Visualization, Interaction and Communication between Agents in the workplace includes ten studies, in which RFID-BIM solutions and applications focused on the supply chain, construction, and quality management were prevalent. Motamedi and Hammad (2009) discuss the benefits of tracking, storing, and sharing real-time building object information (location, installation status, inspection and/or maintenance) using RFID markers, synchronizing them with databases and viewing them contextualized in the building models, using integration BIM tools (Graphisoft Constructor, Control, and 5D Presenter). In turn, Xie, Shi, and Issa (2010) propose an immersive and interactive virtual environment, enriched with RFID-BIM integration, for design and construction teams and owners. The emphasis of the environment is on the manufacture of steel and its lifting in the construction site. The purposes of the applications are to get visual and remote feedback from the site in real time, analyze production progress alternatives, temporarily reorganize facilities and equipment, and identify security problems. Wang et al. (2012) conceptually explain the integrated use of BIM models and AR technology to improve the visualization of information in a range of applications. The applications aim to support the interaction and effective communication between agents, including the management and tracking of the material flow with integrated RFID-BIM solutions in the context of the BIM/IoT Interfacing, where the AR is responsible for promoting the visualization of this information at the building site in real time. Ikonen et al. (2013) present an RFID-BIM information system, used in the real-time tracking, control, and visualization of prefabricated concrete elements. Access is distributed using a BIM solution (Tekla Server), mobile devices and web interface. Feng et al. (2015) present an intelligent model consisting of a centralized repository of building elements information in the cloud, coupled with RFID, GPS, BIM, and the construction schedule. The goal of this solution is to distribute information to mobile devices in real time to assist logistics and building management activities for prefabricated buildings using the BIM model (e.g., assembly, testing, and maintenance). Akanmu et al. (2015) describe the development and implementation of an automated system for the generation of building site layouts from the integration of BIM models (in the Autodesk Navisworks tool), genetic algorithms, and RFID for real-time object tracking. The convergence of these technologies maximize the integrity of the generated layouts. Lee et al. (2012) present a real-time navigation system for cranes, in which the BIM model is integrated to sensors to aid in the visualization of the building site and the handling of the equipment. The applications improve construction logistics and field activities, assisting the workers in charge and the control offices. Dave et al. (2015) explain how the integration of IoT to VisiLean can be used to enable automated and real-time communication of the proposed model with resource management and building production planning and control systems. Within this context, the BIM (4D) model acts as a simultaneous visualization feature to improve the delivery of information at all production stages. Finally, Li et al. (2016a) and Li et al. (2016b) present an RFID-BIM conceptual model for the restructuring of pre-fabricated housing construction processes, based on a SWOT analysis to improve production management in Hong Kong. In addition, they analyze risk factors associated with the pre-fabrication process stakeholders. The solution is pointed out as a strategy to facilitate the communication between agents in the process and to mitigate the risks inherent in critical schedules.

BIM and IoT in Operation and Maintenance

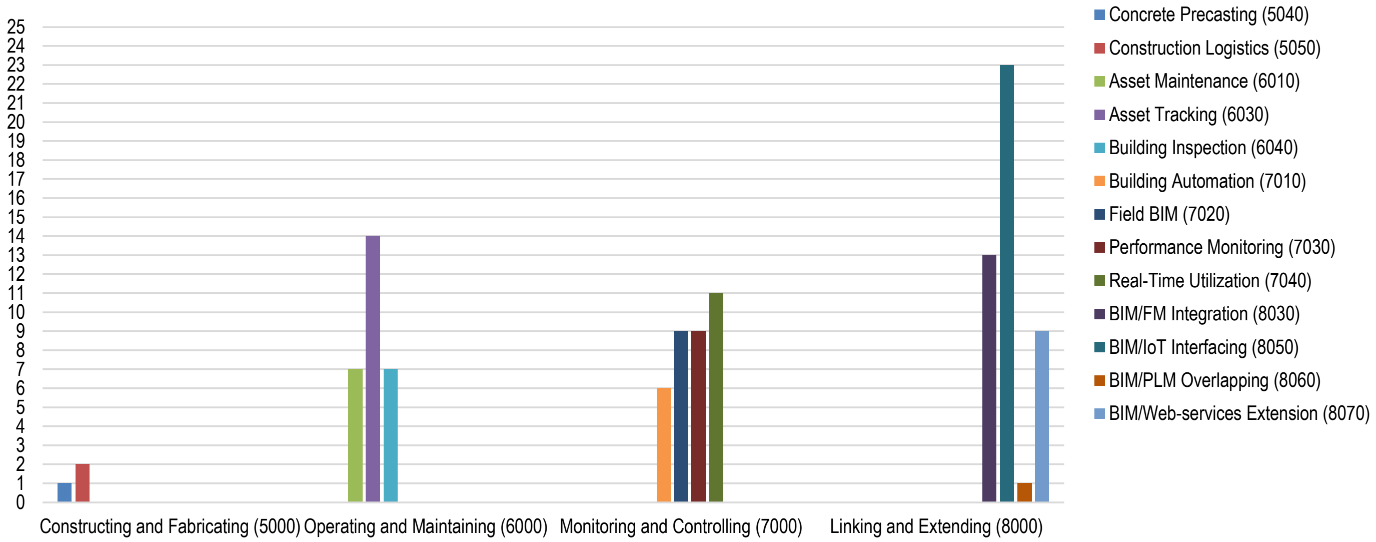
The group of Operation and Maintenance (Table 4) includes twenty-six publications and addresses seven classes of problems: Energy Efficiency Awareness, Instrumentation and Structural Health Monitoring, Emergency Response Operations, Intelligent Systems Planning, Indoor Environmental Quality, Smart Objects Detection and Tracking, and Visualization, Interaction and Communication between Agents in the workplace. The synthesis of the Model Use Series and Model Uses identified in this phase is presented in Figure 7 and Figure 8, and involves seven distinct series associated with thirty-two uses of the model. In this phase it is highlighted the demand for Record Keeping and the emphasis on the Real-time Utilization of the BIM model in the Monitoring and Controlling Series; and Operating and Maintaining, associated with Asset Tracking. There is also a range of applications related to the Simulating and Quantifying Series. We reinforce that such uses are correlated to the Linking and Extension Series, through BIM/FM Integration, the use of BIM/IoT Interfacing and the BIM/Web-services Extension.

Figure 7 - Synthesis of Model Series and Uses: Operation and Maintenance Phase Studies (Part 1)



Source: The authors.

Figure 8 - Synthesis of Model Series and Uses: Operation and Maintenance Phase Studies (Part 2)



Source: The authors.

Table 4 - BIM/IoT Interfacing: Operation and Maintenance **(Continue)**

Classes of Problems	Model Use Series	Model Uses	References
Energy Efficiency Awareness	Capturing and Representing (2000)	Record Keeping (2070)	Crosbie, Dawood, and Dean (2010)* Osello et al. (2013) Gokçe and Gokçe (2013) Gokçe and Gokçe (2014a) Gokçe and Gokçe (2014b) Lee, Cha, and Park (2016)
	Planning and Design (3000)	Design Authoring (3040)	
	Simulating and Quantifying (4000)	Cost Estimation (4070) Energy Use (4090) Lighting Analysis (4120) Sustainability Analysis (4220) Thermal Analysis (4230) Life Cycle Assessment (4250)	
	Monitoring and Controlling (7000)	Building Automation (7010) Performance Monitoring (7030) Real-time Utilization (7040)	
	Linking and Extending (8000)	BIM/FM Integration (8030) BIM/IoT Interfacing (8050) BIM/Web-services Extension (8070)	
Instrumentation and Structural Health Monitoring	Capturing and Representing (2000)	Record Keeping (2070)	Rio, Ferreira, and Poças-Martins (2013) Zhang and Bai (2015)
	Simulating and Quantifying (4000)	Structural Analysis (4210)	
	Operating and Maintaining (6000)	Asset Tracking (6030) Building Inspection (6040)	
	Monitoring and Controlling (7000)	Performance Monitoring (7030) Real-time Utilization (7040)	
	Linking and Extending (8000)	BIM/IoT Interfacing (8050)	
Emergency Response Operations	Capturing and Representing (2000)	Record Keeping (2070)	Rueppel and Stuebbe (2008) Li et al. (2014) Li, Becerick-Gerber, and Soibelman (2014)
	Simulating and Quantifying (4000)	Spatial Analysis (4200)	
	Operating and Maintaining (6000)	Asset Tracking (6030)	
	Monitoring and Controlling (7000)	Field BIM (7020) Real-time Utilization (7040)	
	Linking and Extending (8000)	BIM/IoT Interfacing (8050) BIM/Web-services Extension (8070)	
Intelligent Systems Planning	Capturing and Representing (2000)	Visual Communication (2090)	Boyes (2015) Tomasi et al. (2015)
	Linking and Extending (8000)	BIM/FM Integration (8030) BIM/IoT Interfacing (8050) BIM/Web-services Extension (8070)	
Indoor Environmental Quality	Capturing and Representing (2000)	Record Keeping (2070)	Marzouk and Abdelaty (2014a) Marzouk and Abdelaty (2014b) Habibi (2016)
	Simulating and Quantifying (4000)	Lighting Analysis (4120) Solar Analysis (4190) Thermal Analysis (4230) Wind Studies (4260)	
	Operating and Maintaining (6000)	Asset Maintenance (6010) Building Inspection (6040)	
	Monitoring and Controlling (7000)	Performance Monitoring (7030)	
	Linking and Extending (8000)	BIM/FM Integration (8030) BIM/IoT Interfacing (8050)	

Table 4 – BIM/IoT Interfacing: Operation and Maintenance **(Conclusion)**

Classes of Problems	Model Use Series	Model Uses	References
Smart Objects Detection and Tracking	Capturing and Representing (2000)	As-Constructed Representation (2030) Laser Scanning (2050) Photogrammetry (2060)	Akanmu, Anumba, and Messner (2012)* Motamedi, Soltani, and Hammad (2013) Gai, Azadmanesh, and Rezaeian (2015) Valero, Adan, and Bosche (2015) Motamedi et al. (2015) Niu et al. (2015)*
	Planning and Design (3000)	Construction Planning (3020)	
	Constructing and Fabricating (5000)	Concrete Precasting (5040) Construction Logistics (5050)	
	Operating and Maintaining (6000)	Asset Maintenance (6010) Asset Tracking (6030) Building Inspection (6040)	
	Monitoring and Controlling (7000)	Field BIM (7020) Real-time Utilization (7040)	
	Linking and Extending (8000)	BIM/FM Integration (8030) BIM/IoT Interfacing (8050) BIM/Web-services Extension (8070)	
Visualization, Interaction and Communication between Agents in the workplace	Capturing and Representing (2000)	Record Keeping (2070) Visual Communication (2090)	Motamedi and Hammad (2009)* Motamedi et al. (2011) Lee and Akin (2011) Olbrich et al. (2013)
	Planning and Design (3000)	Construction Planning (3020)	
	Simulating and Quantifying (4000)	AR Simulation (4030) RV Simulation (4240)	
	Constructing and Fabricating (5000)	Construction Logistics (5050)	
	Operating and Maintaining (6000)	Asset Maintenance (6010) Asset Tracking (6030) Building Inspection (6040)	
	Monitoring and Controlling (7000)	Building Automation (7010) Field BIM (7020) Real-time Utilization (7040)	
	Linking and Extending (8000)	BIM/FM Integration (8030) BIM/IoT Interfacing (8050) BIM/PLM Overlapping (8060) BIM/Web-services Extension (8070)	

Note: *Studies that address more than one phase of the building life cycle. Source: The authors.

The class of problems related to Energy Efficiency Awareness is addressed in six studies. In Osello et al. (2013), the authors create a web-based infrastructure to display energy consumption information collected by sensors. The BIM model and interoperability solutions are used to process data and promote the semantic contextualization of information, including applications for both consumption simulations and facility management. The studies by Gokçe and Gokçe (2013, 2014a, 2014b) present a system developed to process data and analyze performance information from multiple sources for monitoring and intelligent control of the building, with the purpose to reduce energy consumption in the O&M phase. Gokçe and Gokçe (2014a) add to the sources the simulated energy data acquired from the project through the BIM model, to compare them with the information extracted from the data collected from the physical environment – so to assist building operation strategies. This logic is similar to that used by Crosbie, Dawood, and Dean (2010) when they designed their operation model, as previously explained in the Planning/Programming and Project phase. Finally, Lee, Cha, and Park (2016) present an integrated web monitoring and control platform for the energy efficiency of buildings. Sensors, meters, and automation systems are responsible for collecting and transmitting data in real time, enabling the extraction of consumption information. The BIM model, in turn, is used as an effective method of spatially visualizing this information linked to the location of the building.

The class of problems related to Instrumentation and Structural Health Monitoring is addressed in two studies. Rio, Ferreira, and Poças-Martins (2013) explore ways of modeling structural integrity maintenance systems, which include structural behavior data collected from the building (e.g., safety, integrity, performance, damage detection) and BIM as the standard information management. For this purpose, the authors evaluate the use of the Industry Foundation Classes (IFC) schema in the process of integrating the model to the physical environment, to view in visualization tools (Solibri Model Viewer). In addition, they evaluate the use of the schema in structural analysis tools. In turn, Zhang and Bai (2015) present a wireless structural condition scanning system based on strain sensor technology, BIM, and RFID. The objective of the system is to allow the contactless scanning of the structural deformation and to point it at the corresponding structural element of the model in an authoring BIM tool (Autodesk Revit) in order to provide warning signals to engineers and other decision makers. Applications include monitoring, prognosis and health management of civil infrastructures, especially for rapid inspection of post-risk structural conditions.

The class of problems related to Emergency Response Operations is addressed in three studies. Rueppel and

Stuebbe (2008) present the model of an indoor navigation platform, accessed via mobile devices. This platform consists of using RFID, Ultra-Wide Band (UWB) and WLAN technologies integrated with the BIM model, which acts as a repository of public building information (e.g., spatial context). The solution contributes to the orientation and safety of rescuers, enabling the positioning, calculation, and visualization of escape routes. Li et al. (2014), and Li, Becerick-Gerber, and Soibelman (2014), continuing studies, tackle solutions involving Radio Frequency (e.g., BLE) and BIM technologies, in which the model is integrated with a system for tracking first responders and occupants for (i) spatial analysis; (ii) providing geometric information of the sensed areas; and (iii) acting as a user interface for real-time monitoring and visualization. The applications aim to facilitate the work of emergency teams.

Two studies contemplate the class of problems related to Intelligent Systems Planning. Tomasi et al. (2015) present a WSN-BIM solution using UWB technology for indoor positioning. The intention is to help in the development of WSN. The authors believe that, in this context, the proper geometry and information available in the BIM model can improve IoT-related tasks during the planning and commissioning phases of WSN – in case the interoperability between the tools works. The applications should benefit BIM users, developers, and experts. In turn, Boyes (2015) defines security and privacy, with emphasis on the vulnerability of using the BIM model as a centralized database of building registration information integrated with IoT facilitation technologies for facilities management.

The class of problems related to Indoor Environmental Quality comprises the studies of Marzouk and Abdelaty (2014a, 2014b) and Habibi (2016). The first group of authors presented a WSN-BIM solution to monitor the thermal conditions (temperature and humidity) and the concentration of suspended particles in subway stations. Using an authoring BIM tool (Autodesk Revit), the model is used to enhance the visualization of information provided by the WSN and specific measurement devices. The applications aim to broaden the station operators' knowledge about spaces that tend to have thermal comfort problems. Benefits extend to asset maintenance, especially HVAC equipment, by providing information necessary for preventive actions. Habibi (2016), in turn, creates a real-time monitoring system to achieve optimum comfort conditions - in terms of building performance and user satisfaction. This system addresses the use of the BIM model in predictive simulations to extract reference environmental information, which is compared to those collected by the WSN and graphically viewed in MATLAB in monitors. The applications aim to influence the users' behavior and to improve existing operation strategies in retrofit scenarios.

The class of problems related to Smart Objects Detection and Tracking is covered by five studies. Motamedi, Soltani, and Hammad (2013) and Motamedi et al. (2015) investigate indoor asset tracking methods to aid agents such as facility managers, building inspectors, and occupants by using RFID-BIM solutions. For this purpose, RFID markers containing information (e.g., location, date of inspection), synchronized and/or extracted from the BIM model, are attached to the objects. The use of the IFC schema in this solution is addressed in the most recent study. The information stored is accessed using mobile applications and/or in a contextualized fashion in the model. Valero, Adan, and Bosche (2015) present a data processing algorithm that is integrated with laser scanning and RFID technologies to generate detailed and precise semantic 3D models of inhabited indoor environments. RFID markers attached to objects provide access to information stored in the building's digital FM system database. The goal is to make the process of automated generation of BIM record models fast, accurate and robust. Gai, Azadmanesh, and Rezaeian (2015) present a hybrid approach for application in indoor environments. The information inherent to the BIM model is used to indicate the 3D spatial location of tracking sensors. Finally, Niu et al. (2015), as presented in the Construction and Commissioning phase, explains/applies the SCOs.

The class of problems related to Visualization, Interaction and Communication between Agents in the workplace is covered by four studies. Motamedi and Hammad (2009) and Motamedi et al. (2011) are continuing studies that, as indicated in the Construction and Commissioning phase, address RFID-BIM solutions for tracking and accessing information about the building staff and objects. In the case of O&M, the authors point out benefits for occupants, security guards, firefighters, building inspectors, and maintenance staff. Lee and Akin (2012) present O&M's difficulty to collect various types of data to locate or diagnose equipment and facilities accurately. The authors develop a system to provide information extracted from this just-in-time collection, based on the BIM model (geometry and building information), the FM tools (maintenance information), the Building Automation System (BACnet), and the AR technology - to improve the efficiency of fieldwork by integrating and visualizing a range of information in real time. Finally, Olbrich et al. (2013) present a web solution distributed onto mobile devices that integrates, in real time, BIM, AR technologies, and tracking to support maintenance activities. The solution, enriched by a semantic annotation feature, can be applied in both external and internal environments.

BIM and IoT in Demolition or Disposal

The Demolition or Disposal phase (Table 5) adds two studies related to the Visualization, Interaction and Communication between Agents in the workplace class of problems. Motamedi and Hammad (2009), as mentioned in previous phases, address RFID-BIM solutions for tracking and accessing building object information. In case of the Demolition and Disposal phase, the authors pinpoint improvements for the end-of-life management of objects and reverse manufacturing. In turn, Ness et al. (2014) propose a conceptual system to reuse structural steel elements using a RFID-BIM solution, which allows the monitoring of the parts throughout the life cycle until the moment of deconstruction. The application of the system aims to help metal structure companies to manage information for the reuse of these parts in new buildings. The benefits extend to sustainable decision making when the specification of reused materials during design and the installation influences the construction logistics. In this context, the use of the model for BIM/PLM Overlapping (Linking and Extending) - which involves a product life cycle management and its impacts - is highlighted.

Timeless BIM and IoT

Underwood and Isikdag (2011) - the only timeless publication of the sample - addresses the evolution of the BIM model mediated by ICTs. Among the technologies mentioned, the authors emphasize how the integration of WSN to the model should contribute to a more consistent relationship between BIM and IoT.

Discussion

Given the summarization of the SLR results, it is possible to understand the main purposes of the BIM and IoT integration and its varied applications. Concerning IoT, it can be said that this is a convergence of sensing, information, and communication technologies responsible for the acquisition, processing, and aggregation of data collected from the physical environment in real time, for transformation into information and knowledge. As for BIM, three general roles are considered: the first associated with the Service Layer and the other two to the IoT Interface Layer.

The BIM is responsible for:

(1) acting as a building virtual data structure, in order to support the classification and association of data sensed from the physical environment with geometric and non-geometric data stored in virtual objects, and assisting in the generation and extraction of semantically contextualized information;

(2) supporting performance simulations and predictive analysis, to confront data sensed from physical environment with simulated data, and defining reference lines for the establishment of rules and strategies for design, construction, and operation; and

(3) playing the leading role of information viewer, providing the semantic and spatial contextualization of the integrated information.

Table 5 - BIM/IoT Interfacing: Demolition or Disposal

Classes of Problems	Model Use Series	Model Uses	References
Visualization, Interaction and Communication between Agents in the workplace	Capturing and Representing (2000)	Record Keeping (2070)	Motamedi and Hammad (2009)* Ness et al. (2014)
	Planning and Design (3000)	Construction Planning (3020) Selection and Specification (3090)	
	Simulating and Quantifying (4000)	Sustainability Analysis (4220) Life Cycle Assessment (4250)	
	Constructing and Fabricating (5000)	Construction Logistics (5050) Sheet Metal Forming (5070)	
	Operating and Maintaining (6000)	Asset Maintenance (6010) Asset Procurement (6020) Asset Tracking (6030) Building Inspection (6040)	
	Monitoring and Controlling (7000)	Field BIM (7020) Real-time Utilization (7040)	
	Linking and Extending (8000)	BIM/FM Integration (8030) BIM/IoT Interfacing (8050) BIM/PLM Overlapping (8060) BIM/Web-services Extension (8070)	

Note: *Studies that address more than one phase of the building life cycle. Source: The authors.

The groups of studies in the four phases of the building life cycle allowed the identification of the most recurrent uses of the BIM model for the roles portrayed. In the Planning/Programming and Design phase, the model's uses in Lighting, Solar, and Energy Use Analysis (Simulating and Quantifying Series) to support Conceptualization and Design Authoring are highlighted. The BIM and IoT integration acts in the initial stages of the process and/or in retrofitting scenarios, promoting the dialogue between physical and virtual prototypes, as well as enabling spatial analysis for intelligent systems planning. In the Construction and Commissioning phase, it is emphasized the uses of the model in the Field BIM and in Real-time Utilization (Monitoring and Controlling

Series), focused on Asset Tracking (O&M Series) and Construction Logistics (Constructing and Fabricating Series). The BIM and IoT integration involves these uses aggregated to the WSN, RFID, and BLE technologies, and ensures the distribution of information through the Web-services Extension (Linking and Extending Series). In the Operation and Maintenance phase, the emphasis is on the Monitoring and Controlling Series through uses associated with Building Automation, Performance Monitoring and Real-time Utilization of BIM models. WSN and RFID technologies are the most recurring in the indicated uses. On the other hand, we found several types of predictive simulations to establish building performance reference lines, and again the relevance of the information distributed between agents via web is identified. In the Demolition or Disposal phase the use of the model integrated to the management of product's life cycle, and the tracking of this product using technologies such as RFID stand out.

Among the highlighted phases, we mapped nine classes of problems that tend to be solved by the integration of BIM and IoT (Table 6). The class that concentrates the largest number of scientific investigations is Visualization, Interaction and Communication between Agents in the workplace - with fourteen studies. Considering a greater coverage on artifacts according to DSR (DRESCH; LACERDA; ANTUNES JUNIOR, 2015), four classes of problems present more developed research lines: Energy Efficiency Awareness, Occupational Health and Safety Management, Smart Objects Detection and Tracking, and Visualization, Interaction and Communication between Agents in the workplace. This logic is due to the fact that these lines aggregate all types of DSR artifacts - construct, model, method, and instantiation. Conceptualization and Design Authoring is at its initial stage of investigation since it contains only the artifacts of method and instantiation.

In addition, there are four classes of problems that cover more than one phase of the building life cycle: Energy Efficiency Awareness; Intelligent Systems Planning; Smart Objects Detection and Tracking; and Visualization, Interaction and Communication between Agents in the workplace. These classes indicate the interaction and/or continuity in the uses of the BIM model by the agents (designers, suppliers, construction site team, facilities managers, owners, occupants). The remaining classes show specific applications of a life cycle phase and consist of isolated investigations involving agents of a given context. Therefore, it is verified that in the integration process a variety of agents profited by this evolution vector pertinent to post-BIM (Table 6).

Finally, Figure 9 shows the countries that pioneer in the BIM and IoT integration, considering the institution the first author of each study is linked to. We mapped twelve different countries in the sample, and the largest number of publications belong to the group of institutions located in the USA.

Table 6 - BIM/IoT Interfacing: Classes of Problems **(Continue)**

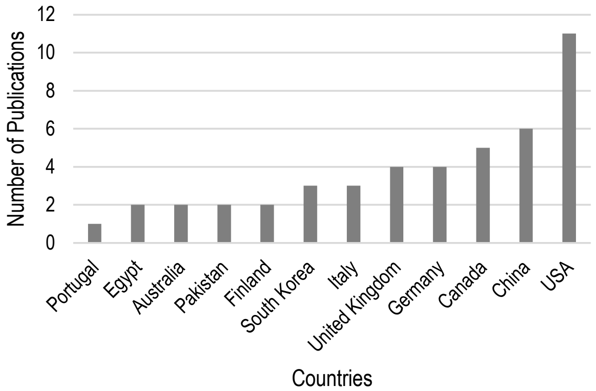
Classes of Problems	Description	Agents	Life cycle Phases	Artifacts
Energy Efficiency Awareness	Elaboration of strategies based on performance aiming at reducing the building energy consumption	Designers; Building Inspectors; Facilities Managers; Owners; Occupants	Planning/Programming and Design Operation and Maintenance	Construct Model Method Instantiation
Intelligent Systems Planning	Integrated planning and design of sensor networks and architecture for intelligent environments Elaboration of security and privacy solutions for intelligent environments	Designers; Developers/Integrators; *Facilities* Managers; Vigilant; Occupants	Planning/Programming and Design Operation and Maintenance	Construct Method Instantiation
Indoor Environmental Quality	Simulation and monitoring of environmental parameters to ensure quality in indoor environments aiming at user satisfaction and energy performance of the building	Designers; *Facilities* Managers; Occupants	Operation and Maintenance	Model Method Instantiation
Conceptualization and Design Authoring	Integration of physical and virtual models via monitoring and control to support conceptualization and design authoring	Designers	Planning/Programming and Design	Method Instantiation
Occupational Health and Safety Management	Monitoring environmental conditions in the workplace Tracking and monitoring of personnel, workflows and logistics at the construction site	Construction Managers; Health and Safety Managers; Contract Managers	Construction and Commissioning	Construct Model Method Instantiation

Table 1 – BIM/IoT Interfacing: Classes of Problems **(Conclusion)**

Classes of Problems	Description	Agents	Life cycle Phases	Artifacts
Smart Objects Detection and Tracking	Assigning intelligence and new properties to objects for applications in the various phases of the building life cycle	Field Workers; Project Managers; Production Managers; Construction Managers; Health and Safety Managers; Building Inspectors; Suppliers; Facilities Managers; Vigilant; Occupants	Construction and Commissioning Operation and Maintenance	Construct Model Method Instantiation
Visualization, Interaction and Communication between Agents in the workplace	Application of ICTs in the various activities of the Construction Site and O&M to increase efficiency and productivity	Designers; Project Managers; Field Workers; Contractors / Subcontractors; Production Managers; Construction Managers; Contract Managers; Building Inspectors; Suppliers; Facilities Managers; Vigilant; Occupants; Owners	Construction and Commissioning Operation and Maintenance Demolition or Disposal	Construct Model Method Instantiation
Instrumentation and Structural Health Monitoring	Instrumentation and monitoring of the structural integrity to support the maintenance activities of a building	*Facilities* Managers	Operation and Maintenance	Construct Model Instantiation
Emergency Response Operations	Indoor tracking for emergency response operations (e.g., fire)	Lifeguards; Occupants	Operation and Maintenance	Model Method Instantiation

Source: The authors.

Figure 9 - Countries that host the pioneering institutions in the BIM-IoT approach



Source: The authors.

Final Considerations

This paper aimed at identifying and analyzing existing artifacts reported in the literature, published in journals between 2000 and 2016, which discuss the BIM and IoT integration by carrying out an SLR in the SCOPUS, Compendex, ASCE Library and Web of Science databases. We identified that most artifacts are concentrated in the Operation and Maintenance phase. On the other hand, a growing interest in integration in Construction and Commissioning was noted, due to the predominance of publications about this phase in 2016. The most recurrent artifacts were models and instantiations.

During the process of classifying the studies, we mapped nine classes of problems and identified the involvement of different agents. Energy Efficiency Awareness, Intelligent Systems Planning, Smart Objects Detection and Tracking, and Visualization, Interaction and Communication between Agents in the workplace were classes that appeared in more than one phase of the building life cycle. The remaining classes were guided to specific applications. Energy Efficiency Awareness, Occupational Health and Safety Management, Smart Objects Detection and Tracking, and Visualization, Interaction and Communication between Agents in the workplace were considered the most advanced research lines. In turn, the class of problems related to Conceptualization and Design Authoring is in its initial stage of investigation. Finally, the integration points the purpose of IoT to acquire, process, and aggregate data collected from the physical environment in real time for its transformation into information and knowledge.

The purposes of BIM include: acting as a building data virtual structure; assisting performance simulations and predictive analysis; and playing the leading role of information viewer. Therefore, we understand that the BIM and IoT integration is not incipient and is in full development, which requires a large demand of computational programming. The post-BIM stage is an indicator for new research fields in which building information modeling transcends for a multidisciplinary context, encompassing specific ICT solutions that should extend static or dynamic relationships between physical and virtual environments.

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Notes

(1) BIM objects virtually represent physical-functional characteristics of the building and enable the acquisition, interpretation, and analysis of geometric and non-geometric data and information by the user and a set of applications (NBIMS, 2006).

(2) The Semantic Web is a web of qualified information, derived from data by means of a semantic theory to interpret symbols (SHADBOLT; BERNERS-LEE; HALL, 2006).

(3) Succar, Saleeb, and Sher (2016) attribute a codification to each series and use of the BIM model, which refers to the concepts adopted by the authors. They can be checked at: <http://www.bimexcellence.org/model-uses/>.

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