

Received July 11, 2020, accepted August 3, 2020, date of publication August 17, 2020, date of current version September 3, 2020.

Digital Object Identifier 10.1109/ACCESS.2020.3016919

# Building Information Modelling (BIM) and the Internet-of-Things (IoT): A Systematic Mapping Study

**BAYDAA HASHIM MOHAMMED<sup>1,2</sup>, NURHIZAM SAFIE<sup>1</sup>, HASIMI SALLEHUDDIN<sup>1</sup>, AND AFIFUDDIN HUSAIRI BIN HUSSAIN<sup>1</sup>**

<sup>1</sup>Faculty of Information Science and Technology, Universiti Kebangsaan Malaysia, Bangi 43600, Malaysia

<sup>2</sup>Department Computer Techniques Engineering, Al-Esraa University College, Baghdad 10069, Iraq

Corresponding author: Baydaa Hashim Mohammed (baidaa81@gmail.com)


This work was supported by the Faculty of Information Science and Technology, Universiti Kebangsaan Malaysia, Bangi, Selangor, Malaysia.

**ABSTRACT** Of recent, Building Information Modelling (BIM) has become an influential paradigm for the development of better project delivery practices to improve construction and operational efficiencies. In the last 6 years, a significant number of studies have been published on the integration of BIM in Internet of Things (IoT). This paper aims to examine the general research productivity, demographics, and trends shaping the research domain. Hence, the paper will also help to identify, categorize, and synthesize important studies in the research domain. In doing so, we adopt an evidence-based systematic mapping methodology to ensure the coverage of key studies through a systematic and unbiased selection and evaluation process which results in the final selection of 55 relevant studies. The results of the mapping study show that the research on the integration of BIM in IoT is gaining more attention in last 6 years with stable and consistent publication output. Prominent application domains, validation methods, contribution facets, research types, and simulation tools in the field of study were identified and presented. Five research types were also identified, i.e. solution proposal, experience paper, evaluation research, validation research, and opinion paper, with solution proposals getting more research attention. In general, the overall demographics of the research domain were presented and discussed.

**INDEX TERMS** IoT, BIM, prefabrication, digital construction.

## I. INTRODUCTION

Building Information Modelling (BIM) has become an influential paradigm for the development of better project delivery practices to improve construction and operational efficiencies. BIM projects give high reliability, geometrically, well-positioned, and accurate identifiable building components data sets. On the other hand, Internet of Things (IoT) is the interconnection of sensing and actuating devices providing the ability to share information across platforms through a unified framework, developing a common operating picture for enabling innovative applications [1]. Some IoT enabling technologies includes sensing technologies, software and cloud platforms, position technologies, and so on [2]. The integration of BIM with IoT devices is vital for applications

The associate editor coordinating the review of this manuscript and approving it for publication was Alicia Fornés .

and is a relatively new development. In general, BIM and IoT data offer complementary views of a project, whereby together they enhanced the limitations of each of them. BIM models offer high trustworthiness depictions of a project at the component level.

In the last 6 years, with the persistent interest from the research community, a significant number of studies have been published on the integration of BIM in IoT. However, to the best of knowledge, systematic mapping studies in this research domain are non-existent. In this mapping study, we intend to fill this research gap by comprehensively analysing important studies published in the last five years (2015 - 2020). This study will primarily help researchers in identifying the key application domains, validation methods, contribution facets, research types, simulation tools, performance measures, and the general demographics of the selected studies in the field of study.

In an effort to ensure transparency and inclusion of all important studies, we adopt an evidence-based systematic mapping methodology to ensure the coverage of key studies through a systematic and unbiased selection and evaluation process [3]. Furthermore, the study initiates with the construction of a systematic mapping protocol comprising of a search strategy, inclusion and exclusion criteria, study selection process, data extraction, and data synthesis strategies. Hence, this mapping also examines the general research productivity, demographics, and trends that are shaping the landscape of this research domain.

The main contributions of this mapping study are as follows:

- A comprehensive systematic mapping study on the integration of BIM in IoT.
- Detailed analysis and synthesis of existing studies in the research domain.
- An investigation of the general productivity, demographics, and trends in the research domain.

This study is structured into six sections. Section II gives the related works. The systematic mapping process is presented in Section III. Section IV provides the study results with respect to the research questions provided. In section V, the discussion is given. Lastly, the study is concluded in Section VI.

## II. RELATED WORK

In this section, the existing survey/review papers in the field of study are highlighted with the emphasis on the need for our contribution. We have identified three prominent review studies conducted in the research domain.

In a study by Carneiro *et al.*, the authors conducted a review on works that aimed at intelligent management of cities infrastructures that uses technologies such as Geographic Information Systems, BIM, IoT, and Virtual/Augmented Reality (VR/AR) [4]. In a recent study by Singh [5], the author conduct a qualitative review of studies based on digitization, BIM ecosystem. Hence, the author gives projections on the future of built environment and the practical implications of his findings. In another study by Tang *et al.*, the authors conduct a comprehensive review so as to identify the emerging areas of application and common design patterns to tackle the issues of BIM-IoT devices integration [1]. The authors also highlight the current limitations in the field of study with future research directions.

However, based on our analysis of the existing survey/review studies, there are no systematic studies in this research domain. The existing survey/review study selection procedure are arbitrary with no clear and repeatable evidence-based study selection procedure. Moreover, there are no survey/review in this domain that classify and analyze studies based on their contribution facets, research types, validation methods, publication trends/fora, articles citation impacts, and important institutions/countries of the selected studies. Therefore, the objective of this study is to fill these research gaps.

## III. SYSTEMATIC MAPPING PROCESS

In this research, we used a Systematic Mapping Study (SMS) method [3], [6]. SMS gives an evidence-based systematic and objective procedure for identifying highly relevant available empirical study data in a specific area of study to answer a specific Research Questions (RQs) [7]. Systematic Literature Reviews (SLRs) are aimed at identifying, evaluating, and interpreting relevant research for a particular question. On the other hand, SMS is aimed to “map out” the conducted relevant research rather than evaluating and interpreting RQs in detailed [3], [6]. Hence, the good practices and procedures in writing an SMS were defined in [3].

SMS composed of analyzing primary selected studies that work on related predefined RQs, which are aimed at categorizing and synthesizing evidence to support or refute specific research hypothesis. Hence, the key reasons to conduct SMS are stated as follows:

- To conduct an unbiased assessment of retrieved studies and identify current research gaps and contributions.
- To gives a systematic procedure for identifying available relevant studies to answer the defined RQs.
- To help in mapping out the undertaken research.
- To aid in the introduction of new research that will help in avoiding unnecessary study duplications in a field of study.

In this study, we used the mapping method from Petersen *et al.* [3]. Hence, Figure 1 presents the mapping process for this study.

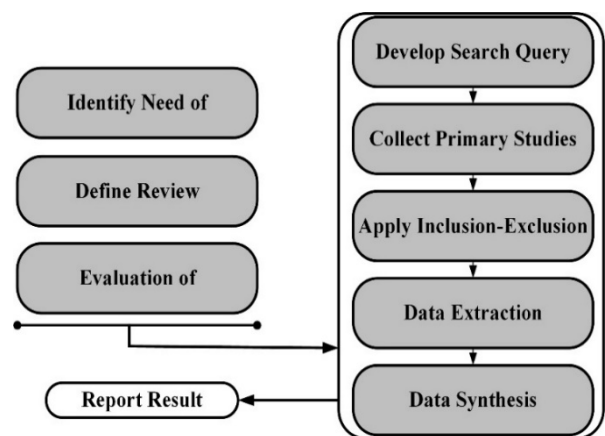


FIGURE 1. The mapping process.

### A. RESEARCH QUESTIONS

The main objective of this study is to identify, evaluate, analyze, and synthesis research activities on the integration of BIM in IoT so as to provide new and veteran researchers with a summary of all works done in the field of study. The defined RQs for our study are highlighted in Table 1.

### B. REVIEW PROTOCOL

By definition, primary selected studies relate to the literature being mapped. Hence, to have a good mapping,

**TABLE 1. Research questions.**

RQ#	Research Question	Motivation
RQ1	What are the different application domains in the selected studies?	To identify the application domains in the field of study.
RQ2	What are the contribution facets in the selected studies?	To identify the contribution facets (framework, evaluation, platform, system, approach, method, model, strategies, and ontology).
RQ3	What are the research types in this domain?	To identify the research facets (solution proposal, experience paper, evaluation research, validation research, and opinion paper) in the field of study.
RQ4	What are the validation methods used by the selected studies?	To highlights the prominent validation methods in the field of study.
RQ5	What are the simulation tools used by the selected studies?	To highlights the existing simulation tools utilized in the field of study.
RQ6	What are the different performance measures used in the research domain?	To highlights the performance measures used in this research domain.
RQ7	Are the selected studies empirically validated?	To substantiate if the selected studies were empirically validated or not.
RQ8	What are the demographic characteristics of the selected studies?	To highlights the publication trend, publication fora, most cited articles, most active institutions, and geographical distribution of the selected studies.

it is imperative that the selection of primary studies to be done with great care. It is always good to conduct an exhaustive search for the selection of studies, however, in some cases, it is not possible due to the availability of primary studies. In cases like this, search criteria become significant.

Initially, we defined the search scope with respect to the time period and the electronic databases for our study. Defining the search scope is important in reflecting the objectives of the review and also the significance of the studies to be selected. In this study, studies from 2015 to 2020 were selected. Moreover, eight electronic databases were selected to conduct our search.

The databases are IEEE Xplore (<http://ieeexplore.ieee.org/>), Springer Link (<http://link.springer.com/>), Science Direct (<https://www.sciencedirect.com/>), WoS (<http://wokinfo.com/>), Emerald (<https://www.emerald.com/insight/>), Taylor & Francis (<https://taylorandfrancis.com/>), Wiley Online Library (<http://onlinelibrary.wiley.com/>), and ACM Digital Library (<http://dl.acm.org/>). These electronic databases provide a good source for Journal papers and events (Conferences, Workshops, Symposiums, and Book Chapters).

1) SEARCH STRING

In order to retrieve the relevant studies for our review, automatic searches were performed in the selected electronic

databases using our formulated search string. A search is basically the combination of key characters and words inputted by a researcher into a search engine to find the preferred results. Hence, the search result is directly related to the information provided to the search engines. Therefore, the careful selection of keywords used in our search string is vital so as to ensure we did not miss all the vital studies that our mapping is trying to address. Hence, a generic search string was formulated to maintain search consistency across all databases. The generic search is as follows:

2) GENERIC: ((BUILDING INFORMATION MODELLING OR BIM) AND (IOT OR INTERNET OF THINGS))

However, we observed that each database is unique in terms of the interface for advance search and command search, therefore, Table 2 shows the search string used with respect to each database.

**TABLE 2. Search process.**

Database	Queries
Science direct	<i>(("BUILDING INFORMATION MODELLING" AND "IoT") AND ("FACILITY MANAGEMENT") OR ("CLOUD COMPUTING"))</i>
IEEE Xplore	<i>((("Abstract":BUILDING INFORMATION MODELING) OR "Abstract":BIM) AND "Abstract":IoT)</i>
WoS	<i>(BIM) AND (IoT)</i>
Springer	<i>"BUILDING INFORMATION MODELING" AND "IoT"</i>
ACM	<i>("IoT "+"BUILDING INFORMATION MODELING")</i>
Wiley	<i>"BUILDING INFORMATION MODELING" AND "IoT"</i>
Emerald	<i>(IoT) AND (BIM)</i>
Taylor and Francis	<i>(IoT) AND (BIM)</i>

3) INCLUSION-EXCLUSION CRITERIA

After obtaining our search results using the search string, studies that are either not in-line with the scope and objective of the mapping or do not add any value to the mapping may be retrieved. With this reality, inclusion-exclusion criteria were carefully designed to be applied to the retrieved studies in order to remove studies that do not match the objective of the mapping.

4) INCLUSION CRITERIA

- Studies on the integration of BIM in IoT.
- Studies published in the last 6 years (2015 – 2020).
- Inclusion of the latest studies in case of multiple studies on the same theme.
- Peer-reviewed studies.

## 5) EXCLUSION CRITERIA

- Survey and review papers
- Studies that are not based on BIM in IoT.
- Studies other than English language.

## 6) REVIEW COMMITTEE

We formed review committees composed of two researchers each in order to rate all the primary studies retrieved from our search. All the studies were examined independently on the basis of the criteria defined in our Inclusion-Exclusion Criteria. The utilization of the inclusion-exclusion criteria resulted in 55 studies out of the total of 213 studies being selected for quality analysis (see Table 3). These review committees conducted independent data analysis and their results were aggregated in a review meeting comprising of all independent researchers. During this meeting, if dispute on results arises, these disputes are resolved by giving final weighting to the opinion of the committee comprising of senior researchers in the domain.

**TABLE 3. Search result.**

Database	Initial results	Screened result based on relevance	Final selected studies
Science Direct	121	44	12
IEEE Xplore	179	36	16
WoS	12	11	8
Springer	157	8	2
ACM	77	71	2
Wiley	37	4	0
Emerald	35	20	5
Taylor & Francis	40	19	10

## 7) DATA EXTRACTION

In the quest of extracting meaningful information of each selected study in a way that the RQs can be answered, a data extraction method needs to be clearly defined. Therefore, this information was extracted to a predefined data extraction form. The form is filled for each study that passes the inclusion-exclusion criteria. Hence, the form is composed of the following list of items.

- Title
- Publication year
- Publication venue
- Application domain
- Contribution
- Research type
- Validation method
- Simulation tool
- Performance measure

## IV. RESULTS

In this section, our results based on the analysis conducted are presented. Hence, all the RQs are answered by analyzing data extracted from our selected studies (Appendix 1).

### A. RQ1: WHAT ARE THE DIFFERENT APPLICATION DOMAINS IN THE SELECTED STUDIES?

Based on our analysis of the selected studies, we identified four prominent application domains in the field of research. These application domains are highlighted in Table 4. 67.27% of the studies are based on the Construction Operation and Monitoring application domain and 21.83% of the studies are based on Facility Management (FM) domain. Followed by Construction Logistic & Monitoring and Health & Safety (H & S) Management with 5.45% and 5.45%, respectively. Therefore, the later domains (Construction Logistic & Monitoring and Health & Safety (H & S) Management) are utilized less by our selected studies.

During the analysis, we observed that 56.7% of studies that are in Construction Operation and Monitoring domain did not use any performance measures for their studies, while 66.7% of the studies that are in FM domain do not use any performance measures as well. This means that the majority of the studies at the top 2 application domains in the field of research are not empirically validated. However, we generally see a trend in the selected studies where for the studies that did not use any performance measures, they either have no validation method or they validate their work based on “feasibility study method” (see Section 4.4). Therefore, this is understandable, because validation methods such as experiment, simulation, and case study often need to be evaluated by performance measures.

**TABLE 4. Application domain in the field of study.**

Application domain	Studies	Number of Studies	%
Construction Operation and Monitoring	[8]–[29][29]–[43]	37	67.27%
Facility Management (FM)	[44]–[51][52]–[55]	12	21.83%
Construction Logistic and Management	[56]–[58]	3	5.45%
Health and Safety (H & S) Management	[59], [60][61]	3	5.45%

### B. RQ2: WHAT ARE THE CONTRIBUTION FACETS IN THE SELECTED STUDIES?

In this section, results based on the selected studies contributions are given. This classification is inspired by [3] in order to help structure the research area. Hence, the selected studies are structured into specific contribution types including Framework, Evaluation, Platform, System, Approach, Method, Model, Strategies, and Ontology. The classification of the selected studies based on the contribution given is presented in Table 5.

The results of this analysis reveal that the contribution facet for Framework is 29.09%, which makes up the most studies with 16 studies, followed by System and Evaluation with 21.82% and 18.19%, respectively. Conversely, contribution facets in terms of Strategies and Ontology are

1.82% each, which makes up the least number of studies with only one study each. However, we further observed that one study [8] was not clear on the contribution provided. Therefore, we classified the study as “none”.

**TABLE 5. Contribution facet.**

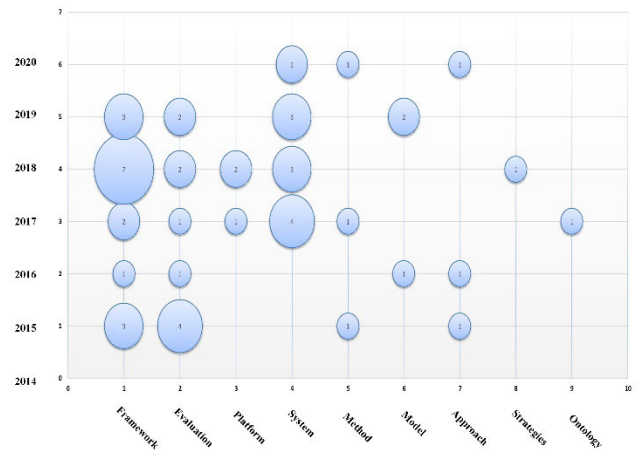
Contribution	Studies	%
Framework	[10], [11], [17]–[19], [21], [22], [29], [46]–[48], [50], [58], [60]	29.09%
System	[16], [49], [59]	21.82%
Evaluation	[15], [26]–[28], [45]	18.19%
Approach	[14], [25], [44]	9.09%
Platform	[51], [56], [57]	5.45%
Method	[23], [24]	5.45%
Model	[20][13]	5.45%
Strategies	[9]	1.82%
Ontology	[12]	1.82%
None	[8]	1.82%

Lokshina *et al.* proposed a system that used a blockchain technology to secure and control the framework that involves integrated IoT and BIM technologies [37]. The proposed integrated system shows some promise. In another study by Mohamed *et al.*, the authors proposed a new approach for existing building facilities. The authors present an ontological system that relies on integrating the as-is information BIM and semantic web technology [55]. The proposed framework shows some improvements.

Arslan *et al.* develop a system that utilizes BIM software and a wireless sensor technology primarily to develop a proactive safety management system [54]. The proposed system shown to be effective by reducing safety hazards during facility management phase of a building. In a study by Boddupalli *et al.*, a visualization tool was proposed that enables an automated sensor data inventory into BIM environment [61]. The proposed tool provides systematic maintenance and risk management. The study shows that the proposed tool is potentially user-friendly and a key economic framework. Another integrated interface of manufacturer-based life cycle assessment (LCA) data into a BIM platform was proposed by Bueno *et al.* [32]. The result shows some promise. With the goal of resolving the issue of low efficiency and low success rate in the conversion of BIM models to GIS platform, Xiang *et al.* proposed a new integration model. This model aid in converting BIM models to GIS models efficiently [41]. The result shows that the proposed integrated model performs very effectively. In another study by Yuan *et al.*, a BIM-based Performance Management System (BPMS) was proposed. The proposed system combines BIM with web and cloud technology to achieve performance measurement, performance monitoring, and performance-based payment [31]. The proposed system shows some promise with respect to guiding stakeholders in improving work efficiency with the help of BIM and other technologies.

Figure 2 highlights the map of research for contribution facets with respect to year of publication. Based on the result presented in the bubble plot, one can observe that despite Framework been progressively the most proposed,

only one proposal was done in 2016. The readers can also observe that of recent (from 2017), Platform and System have been proposed. In general, Framework and Evaluation are more consistently proposed in the field of study. Perhaps researchers can give more attention to Models, Approaches, and Strategies to improve the adoption of BIM in IoT.



**FIGURE 2. Mapping of Contributions Based on Years of Publication.**

**C. RQ3: WHAT ARE THE RESEARCH TYPES IN THIS DOMAIN?**

In this section, we highlighted the identified research types in this research domain. Figure 3 presents the research facets that were identified. Hence, five research facets were identified. Research facets were classified into solution proposal, experience paper, evaluation research, validation research, and opinion paper. Solution proposals are researching that proposes solutions for a given problem which can be novel or a vital extension of an existing approach or framework. The example of solution proposal can be found in [56]. The authors’ proposed multi-dimensional internet of things (IoT)-enabled BIM platform (MITBIMP) so as to achieve real-time visibility and traceability in prefabricated construction. Experience papers explain how a solution is done in practice. This kind of research is based on the personal experience of the author. The example of this kind of study are [22], [50], [51]. Evaluation research is when a proposal is implemented in practice and the proposal is evaluated mainly in terms of its benefits and drawback. The kind of studies that conduct this kind of research are [13], [28], [60]. Validation research is proposed proposals that are novel and have not yet been implemented in practice. Example of this research type are [17], [20]. Lastly, opinion papers are papers that express the personal opinion of a researcher on a certain proposal on whether it is good or bad, or how things should be conducted. Example of this kind of research is [45].

Based on our analysis of the selected studies, we observed that most studies were conducted using a solution proposal research type (58%), followed by experience paper with 18% contribution. The selected studies also conduct research based on evaluation research and validation research with

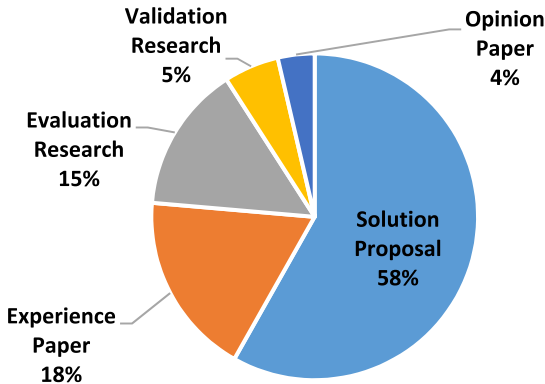


FIGURE 3. Research facets.

15% and 5% contribution, respectively. The least is opinion paper with 4% contribution. The result implies that most of the work in this field of research is based on novel solution proposals to tackle specific research problems. However, there are a lot of experience papers in this research area as well. This signifies that a lot of studies are based on explaining how solutions are done or implemented in practice. However, the research area is very diverse in terms of the type of research been conducted in recent years.

**D. RQ4: WHAT ARE THE VALIDATION METHODS USED BY THE SELECTED STUDIES?**

In this section, we determine the existing validation methods adopted by the selected studies and the studies that utilized them. It is important that we identified the existing validation methods from the selected studies, as it will aid readers to understand how researchers validate the existing proposals in the research domain. Table 6 highlights the validation methods identified. Out of the 55 selected studies, five validation methods were identified which are feasibility study, experiment, case study, simulation, and hybrid method. These methods are vital in validating existing proposals in the field of study.

We observed that 34.54% of the selected studies used feasibility study method, which amounts to the largest validation method used among the selected studies. The second most used method is case study with 23.64% of the selected studies utilizing it, followed by experiment and simulation with 21.82% and 12.73%, respectively. However, we identified 3 (5.45%) that have not used any validation method. Moreover, 1 (1.82%) study used hybrid method [18]. This study used the combination of two validation methods, which are case study and simulation method.

Figure 4 presents the map of research for validation methods against the application domains that used them the most. We observed that feasibility studies are predominantly done in the domain of Construction Operation & Monitoring with only two feasibility study done in Facility Management (FM) domain. Another observation is there are only three studies under the domain of Construction Logistic & Management [56]–[58], these studies all used the case study validation method.

TABLE 6. Validation methods.

Validation method	Studies	Number of Studies	%
Feasibility study	[9], [11], [17], [20], [23]–[25], [27]–[29], [44][32], [34]–[37], [39], [40], [53]	19	34.54%
Case study	[14], [19], [22], [46], [50], [56]–[58][31], [33], [41]–[43]	13	23.64%
Experiment	[10], [12], [47], [48], [51], [60][29], [30], [38], [54], [55], [61]	12	21.82%
Simulation	[13], [15], [16], [21], [49], [59][52]	7	12.73%
None	[8], [26], [45]	3	5.45%
Hybrid	[18]	1	1.82%

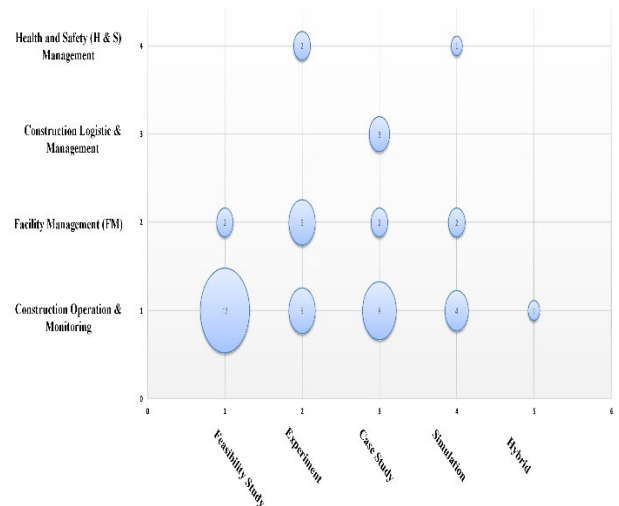


FIGURE 4. Mapping of Validation Methods against Application Domains.

**E. RQ5: WHAT ARE THE SIMULATION TOOLS USED BY THE SELECTED STUDIES?**

In this section, we elaborate on the distribution of simulation tools used by the selected studies. Out of the 35 selected studies, six studies were identified to have used a simulation tool, which is compatible with our findings in Table 6 of having six studies based on simulation validation method. Table 7 highlights the identified simulation tools.

TABLE 7. Simulation tools.

S/N	Simulation tool	Study
1	Risk Management System	[59]
2	PyroSim	[49]
3	Social Network Analysis	[13]
4	Contiki, Cooja, and VMware	[15]
5	3Dui	[16]
6	Otaniemi3D	[21]

**F. RQ6: WHAT ARE THE DIFFERENT PERFORMANCE MEASURES USED IN THE RESEARCH DOMAIN?**

In this section, we identified the performance measures used to aid in validating proposals in the field of study. Performance measures are vital in the process of validation of a proposal. Table 8 highlights the performance measures used by studies in the field of study. Out of the 55 selected studies, 22 studies used performance measures which amount to 40% of the selected studies. On the other hand, we identified 33 studies that did not indicate the performance measures they used, which amount to 60% of the selected studies. The studies are [8]–[11], [20], [23]–[29], [44]–[48], [56], [59], [60][29], [30], [54], [55], [61], [34], [36]–[38], [40], [42], [43], [53].

**TABLE 8. Identified performance measures.**

S/N	Performance measures	Studies
1.	Temperature, humidity, luminosity, and PRR	[22]
2.	Temperature	[21]
3.	Accuracy	[19]
4.	Effectiveness	[58]
5.	Mean Bias Difference (MBD), Root Mean Square Difference (RMSD), and Mean Absolute Difference (MAD)	[18]
6.	Temperature, humidity, and Accuracy	[51]
7.	Efficiency and Effectiveness	[57]
8.	Performance	[17]
9.	Weather, dust pollution, and Real-time data	[50]
10.	Temperature	[49]
11.	Temperature	[16]
12.	Temperature and time stamping	[15]
13.	Temperature	[14]
14.	Network density, network cohesion, nodal degree, betweenness centrality, status centrality, and brokerage	[13]
15.	Performance	[12]
16.	Performance	[35]
17.	Accuracy	[39]
18.	Performance	[32]
19.	Efficiency and Accuracy	[41]
20.	Performance	[33]
21.	Performance	[31]
22.	Effectiveness	[52]

**G. RQ7: ARE THE SELECTED STUDIES EMPIRICALLY VALIDATED?**

In this systematic mapping study, we observed that 32 studies out of 55 were not empirically validated [8]–[11], [20], [23]–[29], [44]–[48], [56], [60][29], [30], [54], [55], [61], [34], [36]–[38], [40], [42], [43], [53], which amount to 58.18% of the selected studies. We come to this conclusion by taking two things into consideration, which are the performance measure and simulation tool of a given study. Therefore, if a study did not use a performance measure for empirical measurements and did not use a simulation tool, then, we classify the study has not been empirically validated. However, some studies such as [59] that use simulation tool with no performance measures are considered empirically validated in this study, because these kinds of studies have some simulation data. On the other

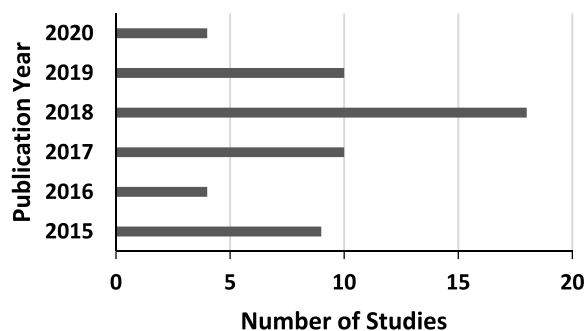
hand, we identified 23 (41.82%) studies that are empirically validated, which are [12]–[19], [21], [22], [49]–[51], [57]–[59][31]–[33], [35], [39], [41], [52].

**H. RQ8: WHAT ARE THE DEMOGRAPHIC CHARACTERISTICS OF THE SELECTED STUDIES?**

The 55 studies that were selected for the final analyses were analyzed deeply in order to answer this RQ. Hence, to answer this RQ, five aspects of the selected studies were examined: publication trend, publication fora that published important studies, the most cited articles, the geographical distribution of the selected studies, and the most active institutions in the field of study.

**1) PUBLICATION TREND**

From 2015 to 2020, 55 studies were extracted from the literature by following the research methodology in Section 3. Figure 5 highlights the evolution of research in this domain. Hence, the research area is growing in recent years. From 2015 – 2017, there is a stable number of publications. However, in 2016, the frequency of publication reduces with only four studies published [13], [27], [33], [43]. This can be explained because the most active Journal which is Automation in Construction did not publish any paper in this year (see Table 9). The interest increases considerably in 2018, with 18 studies published which is the highest number of studies in the entire timeframe of this study. We further observed that the studies in 2020 were lower, perhaps because the year is still active, so many studies might be expected before the end of the year.



**FIGURE 5. Number of publication per year.**

Moreover, in 2018, 10 Journal papers were published which was the highest across the years analyzed. But, this is obvious, because 2018 has the highest number of publications. Generally, despite the decrease in publication for the year 2019, the research area is very promising. Hence, more studies are expected in this research area in years to come.

**2) WHICH PUBLICATION FOR A'S PUBLISHED THE SELECTED STUDIES?**

In this paper, we identified 23 different Journals, 15 Conference proceedings, 3 Workshops, 1 Symposium, and 1 Magazine (see Table 9 and Appendix 2). In Figure 6, most of

the selected studies were published in Journals (34 studies), followed by Conference proceedings (15 studies), Workshop (4 studies), Symposium (1 study), and lastly, Magazine (1 study). Table 9 presents the 15 identified Journals with respect to the studies that were published in them. The Journal of Automation in Construction is the most active in this research domain with nine studies. However, the other 19 Journals as listed in Table 9 all have one study each, respectively. Moreover, we further observed that 7 (30.43%) out of the 23 identified Journals were published from Elsevier and 9 (39.13%) were published by Taylor & Francis.

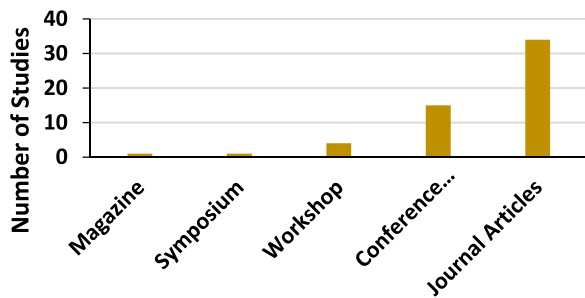


FIGURE 6. Publication channel.

Hence, in this study, we categorize Conference, Workshops, Symposiums, and Magazines as proceedings. However, because these proceedings all contain one paper each, we did not rank them. Hence, we present them in Appendix 2.

### 3) MOST CITED ARTICLES

Generally, citations are mainly influenced by a study date of publication (among other factors). Hence, studies published earlier tend to have more citations in virtually any field of research. Also, studies published in Journals tend to have higher citations in comparison to studies published in proceedings. Therefore, having analyzed our selected studies, we identified the top 10 studies that are so far more influential in terms of citations in the field of study (see Table 10).

The citation count of each study was obtained from Google Scholar, which is subject to change at any moment in time. We identified four studies with more than 20 citations [13], [18], [56], [57]. From Table 10, the top 3 most cited studies are all published in Journals, and also, six out of the top 10 studies are equally published in Journals. Moreover, the most cited article with 79 citations was an early study, which was published in 2016 [13].

### 4) GEOGRAPHICAL DISTRIBUTION OF THE SELECTED STUDIES

Table 11 highlights the top 10 most represented countries. In other words, countries that have more publications. From our selected studies, we identified 15 active countries. China with 14 publications is the most active country in this research field, followed by United Kingdom and USA with 9 and 9 publications, respectively. Countries such as Italy (3), Canada (3), Taiwan (3), and Finland (2) have relative number

TABLE 9. Top representative journal.

Title	Publishers	Studies	No.
Automation in Construction	Elsevier	[12], [19], [21], [56], [57][36], [38], [39], [55]	9
Journal of Cleaner Production	Elsevier	[13][30]	2
Engineering, Construction and Architectural Management	Emerald	[28][31]	2
Architectural Engineering and Design Management	Taylor & Francis	[32], [34]	2
Applied Sciences	MDPI	[51]	1
Advanced Engineering Informatics	Elsevier	[49]	1
IFAC Papers Online	Elsevier	[58]	1
IEEE Access	IEEE	[47]	1
Journal of Structural Integrity and Maintenance	Taylor & Francis	[48]	1
Cities	Elsevier	[11]	1
Technology Architecture + Design (TAD)	Taylor & Francis	[8]	1
International Journal of Construction Management	Taylor & Francis	[46]	1
Procedia Social and Behavioural Sciences	Elsevier	[17]	1
Journal of Structural Integrity and Maintenance	Taylor & Francis	[9]	1
The International Journal of Advanced Manufacturing Technology	Springer	[20]	1
Structure and Infrastructure Engineering	Taylor & Francis	[61]	1
Journal of Engineering, Design, and Technology	Emerald	[60]	1
Journal of Engineering, Design and Technology	Emerald	[42]	1
Engineering Project Organization	Insight	[35]	1
Journal of Building Performance Simulation	Taylor & Francis	[33]	1
Construction Management and Economics	Taylor & Francis	[53]	1
Facilities	Emerald	[43]	1
Procedia Computer Science	Elsevier	[37]	1

of studies. The rest of the countries all have one publication each. Furthermore, we also observed that most of the highly cited studies such as [12], [13], [45], [56]–[58], [60] are published in the top two countries (China and United Kingdom).

### 5) MOST ACTIVE INSTITUTIONS

Table 12 gives the top 10 most represented institutions in the research domain with respect to the number of studies that were published from these institutions. From our selected studies, we have identified 21 unique institutions in the field of research. The University of Hong Kong, China,



TABLE 10. Top 10 Most cited articles.

Title	Year	Publication channel	Citation count
Schedule risks in prefabricated housing production in Hong Kong: a social network analysis [13]	2016	Journal	108
Prefabricated construction enabled by the internet-of-things [56]	2017	Journal	108
Integrating RFID and BIM technologies for mitigating risks and improving schedule performance of prefabricated house construction [30]	2017	Journal	65
An internet of things-enabled BIM platform for on-site assembly services in prefabricated construction [58]	2018	Journal	64
A framework for integrating BIM and IoT through open standards [21]	2018	Journal	60
The challenges and potentials of utilizing building information modeling in facility management: the case study of the centre for properties and of the University of Helsinki [53]	2015	Journal	53
Building energy modelling and monitoring by integration of IoT devices and building information models [18]	2017	Conference	39
A framework to integrate object-oriented physical modeling with building information modeling for building thermal stimulation [33]	2016	Journal	35
Integrating building and urban semantics to empower smart water solutions [12]	2017	Journal	32
Perspectives on a BIM-Integrated software platform for robotic construction through contour crafting [36]	2015	Journal	32

TABLE 11. Top 10 most represented countries in the research domain.

Countries	Studies	Number of Studies
China	[10], [13], [20], [47], [48], [50], [56]–[59][30], [31], [39], [41]	14
United Kingdom	[11], [12], [15], [26]–[28], [44], [45], [60]	9
USA	[8], [19], [29], [60][29], [33], [36]–[38]	9
Italy	[9], [14], [18]	3
Taiwan	[49], [51][52]	3
Canada	[46][61][43]	3
Finland	[16], [21]	2
Sweden	[25]	1
Turkey	[23]	1
Republic of Korea	[17]	1

The Hong Kong Polytechnic University, and Tsinghua University, Beijing are the top 3 most active institutions with 3, 3, and 2 studies, respectively. Furthermore, we observed that despite USA being in the top three most represented countries (see Table 9), USA institutions are virtually absent in our ranking in Table 10. Oregon State University, USA is the only institution from USA that makes the top 10 ranking with two studies, respectively. On the other hand, we identified five Chinese institutions at our top 10 institutions ranking in Table 12. This means that China and its institutions have

TABLE 12. Top 10 most represented institutions in the research domain.

Institution	Studies	Number of Studies
The University of Hong Kong, China	[56]–[58]	3
The Hong Kong Polytechnic University	[13], [56][57]	3
Tsinghua University, Beijing, China	[48], [59]	2
Cardiff University, UK	[12], [15]	2
Aalto University, Finland	[16], [21]	2
Oregon State University, USA	[19], [29]	2
Politecnico di Milano, Italy	[9]	1
Politecnico di Torino, Italy	[18]	1
Chang’an University, China	[10]	1
Huaqio University, China	[10]	1

contributed a lot in this research domain with 10 studies collectively.

### V. DISCUSSION

In this section, the results of this study in relation to the RQs are summarized and discussed. The identified research challenges with recommendations for future works were also highlighted. Furthermore, the threats to the validity of the work is also presented.

#### A. PRINCIPAL FINDINGS

The key objective of this mapping study was to examine the current knowledge on the integration of BIM in IoT. With this objective in mind, 55 studies were carefully selected by following our methodology in Section 3. Hence, the following are the principal findings of this study.

- Based on our findings with regards to how active this research area is, we observed that research on the integration of BIM in IoT is quiet new with little and yet growing amount of studies since from 2015. Hence, the research area is growing consistently with 18 studies published in 2018. Although publications were quiet little in 2020 (due to our data collection cap), we believe that more work will be expected in years to come.
- About 58% of the selected studies reported solutions to the application of BIM in IoT. This observation shows that the research field has not attained sufficient maturity for evaluation. Because the main objective of the selected studies is to propose solutions for various research problems. This is obvious from our result in Figure 3, where only 15% of the selected studies are based on evaluation research. Hence, experience papers were observed to be the second most adopted research type with 18% of the selected studies. This research type reports authors’ experiences.
- In this study, we identified four application domains. 67.27% of the selected studies are in Construction Operation and Monitoring domain, followed by Facility Management (FM), Construction Logistic and Management, and Health and Safety (H & S) Management with 21.83%, 5.45%, and 5.45%, respectively.

- Nine contribution facets were identified in this research area. Framework with 29.09% is the most proposed contribution, followed by Evaluation and Platform with 21.82% and 18.19%, respectively. Also, Framework and Evaluation are more consistently proposed in the last 6 years. Perhaps, researchers can give more attention to Models, Approaches, and Strategies to improve the adoption of BIM in IoT.
- We also found that most of our selected studies (34.54%) performed feasibility study as their form of validation. Even though the majority of the studies are solution proposals (58%), empirical validation methods such as experiment and simulation have not been adopted by most of the studies. Validation based on experiment and simulation both were adopted by 21.82% and 12.73% of the selected studies each. Hence, we encourage more studies to adopt these validation methods in order to improve empirical evaluation in the field of study.
- Different performance measures were used by the selected studies. However, only 22 (40%) of the selected studies used these performance measures for their evaluation. The most used performance measure is temperature with 7 (31.82%) of the selected studies utilizing it. With respect to simulation tools, we identified 6 (10.91%) studies that used different simulation tools as highlighted in Section 4.5.
- With regards to whether the selected studies are empirically validated or not, we found out that 58.18% of the studies were not empirically validated. This is a critically important observation, which means that majority of the proposals in the field of study are not solid and fully examined. Hence, efforts need to be put by new and veteran researchers to fill this gap.
- From the selected studies, we found that about 34 (61.82%) of the studies were published in Journal, while 21 (38.18%) were published in proceedings (Conference, Workshop, Symposium, and Magazine). We also observed that 47.06% of the Journals that published the selected studies are from Elsevier and 26.47% were from Taylor & Francis. With regards to the most represented countries, China is the most active with 25.45% of the selected studies from there institutions, followed by the United Kingdom and USA with 9 and 9 studies, respectively. The University of Hong Kong and The Hong Kong Polytechnic University are the most active institutions with 3 studies each.

**B. IDENTIFIED RESEARCH CHALLENGES AND DIRECTION FOR FUTURE WORKS**

In this study, a comprehensive analysis of the selected studies was conducted. Hence, in this section, we highlighted few research challenges in this domain (with respect to the scope of this paper) for the research community to address. The direction for future works is also given to give researchers guidance on feasible future research directions.

**TABLE 13. Selected studies.**

S/N	Study	S/N	Study
1	Schedule risks in prefabricated housing production in Hong Kong: a social network analysis	19	Utilizing building information models as operating systems for smart homes
2	Integrating building and urban semantics to empower smart water solutions	20	Comparison of two workflows for web-based 3D smart home visualizations
3	Prefabricated construction enabled by the internet-of-things	21	Building energy modelling and monitoring by integration of IoT devices and building information models
4	Implementing a digital model for smart space design: practical and pedagogic issues	22	BIM-enhanced collaborative smart technologies for LEAN construction processes
5	Toward physical internet-enabled prefabricated housing construction in Hong Kong	23	Framework for an IoT-based shop floor material management system for panelised homebuilding
6	Wireless electric appliance control for smart buildings using indoor location tracking and BIM-based virtual environments	24	Connecting BIM and IoT for addressing user awareness toward energy savings
7	An internet of things-enabled BIM platform for on-site assembly services in prefabricated construction	25	BIM- and IoT-based monitoring framework for building performance management
8	A conceptual framework for the alignment of infrastructure assets to citizen requirements within a Smart Cities framework	26	A BIM-based visualization and warning system for fire rescue
9	BIM and sensor-based data management system for construction safety monitoring	27	Intelligent manufacturing model of construction industry based on internet of things technology
10	Evaluating critical success factors for implementing smart devices in the construction industry	28	Cyber-physical systems and the built environment
11	The emulation and simulation of internet of things devices for Building Information Modelling (BIM)	29	Use of templates and the handle for large-scale provision of security and IoT in the built environment
12	BIM and IoT: A synopsis from GIS perspective	30	Smart steel bridge construction enabled by BIM and internet of things in industry 4.0: A framework
13	An automated IoT visualization BIM platform for decision support in facilities management	31	Sensing information modelling for smart city
14	Integration of BIM solutions and IoT in smart houses	32	Security, privacy, and the built environment
15	Integrating BIM and IoT technology in environmental planning and protection of urban utility tunnel construction	33	Putting asset data at the heart of organizational decision-making using an integrated workplace management system
16	Design of an IoT-BIM-GIS based risk management system for hospital basic operation	34	Matching real-world facilities to building information modelling data using natural language processing

Despite the lack of maturity in this research area with respect to how new it is, there are lack of evaluation research. Although we have observed that 58% of the selected studies are solution proposals on BIM and IoT integration, however, critical evaluation of these proposals are needed at

TABLE 13. (Continued.) Selected studies.

17	BIM to IoT: The persistence problem	35	Evaluation of open data models for the exchange of sensor data in cognitive building.
18	A framework of integrating BIM and IoT through open standards	36	Integrating and managing BIM in 3D web-based GIS for hydraulic and hydro-power engineering projects
37	Developing a building information modeling-based performance management system for public-private partnerships	45	Using a change control system and building information modeling to manage change in design
38	Integrating RFID and BIM technologies for mitigating risks and improving schedule performance of prefabricated house construction	46	Building information modeling (BIM) enabled facilities management using Hadoop architecture
39	Research on integration of multi-source BIM models based on GIS platform	47	A scan to as-built building information modeling workflow: a case study in Malaysia
40	Automated building information modeling for fault detection and diagnostics in commercial HVAC systems	48	Designing and evaluation procedures for interdisciplinary building information modeling use – an explorative study
41	Life cycle assessment and environmental-based choices at the early design stages: an application using building information modeling	49	Exploring adoption of integrated building information modeling and virtual reality
42	Improved visualization of infrastructure monitoring data using building information modeling	50	BIM and semantic web-based maintenance information for existing buildings
43	Integration of BIM and GIS to query management on pipeline of building – a case study of dormitory	51	Perspectives on a BIM-integrated software platform for robotic construction through contour crafting
44	The challenges and potentials of utilizing building information modeling in facility management: the case of the centre for properties and of the University of Helsinki	52	BIM assisted building automation system information exchange using BACnet and IFC
53	Utilizing building information models as operating systems for smart homes	55	Application of integrated building information modeling: IoT and blockchain technologies in system design of a smart building
54	A framework to integrate object-oriented physical modeling with building information modeling for building thermal stimulation		

this early stages of this research area. Therefore, research should look into conducting evaluation and investigative studies on the new proposals. Furthermore, despite the increase in research activities in this domain from various part of the globe, we observed that research from this domain has been very limited among African countries. This is evident looking at our selected studies. Therefore, there is need for more research in this domain from this part of the world to improve participation and diversity of ideas.

Empirical validation is key in ascertaining the effectiveness of a given proposal. We observed that 58.18% of the selected studies were not empirically validated. This is critical looking

TABLE 14. List of identified proceedings from the selected studies.

Title	Publisher
IEEE International conference on networking, sensing and control (ICNSC)	IEEE
IEEE International conference on future IoT technologies (Future IoT)	IEEE
International conference on Engineering, technology and innovation (ICE/ITMC)	IEEE
Living in the internet of things: cybersecurity of the IoT-2018	IET
Asset management conference (AM 2016)	IET
IEEE International conference on smartcity/socialCom/sustainCom together with DataCom 2015 and SC2 2015	IEEE
International conference on environment and electrical engineering	Springer
International conference on serious games, interaction, and simulation	Nil
The International archives of the photogrammetry, remote sensing and spatial information sciences	IEEE
IEEE Annual computer software and applications conference	IEEE
IEEE International conference on advanced manufacturing (IEEE ICAM)	Springer
Workshop of the European group for intelligent computing in engineering	ACM
Workshop on human-habitat for health (H3): Human-habitat multimodal interaction for promoting health and well-being in the internet of things Era.	IEEE
Workshop on metrology for industry 4.0 and IoT	IEEE
Internet of anything (IT Professional)	IEEE
IEEE Symposium on service-oriented system engineering	IEEE
International Conference on Applied System Innovation	IEEE
International Conference on Management of Engineering and Technology	IEEE
International Conference on Information Management	IEEE
Conference on Electrical, Communication and Computer Engineering	IEEE

at how practical the research domain is. For future research works, researchers need to empirically validate their proposals. For evaluation purposes, we further observed that only 22 studies out of the 55 selected studies used performance measures to evaluate their proposals. Therefore, proposals need to be evaluated using proper performance measures by researchers. Perhaps, performance measures such as accuracy, performance, effectiveness should be used for future research.

C. THREATS TO VALIDITY

To gain a thorough analysis of the results obtained in this study, it is critical to be considerate of the limitations involved. Hence, the key threats to this SMS validity presented in detail.

This study is limited with the employment of a defined study selection criteria and methodology with the aim of exclusively considering studies considered as highly related and high impact. Furthermore, we limit our search to eight

electronic databases so as to extract relevant studies in the field of study. Therefore, our results and data might slightly differ if we considered other or more databases that were not in any of the eight chosen. In this study, we only considered peer-reviewed studies and also studies that are exclusively published in English language. However, there can be other studies related to the field of study that are written in other languages and might be of great importance to our study.

Hence, there might also be a PhD thesis, MSc dissertations, and technical reports that are partially or unavailable online and might be good for this study. However, our inclusion criteria did not include these kind of studies. Another limitation of our study can be the lack of employment of voting exercise, where decisions are taking based on researchers' viewpoints and perceptions. In this case, some bad studies might be included.

## VI. CONCLUSION

This paper presented a systematic mapping study that presents a 6 year (2015 - 2020) summary of existing relevant literature on the integration of BIM in IoT. Of the 658 studies obtained from our initial search results, 213 studies were identified based on relevance, of which 55 were finally chosen based on our defined inclusion and exclusion criteria.

The results of this mapping study showed that research on the application of BIM in IoT is quiet new, with moderate amount of studies published since 2015. We identified four application domain. 67.27% of the selected studies are in Construction Operation and Monitoring application domain, followed by Facility Management (FM) with 21.83%, respectively. However, we observed fewer studies in the domain of Construction Logistic and Management and Health and Safety (H & S) Management with 5.45% each. Nine contribution facets were identified in this research area. Framework with 29.09% is the most proposed contribution, followed by Evaluation and Platform with 21.82% and 18.19%, respectively. Also, Framework and Evaluation are more consistently proposed in the last 6 years.

From the selected studies, we found that about 34 (61.82%) of the studies were published in Journal, while 21 (38.18%) were published in proceedings (Conference, Workshop, Symposium, and Magazine). We also observed that 47.06% of the Journals that published the selected studies are from Elsevier and 26.47% were from Taylor & Francis. We also found that most of our selected studies (34.54%) performed feasibility study as their form of validation. Even though the majority of the studies are solution proposals (58%), empirical validation methods such as experiment and simulation have not been adopted by most of the studies. Hence, we found out that 58.18% of the studies were not empirically validated. This is a critically important observation, which means that majority of the proposals in the field of study are not solid and fully examined.

This research can be a starting point in investigating better ways to integrate BIM in IoT in the future. Furthermore, the results presented in this study may help researchers to

identify key application domains, validation methods, contribution facets, research types, simulation tools, and the general demographics in the field of study. In general, with stable publication output over the years, we prognosis that the research area would potentially gain much attention from researchers in years to come.

## APPENDIX

### Appendix 1

See Table 13.

### Appendix 2

See Table 14.

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