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ORIGINAL PAPER

# Integration of BIM and GIS for Construction Automation, a Systematic Literature Review (SLR) Combining Bibliometric and Qualitative Analysis

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**Abstract**

For several decades now, the construction industry is suffering from low productivity, especially in comparison to manufacturing industries which have succeeded to benefit from digitalization of their processes. Furthermore, scarceness of qualified workforce is expected in the near future. Construction automation is introduced as a solution to these challenges. The capabilities of construction robots are improving at an accelerated pace. They are starting to be used in non-laboratory contexts for automating processes ranging from infrastructure inspection to digital fabrication. One fundamental requirement of employing robots in construction is their autonomous positioning. Building information modelling (BIM) and geographic information system (GIS) are now a necessity for the construction projects. Integration between BIM and GIS provides holistic digital representation of the built environment that robots could potentially utilize for positioning purposes. Preceding this research, a number of reviews have been conducted on BIM–GIS integration, but none studied it from automation perspective. This research addresses this deficiency through a systematic literature review of the state-of-the-art on BIM–GIS integration with the purpose of robot positioning and navigation on construction sites. Using software tools and "science-mapping" methods, 236 papers were explored. Trends, challenges, potentials, and deficiencies identified and mapped. Citation patterns of journal articles along with the analysis of studies; visualized and analyzed. Bibliometric analysis is followed by a thorough qualitative analysis of the articles identified by the systematic methodology indicating limitations of current studies such as vertical navigation, inaccuracy, dynamics of construction sites, indoor-outdoor navigation. Requirements for robot positioning using BIM–GIS integration are defined.

## 1 Introduction

Productivity has always been an issue in construction industry [1]. According to Scape Group, 58% of construction suppliers and contractors identify scarceness of qualified workforce as the major challenge of improving the productivity of the construction industry in the near future [2]. Studies indicate that the construction industry is falling behind the overall global improvement in productivity [3]. A great number of reasons have been identified, such as persistence of employing traditional methods, lack of implementing industrial approaches of construction processes, taking little benefit from the use of digital tools and communication technologies [4]. Numerous studies, consequently, are carried out to tackle this issue. Barbosa et al. [5] propose adaptation of technology, through leveraging cross-functional teams, and implementing brand new technology simultaneously with the training for it. Another study identifies the privileges of applying Scrum strategy from design to the construction phase [6]. Agarwal et al. [7] have developed a framework to better exploit and leverage current technologies namely, 'rapid digital mapping', 'Building Information Modelling' (BIM), 'collaboration within a digital workplace', 'Internet of Things' (IoT), and 'future-proof design and construction'. 'Future-proof design' is mainly referred to as future anticipation design and development methods not to detriment the future of the existing buildings [8]. Some researchers propose that the construction industry should undergo a deep transformation in order to be able to adopt advanced

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technology. According to Bock [3], the required change in construction industry comes from the current emerging technology referred to as "Industry 4.0".

In that direction, Bowmaster and Rankin [9] have recently modified the multidimensional framework proposed by Froese and Rankin [10], with the purpose to examine the level of maturity of Canadian construction industry in respect to industry 4.0 technologies. The authors conclude that very little research has been carried out with regard to 'construction-based' automation and robotics in Canada causing a gap of 'prototype development' in 'cyber-physical systems' of navigating and positioning [9].

Performing research on one of the pillars of Industry 4.0, García de Soto et al. [4] investigate the productivity of digital fabrication in construction industry with a robot fabricating a complex concrete wall. The results show higher productivity when robotically fabricating a wall in comparison to a conventional method, and provide evidence that employing robots would enhance construction productivity.

Actually, a robot can be associated with every on-site inspection or digital fabrication practice, and a key part of the process is determining the robot's position. Therefore, positioning of robots becomes a fundamental step in construction inspection or digital fabrication.

A virtual representation of the project and its environment can provide a holistic overview of the construction in relation to the existing infrastructures and the surrounding environment. Today, two well developed technologies namely Building Information Modelling (BIM) and Geographic Information System (GIS) provide the digital environment for facilitating the analysis and management of spatial and non-spatial data [11]. BIM, basically, represents geometric and semantic functions of construction projects and provides a shared database enabling construction practitioners to collaborate effectively [12]. BIM facilitates data management of buildings' lifecycle including design, construction, operation, and maintenance of built assets [13]. On the other hand, GIS provides location-related analysis along with spatial representation of built environment in various fields of science [14]. Provided the capability of spatial data analysis by GIS, it is applicable to a broad range of practices including in construction industry [12]. In addition, several GIS-based simulation studies have been conducted for various purposes, which makes this field of knowledge more practical [15].

Built environment stakeholders and geospatial specialists have investigated the integration of BIM and GIS in various research topics and practical applications, such as Smart City [16], urbanization [17], internet of things (IoT) [18], noise assessment [19], energy consumption [20], flood influence evaluation [21], and environmental data analysis [22]. Despite the great benefits of BIM and GIS integration, the process and methodology of such integration are challenging. Wang et al. [12] argue that the different focuses of BIM and GIS causes the integration challenge. The former focuses on building components while the latter—on geospatial information and environment around the building. BIM is more concerned with the internal details of building projects forming micro-level data, whereas GIS is specialized in geospatial analysis. Nevertheless, BIM and GIS have great potential to be used together for the robot navigation and positioning. GIS would provide geo-referenced locations enabling robots to generate a navigation path, and BIM—semantic and geometrical information of the building or infrastructure, thus helping robots to detect obstacles and ultimately generating a navigable path.

This study is the first stage of a larger research project aiming at using BIM and GIS for robots' positioning on construction sites in order to reduce the complexity of the current navigation generating methods by using the common digital environment of the construction project. To be able to define the research focus, initially, current studies in BIM and construction robotics and their characteristics are investigated. Then, GIS and construction robotics are explored to examine how GIS can contribute to construction robots' navigation. In addition, the related works with regard to BIM and GIS integration are studied to examine the current solutions and to identify existing limitations. The research contributes to the scientific knowledge on robots' navigation on a construction site by systemizing the-state-of-the-art in the domain, and by identifying the requirements of robot's navigation on construction sites, integrated with BIM and GIS. The practical application of the projected results will make possible the automatic construction of more complex and 'real-life' building elements, integrating heterogeneous building systems. Ultimately, this has the potential to affect positively the productivity, health and safety on construction sites, as well as the quality and sustainability of a project.

## 2 Methodology

The methodology used in this study is Systematic Literature Review (SLR), which is defined as the identification, evaluation, and interpretation of a field of research that can be reproduced with the same protocol by other researchers [23]. The utilized SLR employs a combination of qualitative analysis [24] and bibliometric network visualization referred to as "science mapping" [25]. The former focuses on qualitatively examining the papers collected through science mapping co-occurrence method, and the latter provides a comprehensive overview of the status in the field. Common methods studied in science mapping are "keyword co-occurrence," "citation relations," and "co-authorship relations." Bibliometric network visualization facilitates the analysis of a vast number of scientific networks by visualizing patterns systematically in bibliographical databases [26]. Science mapping is capable of denoting the potentials of a specific field. In the context of the current study it is about the potentials of BIM and GIS integration in relation to construction robot navigation and positioning. Figure 1 illustrates the overall relationships between bibliometric analysis and qualitative analysis. Keywords co-occurrence is the mutual step in both analyses. Its results in bibliometric analysis is used in qualitative analysis in order to identify the most relevant articles.

Figure 2 illustrates the overall methodology used to identify the most relevant papers to be investigated in the context of the qualitative analysis of this study. In the first phase, this methodology uses the keywords co-occurrence conducted in the bibliometric analysis.

As presented on the figure, the initial keywords co-occurrence analysis is performed on the Web of Science database. It allows for new keywords to be added to the paper identification process. This yielded 236 papers. At the next step, after having identified the journals whose focus is the closest to our target domain, the search is extended to include the following databases: Scopus, Engineering Village, IEEE and the ISARC proceedings, thus resulting 1730 papers. After eliminating the duplicated and the inclusions, we obtain 1021 papers. Their titles, keywords and abstracts are then carefully read to determine their relevance to the targeted domain. Thus, finally, 64 scholarly papers are qualitatively analyzed. The following points present in detail the methodology and the results of the science mapping part of this research.

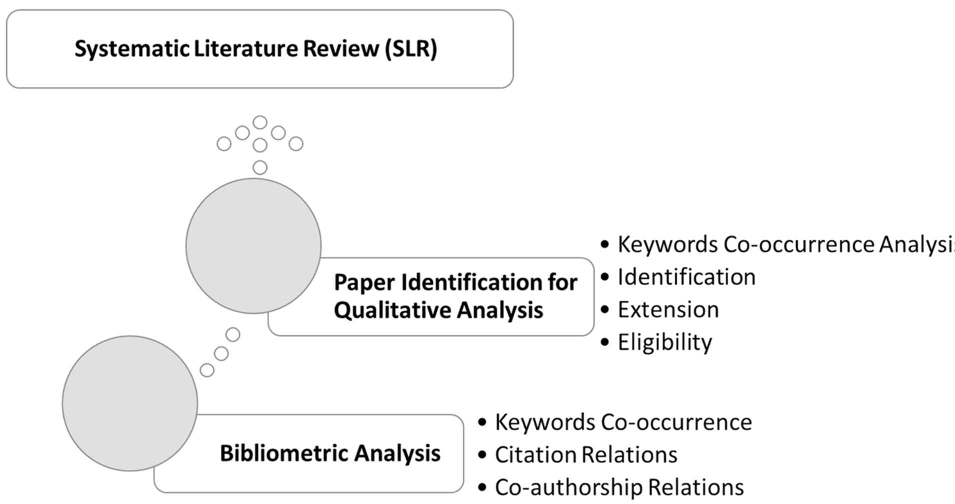



**Fig. 1** Overall Relationship of the SLR methodology with bibliometric and qualitative analyses

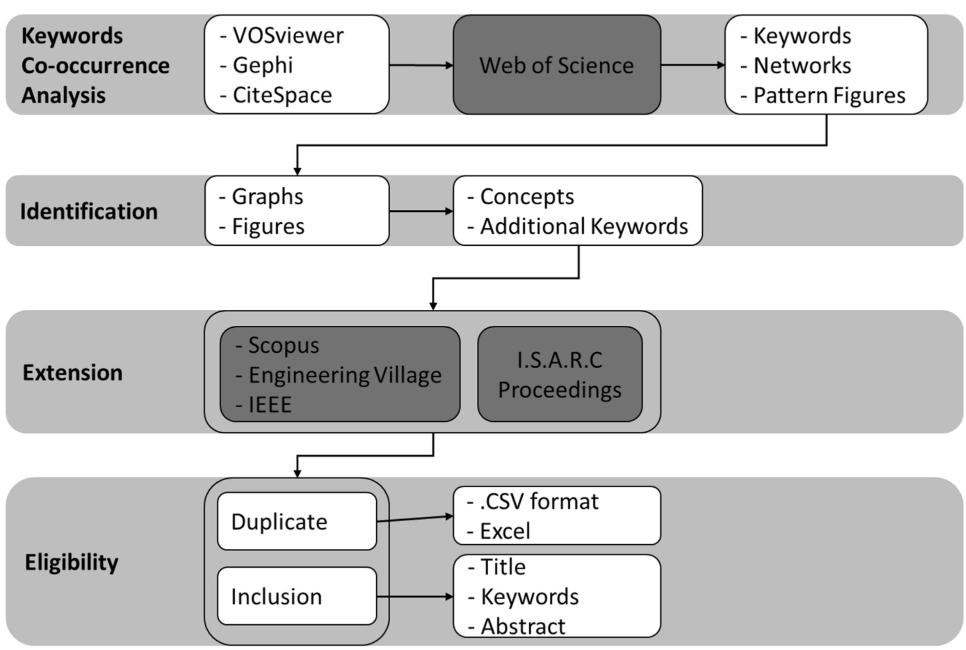



**Fig. 2** Context determination framework to search relevant scholarly journals

## 3 Keywords Co-occurrence Analysis

The purpose of this analysis is to provide a holistic overview of construction robots' navigation and positioning employing BIM and GIS integration. The search strategy is initially to investigate robots' navigation with BIM–GIS integration together. It gave an empty result (0 papers). Hence, to attain the aforementioned goal, the bibliometric study is divided into 3 keyword clusters to investigate their relation with each other. In this step, each category is explored to include the most relevant papers for the qualitative analysis presented in Sect. 4.2.

- **BIM and Construction Robotics:** (bim OR "building information model*") AND (automat* OR robot* OR "digital fabrication" OR dfab) AND (navigat* OR traject* OR path*)

  As illustrated on Fig. 3, the combination of BIM and construction robotics comprises various subdomains, which indicates the applications and the potentials of BIM in construction automation especially in construction robotics. Figure 3, also reveals various technologies employed for robots. It illustrates that "navigation" is a field of study that researchers work on, and suggests that the application of BIM in the construction industry can be related to robot navigation. Additionally, Fig. 3 denotes adjacent subdomains around it, namely: "point cloud", "path planning", "indoor navigation", "indoor modeling". To explore the application(s) of BIM in CR, scholarly papers categorized under each subdomain are identified and subsequently a qualitative analysis is conducted to investigate features and functions in this regard.
- **GIS and Construction Robotics:** (gis OR "geographic information system*") AND (automat* OR "construct* robot*" OR "digital fabrication" OR dfab) AND (navigat* OR traject* OR path*)

  Figure 4 demonstrates the hidden concepts of GIS and construction robotics and how GIS helps navigating and positioning robots. Similar to BIM and construction robotics keywords analysis, one important application of GIS in robotics is "navigation". The other concepts such as "path planning," "digital elevation models," "algorithm," "tracking," "gps," "remote sensing" play different roles in GIS and construction robotics domain. To understand the functions of each concept in navigating construction robots with GIS, detailed qualitative analysis is carried out (in Sect. 4.2) to identify features and methods presented in the papers.
- **BIM and GIS:** (bim OR "building information model*") AND (gis OR "geographic information system*")

  Many subdomains of the BIM and GIS interaction are revealed on Fig. 5. The purpose of conducting this analysis is to collect data needed to integrate building information models and geographic information system in the desired research direction. Figure 5 indicates the current applications of such an integration. "facility management," "layout," "smart city," "optimization," "integration," and "indoor" are some of those. It is also important to mention that IFC (Industry Foundation Classes) and CityGML (City Geography Markup Language) are open standard data model and exchange format for BIM and

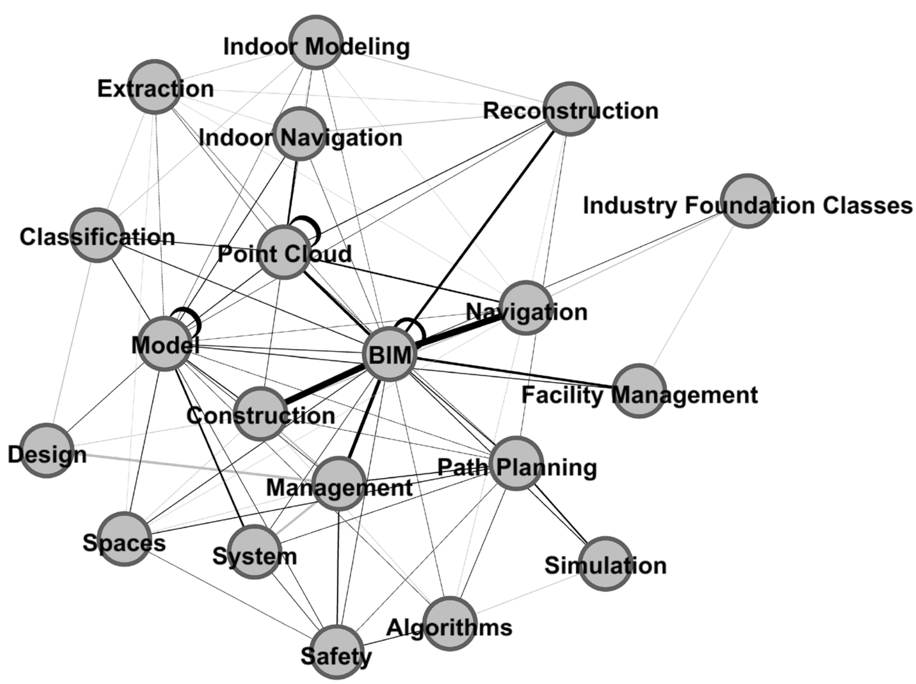



**Fig. 3** Keywords network of BIM and construction robotics

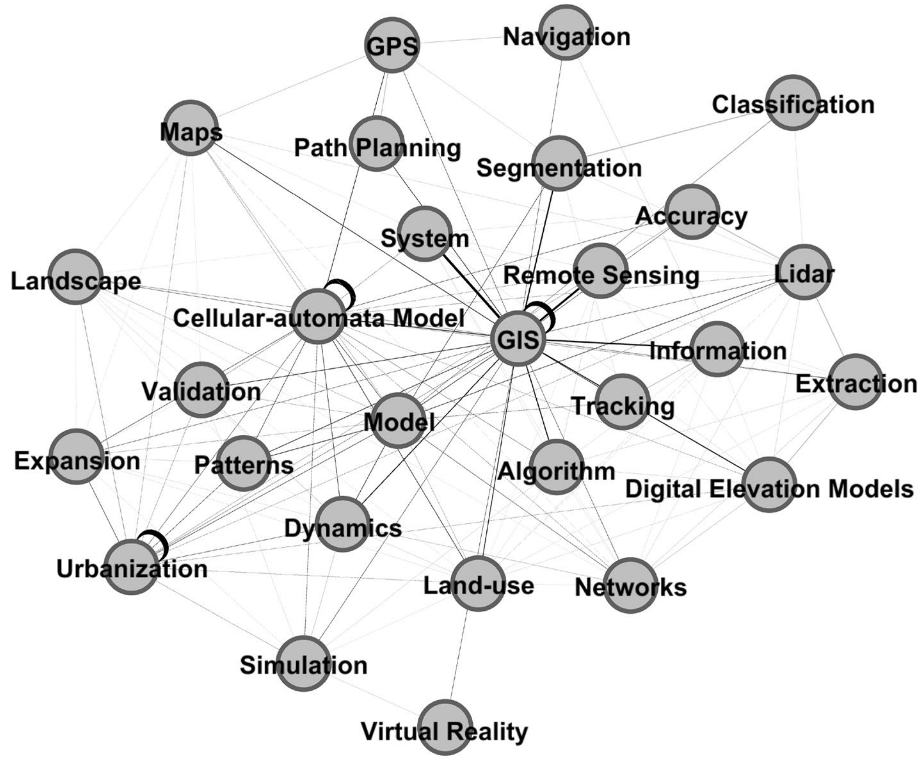



**Fig. 4** Keywords network of GIS and construction robotics

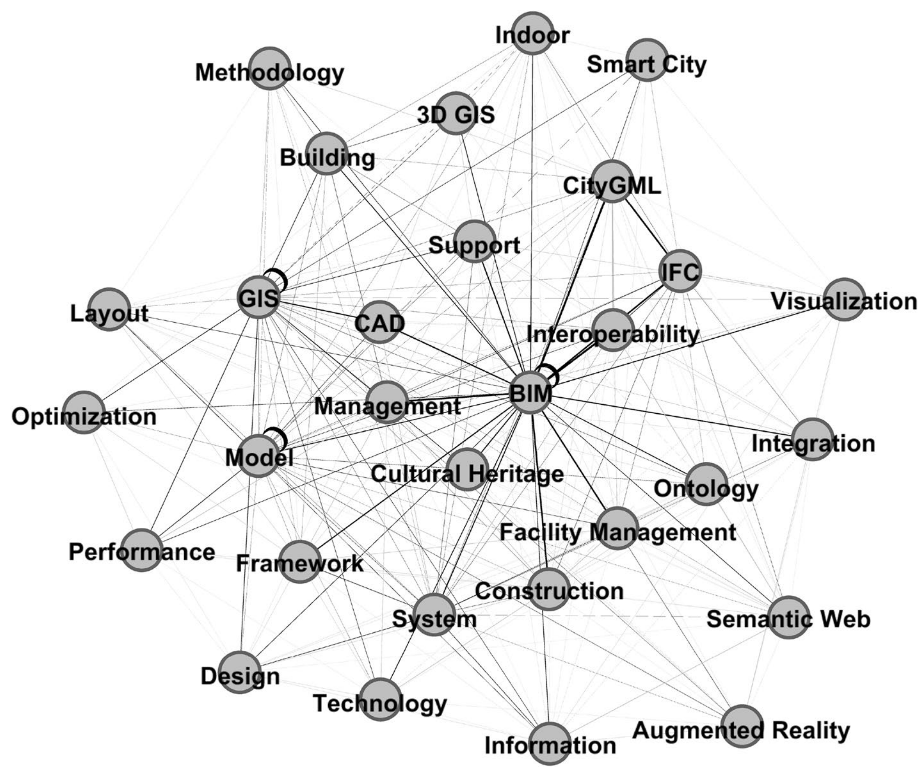



**Fig. 5** Keywords network of BIM and GIS

GIS respectively. Both appear in the keywords network as subdomains. As the two previous categories presented, journal papers categorized under each subdomain is studied qualitatively to provide a comprehensive understanding of current contributions and requirements of integrating them.

All the sets of data derived from Web of Science Core Collection, initially, are submitted to VOSviewer to construct a co-occurrence network of keywords, subsequently, are imported to Gephi to create customizable and detailed visualization and more importantly to run further analysis. With Gephi computing tool, similar concepts such as "building information modelling", "building information modelling" and BIM are merged.

Cobo et al. [26] provide a review of a number of available tools for the purpose of bibliometric analysis, namely: Bibexcel, CiteSpace, CoPalRed, IN-SPIRE, Leydesdorff's Software, Network Workbench Tool, Sci$^2$ Tool, VantagePoint, VOSViewer. The authors conduct a survey to find the advantages and drawbacks of each of the above-mentioned tools. In addition, Van Eck and Waltman [25] compare two "general network analysis tools"—Pajek [27] and Gephi [28] in order to analyze the visualize networks. The authors conclude that Gephi provides more tools on detailed customizable visualization compared to Pajek [25]. According to the above-mentioned analysis and for the purposes of this study, VOSViewer, CiteSpace, and Gephi are selected to perform the bibliometric analysis.

- VOSviewer is devised to constitute and map bibliometric data [29].
- Gephi enables the researcher to carry out deeper analysis on mapped graphs and to make modifications to the networks [30].
- CiteSpace analyzes the trends developing in a specific domain. It also manages to visualize various network layouts, detects clusters and analyzes within a given time period [31].

The Web of Science Core Collection is selected as the preliminary database to run keywords co-occurrence by VOSviewer due to its flexibility to search various combinations of terms, its thorough journals [1] and its compatibility with VOSviewer computing tool. Furthermore, Web of Science Core Collection enables authors to investigate the peer-reviewed, high quality scholarly articles from all over the world. Other widely known databases such as Scopus, Engineering Village, IEEE, and I.S.A.R.C. (International Symposium for Automation and Robotics) proceedings are included later to make this research as thorough as possible (see Sect. 3.3).

A keywords network is generated by running co-occurrence type of analysis on the dataset to constitute a graph based on the keywords. The nodes of the graph indicate the fields of research and the subdomains of which they consist. This is useful for identifying underlying concepts, adjacent topics and hidden links between themes; to illustrate the potentials and more importantly to determine the context of research for qualitative analysis. The fundamental step of bibliometric analysis is to determine the contexts of research, which are relevant to the objective of the survey. In other words, the choice of keywords for the search in the databases, models the entire bibliometric analysis [26].

### 3.1 Identification

Once the keywords network is formed, the subdomains and their keywords identified, the search proceeds a step forward and refines the context determination to the desired ones. Based on the procedure described in Sect. 3.1, Web of Science Core Collection refinement provides the articles, which are the relevant ones to the scope of the study. It is noteworthy to mention that the identified papers are published by 2020. The papers collected by now are the only ones available in Web of Science Core Collection, but they still do not provide a comprehensive outlook to the field, so the search is extended to other databases.

### 3.2 Extension

To enable the literature to synthesize as many as possible related works, Scopus, Engineering Village, and IEEE (Institute of Electrical and Electronics) are added to the search. The I.S.A.R.C. (International Symposium for Automation and Robotics in Construction) proceedings are included too, as the papers published there represent the advances, contributions, and concerns of the researchers for all fields of construction with great concentration on Construction Automation, Robotics, IT, etc. [32].

### 3.3 Eligibility

Eligibility comprises two main steps, which are the identifications of duplicates and inclusion. The former identifies and subsequently removes the duplicated articles from the database and the latter only brings the papers which are precisely to the point of current study into consideration, which is the application of BIM and GIS integration in robots' positioning on construction sites. Although the number of scholarly papers remarkably increased in the extension phase, there are for sure many articles, which are duplicated in the different databases. To tackle this problem, all the databases' information is downloaded and is converted to.csv format in order for Excel to identify the duplicate ones and remove them. The I.S.A.R.C proceedings do not provide such export format so this procedure is done manually.

The final step is to submit only those articles studying, partially or thoroughly, the focus of the current research to qualitative analysis. To reach this objective, all the articles available so far are filtered based on their titles, keywords, and abstracts.

# 4 Findings

## 4.1 Bibliometric Analysis of BIM–GIS Integration

The Science mapping provided in this section is conducted on 236 papers of BIM and GIS from Web of Science Core Collection to provide a generic comprehensive overview of the field. The first study on Building Information Modeling and Geographic Information System occurred in 2008, carried out by Lapierre AND Cote [33], and is published by "URBAN AND REGIONAL DATA MANAGEMENT." As it is illustrated in Fig. 6, from 2008 to 2019, there has been an important growth of the research in the field. In 3 years, during 2014 to 2017, a sharp increase has occurred which implies an exceptional interest of researchers in BIM and GIS together. It also interesting to note that based on the forecasting line provided, it is predicted that this growth continues. New fields of BIM and GIS integration might emerge, or current solutions might be considerably improved.

### 4.1.1 Keywords Co-occurrence Analysis

Following publishers' requirements, the authors of scientific papers indicate their research focus through keywords. In bibliometric studies, the analysis of the keywords shows the width of the research domain, and draws the boundaries in that specific domain [34]. Graphs constituted by related keywords illustrate the relationships among subdomains existing in the studied field [25]. Hence, an analysis is performed based on the keywords co-occurrence method. Every couple of nodes (keywords) is linked via an edge and each edge carries a weight. The number of publications in which two keywords occur together is represented by weight metrics [25].

In this research, VOSviewer software visualizes and shapes the networks of subdomain studies based on the data retrieved from Web of Science Core Collection. Gephi is employed in order to conduct further data analysis of the file exported from VOSviewer. Within Gephi environment, similar areas of studies (such as "geographic information system (gis)", "geographic information system", and "gis") are merged. The result is a graph comprising 30 nodes illustrated in Fig. 7.

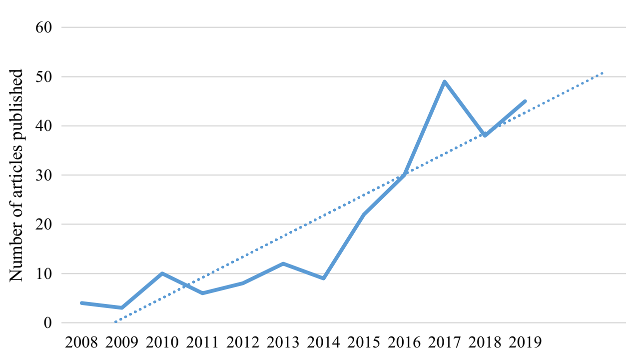



**Fig. 6** Distribution of papers over years (*Source*: Web of Science Core Collection)

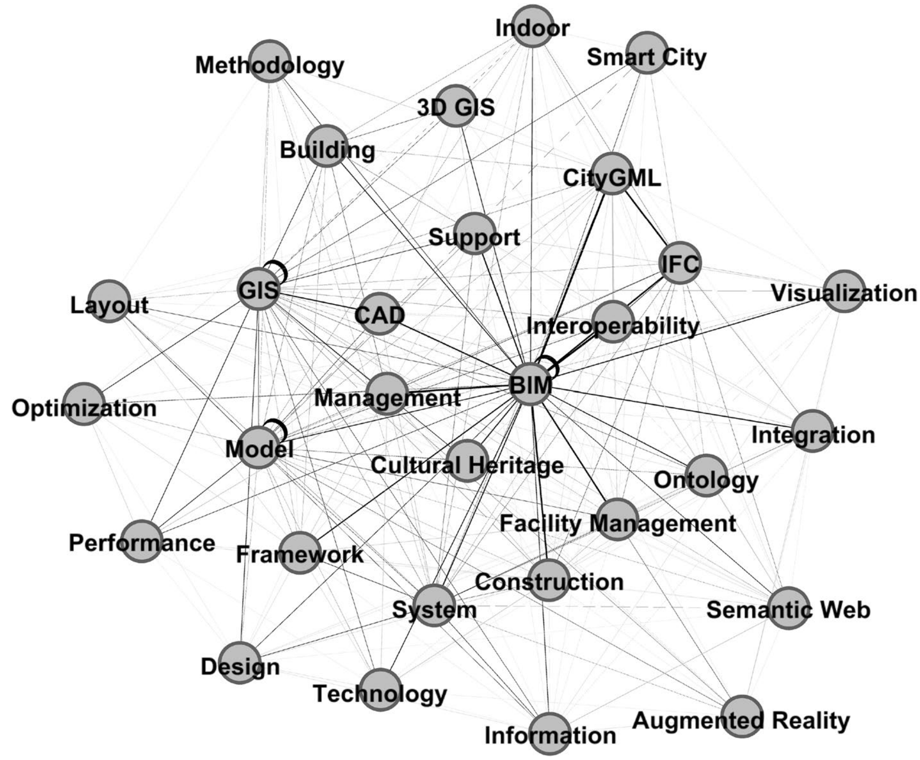
Gephi is capable of analyzing various statistics on a given network. The weighted degree of a node represents the weighted number relations (edges) it has [35]. In other words, the higher the number of weighted degree of a relation is, the more influential that domain is. A 'data laboratory' of Gephi consisting of the metric analysis of the graph on Fig. 7 is presented in Table 1. Moreover, different layouts are available for different purposes in accordance with features of topologies [36]. The current analysis emphasizes the rankings of the research areas. The visualization of the data, therefore, is based on the ranking of the nodes.

Based on the information provided by bibliometric analysis, the following conclusions can be made:

1. The integration of BIM and GIS environments in construction has attracted a great amount of attention in recent years, but its potential applications in construction automation and construction robots' positioning has not been studied. As seen from the keywords subdomains table (apart from BIM and GIS, which are the focal fields of this literature review), "citygml", "management" and "interoperability" attracted higher attention. In addition, analysis of the node weighted degree reveals that these three research areas have much higher relative importance compared to all the others. On the other hand, less attention has been paid to "cultural heritage", "methodology", and "smart city" indicating that researchers investigated these research areas less frequently within the body of the existing literature. More importantly, Fig. 7 and Table 1 denote that construction automation is not one of the studied sub-domains and hence, requires more attention from researchers.
2. The research areas which are in the middle of Table 1 depict the potential areas in BIM and GIS integration. "Augmented Reality", "Facility Management", and "layout" are examples of such potentials. However, other areas, which are not listed in Table 1 are either not investigated or received much less attention, which shows the research gaps in this field.

   Other finding of this scientometric analysis reveal that a great deal of research is directed towards the "management" aspect of construction projects. Table 1, however, denotes that many authors have contributed to the domain by investigating "interoperability" of BIM and GIS, indicating one of the obstacles for the integration of the two digital environments. On the other hand, the "smart city" facet of BIM and GIS integration has one of the lowest weighted degrees (see Table 1) revealing

**Fig. 7** Core research focus—BIM and GIS




that applications of BIM and GIS integration have been more studied in "building" projects rather than in "city planning" even though it could be utilized for both small and large scale projects.

3. As shown on Fig. 7, "ifc (Industry Foundation Classes)" and "citygml (City Geographic Markup Language)" are two data schemas being used for BIM and GIS integration. The former is the open-format standard data schema for BIM and the latter has been developed for GIS interoperability. The bibliometric visualization of the literature database denotes that every region, where several nodes are located close to each other, establishes relationship within the area. For instance, "integration," "interoperability," "ifc", "citygml" and "semantic web" are located close to each other within the network (see Fig. 7) indicating that authors used semantic web technology to enable integration of BIM and GIS with IFC and CityGML schemas.

### 4.1.2 Document Co-citation Analysis

The document co-citation method reveals citation patterns among research studies and provides information regarding the intellectual structure of the studies [37]. Creating a network of document co-citation analysis is a common approach for providing this kind of information via science mapping [37]. CiteSpace is the selected software to conduct this analysis by creating citation clusters which is the most common method for network of co-citation analysis [38]. Figure 8 visualizes the paper clusters computed by CiteSpace, using the Log-Likelihood Ratio (LLR) algorithm. In statistical analysis, a log-likelihood ratio is a test to identify a null model against an alternative model [39]. LLR algorithm is mainly used to calculate p-value to decide on rejection of a null model [39]. In this regard, after using "filter out small clusters", eight clusters (out of 61) are detected as the main research areas where cluster #0 is the largest in terms of size, indicating that this cluster contains the largest number of publications, while cluster #8 is the smallest cluster of the important ones. The labels attached to clusters of Fig. 8 are proposed by CiteSpace. It should be mentioned that CiteSpace focuses on formation of clusters rather than on the underlying contents in the given clusters [37].

Metrics evaluated by CiteSpace computing tool are Modularity $Q=0.7127$ and Mean Silhouette $=0.5206$. The metric modularity ($0<Q<1$) indicates to what extent a network is capable of being independent [40]. The amount of modularity represents the quality of a network's structure meaning that modularity close to 1 indicates a network is well-structured while modularity close to 0 illustrates unclear cluster boundaries within a network [37]. Table 2 illustrates the details of clusters retrieved from CiteSpace.

The other metric "Silhouette" represents the uncertainty of a given cluster and is ranged from $-1$ to 1, meaning that a silhouette close to 1 indicates a cluster well separated from other clusters, whereas a silhouette close to $-1$ introduces

**Table 1** Ranking of the subdomains in relation to BIM–GIS integration

| Label | Degree | Weighted degree |
|---|---|---|
| BIM | 31 | 52.96 |
| GIS | 31 | 16.38 |
| CityGML | 21 | 15.33 |
| Management | 23 | 12.98 |
| Interoperability | 19 | 12.21 |
| Model | 29 | 11.93 |
| Construction | 23 | 11.48 |
| IFC | 15 | 11.11 |
| Facility management | 19 | 10.32 |
| Support | 20 | 9.49 |
| System | 21 | 9.37 |
| Framework | 18 | 9.00 |
| CAD | 9 | 7.00 |
| Information | 17 | 6.66 |
| Semantic web | 19 | 6.50 |
| Design | 17 | 6.40 |
| Integration | 17 | 6.35 |
| Ontology | 14 | 6.35 |
| Performance | 9 | 5.82 |
| Technology | 12 | 5.52 |
| Building | 10 | 5.21 |
| Visualization | 13 | 4.96 |
| Indoor | 16 | 4.77 |
| 3D GIS | 8 | 4.49 |
| Layout | 13 | 4.34 |
| Augmented reality | 14 | 4.26 |
| Optimization | 9 | 4.05 |
| Cultural heritage | 7 | 4.00 |
| Methodology | 10 | 3.09 |
| Smart city | 8 | 2.76 |

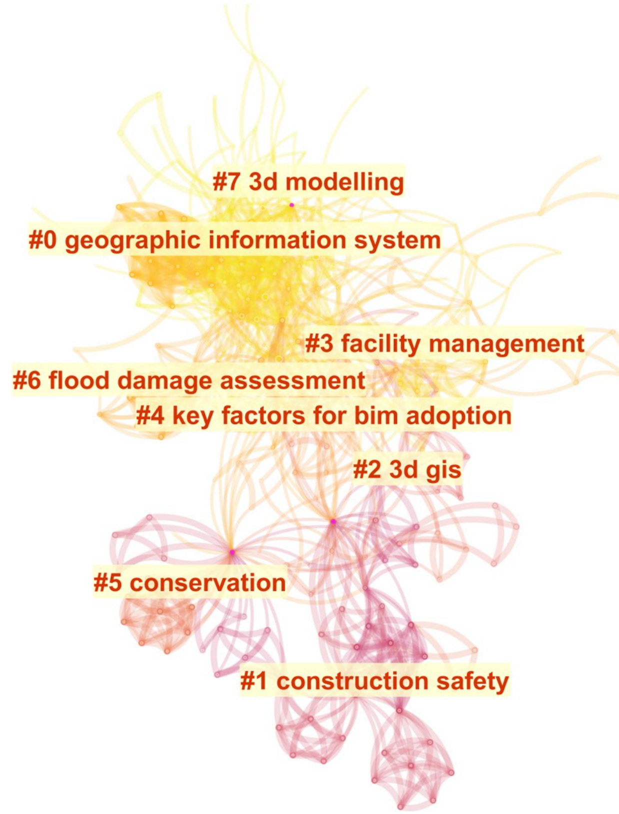



**Fig. 8** Clustering structure of BIM and GIS integration

**Table 2** Core clusters of document co-citation analysis if BIM and GIS

| Cluster ID | Size | Silhouette | Mean year | Focus of cluster |
|---|---|---|---|---|
| 0 | 89 | 0.705 | 2014 | Geographic information system |
| 1 | 29 | 0.918 | 2006 | Construction safety |
| 2 | 29 | 0.838 | 2008 | 3D GIS |
| 3 | 28 | 0.845 | 2013 | Facility management |
| 4 | 28 | 0.800 | 2011 | Key factors for BIM adoption |
| 5 | 27 | 0.954 | 2008 | Conservation |
| 6 | 22 | 0.870 | 2010 | Flood damage assessment |
| 7 | 15 | 0.857 | 2014 | 3D modelling |

heterogeneity of members within a given cluster [41]. By interpreting aforementioned information of the study (Fig. 8; Table 2), the following results can be formulated:

4. By applying document co-citation analysis, the number of articles considered for the clustering are more than the number of articles in the database indicating the fact that there are some that appear in more than one cluster. This indicates that the studies have high integrity and research endeavors took benefit from the previous ones meaning that the research in BIM–GIS integration is built on the studies conducted before. Results of studies conducted in the field of BIM and GIS reflect that researchers exchange their ideas and focus on the field. However, investigators have not studied potentials of BIM and GIS integration in relation to construction automation, which needs to be investigated.

5. An overview on the Mean Year indicates on what subdomain researchers focused during the years. Document co-citation analysis of BIM–GIS integration reveals that the recent attempts are mainly slanted towards Geographic Information System, 3D Modelling and Facility Management. Also, construction safety appears as the one of the earliest applications of BIM–GIS integration studied by researchers. Other research focuses are also complied in the list on Table 2. Citation patterns of BIM and GIS integration (see Fig. 8) reveal that authors of

existing literatures have not investigate the construction automation relations with BIM–GIS integration domain and there exists a lack of exchange of ideas between these two domains.

6. Given the structure of the clusters demonstrated in Fig. 8, BIM–GIS studies indicate a relatively high structural integrity. Silhouette values indicated in Table 2 show that clusters of the visualized network are connected through citations inside and outside of their clusters. As Hicks [42] argues, such structure of clusters occurs when authors cite studies from other clusters, which creates a well-formed citation pattern of a given field. Therefore, as BIM–GIS forms well-structured clusters, this draws a promising future of the field.

#### 4.1.3 Direct Citation of Sources

Direct citation of sources indicates prominent journals in a field of study [25]. Identification of prominent journals is beneficial to readers, authors, and editors. It enables readers to select which journals are focused on their field of study in order to find creditable articles, and it indicates to authors where to publish their studies in order to reach more potential readers in their field [43].

Among Gephi's statistics, HITS (Hyperlink-Induced Topic Search) algorithm is capable of rating web pages [44]. The HITS metric calculates two values for a web page; authority and hub value. By estimating "authority" Gephi provides each node (journal) a score indicating the value of the content within the journal. It also provides a "hub" value for outgoing links of each node (journal) indicating the value of links [45]. Figure 9 illustrates 10 prominent journals in the field of BIM and GIS integration ranked based on the score calculated by Gephi using the HITS algorithm.

Table 3 also illustrates the top journals of the field accompanied by their rank, "authority" value, "hub" score, and the main research areas of each one. The most important outlet of the field is by far "Automation in Construction" with highest hub score (0.772) and highest weighted out degree (71.0). To provide better insight of each journal's research areas, their subdomains are also listed in the table. This helps authors and readers to refine their choice of journals to either publish their work or to read about their field of research. The HITS analysis in Gephi shows the following results:


**Fig. 9** Graph of prominent journals in BIM & GIS

**Table 3** Prominent journals of BIM and GIS

| Rank | Journal | Weighted out degree | Authority | Hub | Research areas |
|---|---|---|---|---|---|
| 1 | Automation in construction | 71 | 0.043792 | 0.772793 | Construction building technology, engineering |
| 2 | ISPRS International Journal of Geo-information | 22 | 0.486019 | 0.379324 | Physical geography, remote sensing |
| 3 | Building and Environment | 9 | 0.222176 | 0.358016 | Construction Building Technology, Engineering |
| 4 | Computers in Industry | 8 | 0.325105 | 0.267654 | Computer Science, Engineering |
| 5 | 5th International Conference on 3D Geo-information | 8 | 0 | 0.152319 | Image Science Photography Technology, Physical Geography, Remote Sensing |
| 6 | eWork and eBusiness in Architecture, Engineering and Construction | 6 | 0.222176 | 0.139729 | Computer Science, Construction Building Technology, Engineering |
| 7 | Journal of Computing in Civil Engineering | 1 | 0.434159 | 0.127924 | Construction Building Technology |
| 8 | Buildings | 0 | 0.222176 | 0 | Computer Science, Engineering |
| 9 | Journal of Information Technology in Construction | 0 | 0.444958 | 0 | Engineering |
| 10 | Journal of Spatial Science | 0 | 0.33123 | 0 | Physical Geography, Remote Sensing |
| 11 | Urban and Regional Data Management | 0 | 0.109054 | 0 | Remote Sensing, Engineering |

The analysis of the network in Fig. 9 can be interpreted as follows:

7. The majority of the articles in BIM and GIS integration are published in two journals namely, *Automation in Construction and ISPRS International Journal of Geo-information.* It is worthy to note that comparison between "weighted out degree" values of these journals shows that flow of information begins from *Automation in Construction* rather than *ISPRS International Journal of Geo-information* with a high difference (see Table 3).
8. The investigation of BIM and GIS integration with regard to construction automation is a focus of study of none of the journals. This fact corroborates the findings of current literature in previous sections that potentials of BIM and GIS integration from construction automation view has not been studied sufficiently. This fact confirms that more attention needs to be paid for applications of BIM–GIS in construction automation.

### 4.1.4 Co-authorship Analysis

Conducting a co-authorship analysis enables researchers to explore and investigate the collaboration networks of pioneer researchers, institutions, and countries to acquire more profound knowledge of the field, develop expertise, increase productivity, and decrease isolation [46]. Additionally, it would be worthy to the scientist who are carrying out research in a specific field to identify the prominent researchers, institutions, and countries to keep track of innovations, novel approaches, or recently developed ideas. Luwel [47] argues that co-authorship analysis provides thorough investigation of scientific collaboration which ultimately leads to higher productivity of the work, higher citation, and attraction of attention. Based on what is discussed above, the following part of the literature analysis is divided into 3 sections namely, pioneer researchers, pioneer institutions, pioneer countries with regard to BIM and GIS integration.

**4.1.4.1 Pioneer Researchers** As Fig. 10 illustrates, there are two major clusters of collaborating researchers in the reference field. Each of the clusters introduces, directly or indirectly, prominent authors in BIM and GIS integration. Direct indication of co-authorship refers to papers the authors published in collaboration, while indirect co-authorship refers to having mutual co-authors. Additionally, HITS algorithm is run to rank the prominent authors through applying authority scores [45]. Quality of the connected nodes with link to other influential nodes of the graph constitutes the authority score [48]. Gephi ranks the nodes with authority score to visualize the prominent researchers in terms of their influence to the field. Thus, the following interpretation can be made of the results shown on Fig. 10:

9. The majority of the BIM and GIS integration researchers collaborate. However, an integral network of collaboration is far to be present. Some isolated authors should identify the collaboration networks in order to be able to enhance their productivity. Nearly 40% of the authors have established a strong relationship working in BIM

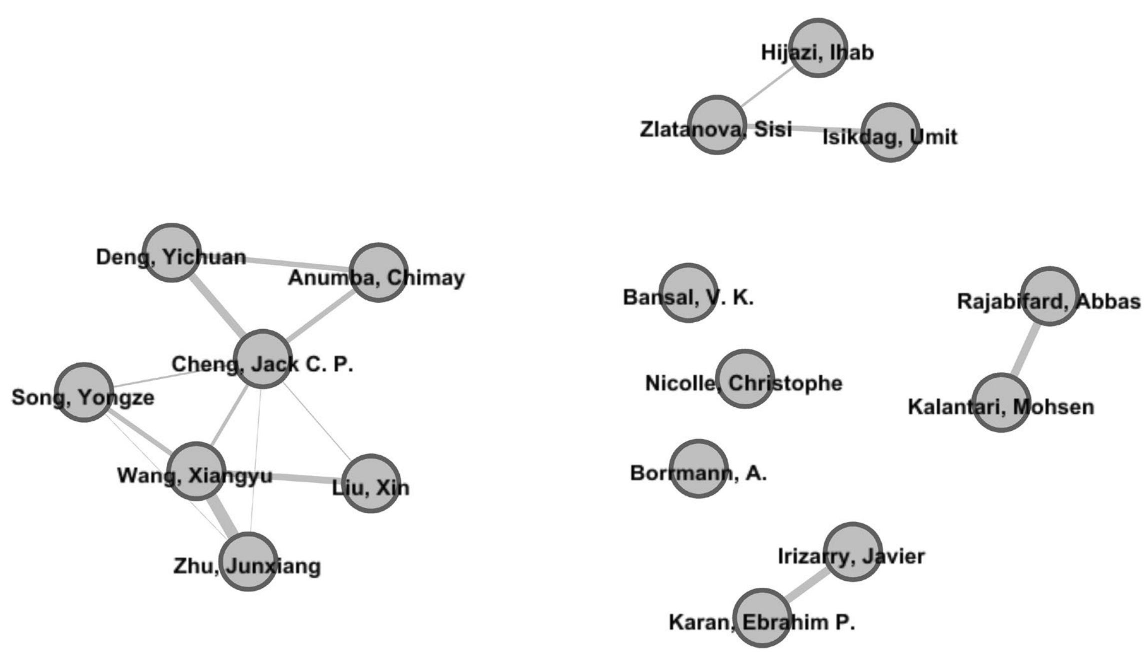



**Fig. 10** Prominent researchers in BIM and GIS

and GIS, which provides prospects for improving productivity of the field in future. Nevertheless, there are a few authors who do not belong to any cluster reflecting the fact that those authors of the network (Fig. 10) are carrying on the research in isolation.

**4.1.4.2 Pioneer Institutions** Similar to individuals' collaboration in the BIM and GIS domain, a network of institutional collaboration can be created to identify the prominent universities and institutes around the world. As Fig. 11 illustrates, the HITS algorithm ranks the institutions based on the "hub" score to show the influence of the nodes' actors [45]. The size of the nodes represents the "hub" score showing the influence of the institution on others. Interpretation of the HITS algorithm analysis along with the network demonstrated in Fig. 11, shows that:

10. Apart from the four isolated ones, the majority of the institutions working on BIM and GIS collaborate. However, this collaboration does not establish a strong relationship among them (visualized by the low number of connections). This indicates one of the problems in the field. Solving this lack of collaboration has the potential to result in significant progress and productivity improvement of the BIM and GIS integration field.

**4.1.4.3 Pioneer Countries** Following a procedure similar to the one identifying prominent researchers and pioneer institutions, Gephi reveals the influential countries in the BIM and GIS integration domain. Directed and undirected edges map the flow of information and closeness among countries (as shown on Fig. 12). Co-authorship analysis of countries can contribute to redefine strategies and to establish policies to improve productivity. Based on the statistical analysis and the graph illustrated in Fig. 12, the results can be interpreted as follows:

11. Taiwan is the only country, which does not work in collaboration with other prominent countries, while the United States connects with all countries. In addition, the flow of information correlates with the USA, which is the most prominent country in BIM and GIS integration.
12. According to the average degree values calculated by Gephi, Canada can be categorized as a country where BIM and GIS integration has not been greatly studied. About 5% (13 out of 236) of the investigated articles are developed in Canada. The names and affiliations

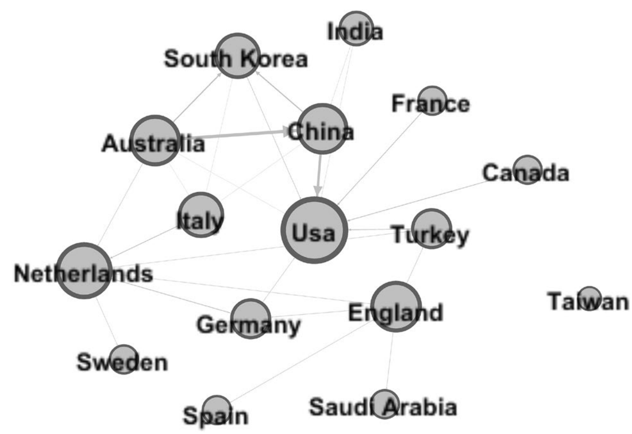



**Fig. 12** Pioneer countries in research on BIM and GIS integration

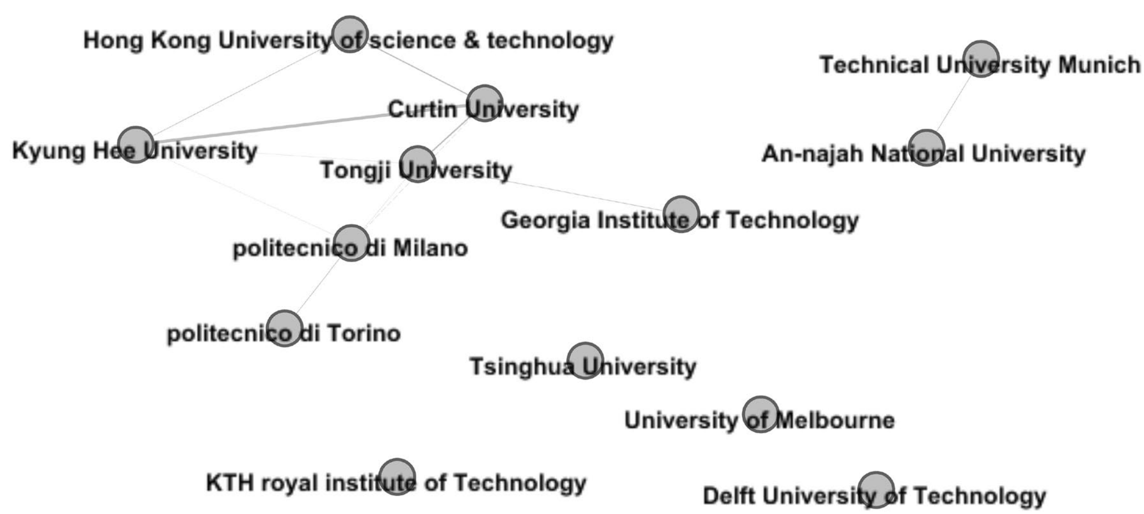



**Fig. 11** Pioneer institutions of BIM and GIS

of the authors with more than 2 published papers are listed in Table 4:

The data on Table 4 implies that BIM and GIS integration field has not been broadly studied in Canada, so more investigations needs to be carried out in this domain.

## 4.2 Qualitative Analysis

Section 3.1 of the current literature review adopted bibliometric analysis to investigate the integration between BIM and GIS. The systematic literature review identified the most relevant articles to the research topic to study in depth the contributions to the field. In what follows, these papers are classified into three categories for explicit distinction between different subdomains, namely: BIM and robotics, GIS and robotics, and BIM and GIS in relation to robots' positioning and navigation on construction sites.

### 4.2.1 BIM and Robotics

The purpose of the current literature review is to investigate the potentials of BIM–GIS integration in relation to construction automation especially in robot's navigation on construction sites. After having a comprehensive bibliometric analysis of the BIM and GIS integration domain, this section is to qualitatively investigate, in depth, the previous contributions of researchers regarding the applications of BIM in robots' navigation. The application of GIS is investigated afterwards. This section describes the previous research attempts followed by the interpretations of the studied papers.

Delbrügger et al. [49] have developed a BIM-based navigation framework for digital twins of factories. It comprises of building information model and factory equipment classified as fixed and dynamic. In addition to BIM, the proposed framework incorporates pathfinding technology. The authors have developed a navigation core utilizing two approaches namely, corridor map method and navigation mesh. The former refers to convex polygons covering navigable surfaces, which are mainly triangles [50] and the latter represents edges as navigation corridors with a free space for collision-avoidance provided by a sphere [51]. The navigation framework for digital twins of factories improves the IFC-format imported files by initially importing the ifcXML file to IFC Engine [52] and subsequently submitting the file into VEROSIM [49]. VEROSIM supports IFC and CityGML files to run simulation for spatial analysis [53]. Delbrügger et al. [49] classify building components as navigable surfaces and objects as either obstacle or agent. Obstacles can be either static or dynamic. They have also developed a scene content containing all the possible components in factories and mapped each element to navigation criteria.

Ibrahim et al. [54] have developed interactive model-based path planning for Unmanned Aerial Vehicles (UAV) to capture data on construction sites. They use a semi-automated approach with a drone to capture visual data on construction sites. Interoperability problems have been eliminated using a web platform technology. With a mobile application, used to plan the flight, the proposed system integrates web platform with visual model derived from the UAV's camera to compare the construction progress with the schedule. A BIM model is used to plan the aerial trajectory in order to inspect the related sectors of the construction sites.

Darwish et al. [55] have created a framework in which RGB and depth (RGB-D) sensors are used to visualize indoor environments, taking structural constraints into account. They propose two main purposes of the RGB-D sensors namely, robot collision avoidance within indoor environment [56] and 3D model reconstruction [57]. Darwish et al. [55] focus on the latter application in their proposed framework, which considers all the features in RGB and depth images to reconstruct an indoor environment.

Nahangi et al. [58] present a method with which UAV localization and navigation can be tackled in GPS-denied indoor construction environments. The proposed method uses connected coordinates of BIM model with AprilTags. With UAV's camera, the data of tags are captured and are transformed so that the UAV can localize. The authors confirm that the Global Positioning System (GPS) is accurate and reliable for outdoor environments, but inefficient for the indoor ones. AprilTags is a visual fiducial system in which the tags can be ordinarily printed. The coordinates of the tags correspond with those in a BIM model so that the UAV is able to localize itself in global coordinate system [58]. In

**Table 4** Prominent researchers of Canada in BIM and GIS integration

| Author | Affiliation | Number of publications | Publication year |
|---|---|---|---|
| Hammad. A | Concordia University | 2 | 2016, 2017 |
| Salimzadeh. N | Concordia University | 2 | 2016, 2017 |
| Pottinger. R | University of British Columbia | 2 | 2017, 2018 |
| Staub-French. S | University of British Columbia | 2 | 2017, 2019 |
| Zadeh. PA | University of British Columbia | 2 | 2017, 2019 |

order to localize the UAV, an on-board camera is employed to detect the AprilTags.

Lin et al. [59] have developed a method for automatic generation of indoor environment employing BIM and GIS at geometry level. With integration of BIM, GIS and i-GIT algorithm, they generate several possible routes for navigation purposes. To accomplish the automatic indoor navigation, they have developed a collective algorithm named Intelligent Generation of Indoor Topology (i-GIT) which supports IFC schema and automatically generates space boundaries for vertical and horizontal navigation. A set of algorithms are employed to generate floor-level paths and non-planar paths and to reduce the complexity and redundancy of path nodes. The former refers to horizontal navigation while the latter responds to vertical navigation needs. ESRI ArcScene is utilized to identify space boundaries of the IFC file and the algorithms were run in that environment.

Siemiątkowska et al. [60] adopt a semantic approach based on a BIM model for robot delivery indoor navigation. They have developed a hierarchical action planning to incorporate time-optimized robot navigation including two technologies namely, object detection based on point cloud and object detection based on image. Both horizontal and vertical navigation are taken into account and are tested within dynamic environment. They employ BIM to extract semantic information and indoor topology in order to be able to run the hierarchical action planning.

Hamieh et al. [61] have developed BIM-based indoor path planning method named BiMov using four definition phases. The first phase identifies all possible paths within a space using algorithms run on an IFC file. The second phase reduces the number of paths by discriminating between a mobile object, a person, or a bulky equipment. The possible paths within a space are further refined in third phase based on the content of the path, which can be influenced by the presence of machinery or restricted areas. Phase 4 considers number of paths affected by real-time situation or building's passages. Although the authors presented four-stage planning regarding robot navigation within indoor environments, they put emphasis only on the first two phases.

Quintana et al. [62] have developed a method using BIM, 3D laser scanner, and a color camera to detect 3 positions of a door within indoor environment. To attain this goal, they integrate geometry and color information obtained from the environment to detect the angle of a given door, and identify it as open, semi-open, and closed. Their system also provides an accurate position of the door in the world-coordinate-system.

Kayhani et al. [63] assess the Extended Kalman Filter (EKF) to improve indoor localization using AprilTags. They use that improvement to navigate Unmanned Aerial Vehicle (UAV) within an indoor environment. They adopt a probabilistic approach towards data fusion in order to improve pose estimation accuracy. In this method, the authors employ BIM to identify coordinates of fiducial markers with a UAV equipped with camera to identify the relative pose. All the information is ultimately put together to calculate the coordinates in the global coordinate system. They use EKF to consider uncertainty, which is the characteristic of construction sites. BIM, in this approach, is specifically used to help the drone to identify the 3D coordinates of the AprilTags.

Neges et al. [64] have developed a system based on the Bluetooth Low Energy (BLE) to improve the quality of indoor location tracking on construction sites and for facility management purposes. The authors classify the work spaces systematically using a building information model and, then, place BLE beacons on different locations. The result of the study shows that the functionality of the proposed method is limited. The experiment also indicates that the signal strength and method robustness is greatly affected by the dynamic nature of construction sites and facilities.

Palacz et al. [65] propose a method to navigate indoor mobile robots using the IFC schema of BIM and a graph, combined with artificial intelligence. They argue that the structure of buildings and the semantics of building components have great influence on the possible routes between two points. This graph-based navigation approach assigns attributes to graph nodes and graph edges. The former contains semantics of building elements and the latter stores the cost of navigation between spaces dependent on different variables namely, opening width, lift existence, space distance, and door types. The authors argue that the information derived from IFC schema only includes construction elements, while other elements such as chairs, anything left on the floor, etc. should be considered. Hence, an additional algorithm could the robot navigation for passing obstacles. This contribution assumes the robot has such algorithm built in [65].

Kim et al. [66] have provided a method in which a mobile robot collects spatial data specifically developed for construction sites with many uncertainties. The proposed system uses Simultaneous Localization and Mapping (SLAM) techniques to build a map of construction site for navigation through point clouds. However, the SLAM technique does not provide obstacle-awareness for a mobile robot so that kinematic modelling of the robot is analyzed. The authors, then, develop an algorithm based on fuzzy control to navigate the mobile robot in unknown environments with obstacles. In this method, real-time 3D environment reconstruction based on laser scanning is used instead of a building information model [66].

Based on the literatures reviewed the following findings are presented:

(I) Many indoor navigation and localization methods are introduced and investigated especially with integration to BIM. Indoor localization methods can be classified in three main categories [67]:

- Wave-based propagation: comprising devices receiving waves of two frequency ranges, namely: ultrasonic and sound waves. Different types of receivers are also presented—such as radio frequency (RF), ultra-wideband (UWB), and wireless local area network (WLAN) [68–70]. Nonetheless, researchers studying the abovementioned techniques have reported several limitations with regard to accuracy. Infrared accuracy is reported at room-level (i.e. its accuracy is limited and it would not be a functional option for larger spaces) and its performance is disrupted by sunlight. WLAN and RFID accuracy is insufficient and varies from 4 to 9 m. UWB, in contrast, provides 9 cm accuracy but it is expensive and requires complicated deployment of transmitters, which makes it inefficient.
- Image-based localization: relies on computer vision techniques and image matching. Computer vision techniques, itself, are categorized into two methods: Global and Local. The former refers to detecting edges and recognizing features, whereas the latter detects landmarks with the help of tags and images. The reported studies indicate that these methods suffer from lack of precision and, more importantly, are not appropriate for dynamic environments such as construction sites.
- Inertia-based localization: this method uses an initial location and navigates through accelerometers, inertia measurement units (IMU), and other motion detectors. Ibrahim and Moselhi [67] have developed a localization technique, which combines IMU and Kalman Filter. Their method produce a higher accuracy compared to ultrasonic and sound waves, but it remains yet inefficient due to the very demanding computational calculations.

(II) Researchers use algorithm-based approaches to navigate mobile robots. Taneja et al. [71] categorize them into three major classes namely: center-line based, metric-based, and visibility-based. Center-line based algorithms select the medial axis of an indoor space, metric-based algorithms move along the navigable boundaries of a given space, and visibility-based algorithms are comprised of nodes and edges representing the end points of a path and the visible lines of a given indoor environment respectively. The limitation associated with these algorithms is that they do not consider the dynamic objects and furniture of an indoor environment to which construction sites are subject.

#### 4.2.2 GIS and Robotics

This section of the literature review studies qualitatively the applications of GIS in robots' navigation on construction sites independent from BIM. In this part, the papers identified in the methodology section are investigated in depth to have a comprehensive overview of GIS and robots' positioning on construction sites. In what follows, the papers are described and later, discussed.

Mangiameli et al. [72] have developed a method based on GIS for generation of raster maps showing obstacles in urban areas. The authors develop this method to enable flight planning of an Unmanned Aerial Vehicle (UAV). Their approach first represents the building data as a vector data shapefile, and then, converts it to raster to be able to use GIS. The authors use Spline algorithm to extract buildings' height for the raster map, identification of possible path within urban environment, and conversion of the path identified to waypoints for navigation of UAV. The possible obstacles are determined and subsequently are georeferenced in order to be avoided.

Zaki and Dunnigan [73] identify three challenges to navigate autonomous robots, namely: representation and schemes, planning algorithm, and the integration architecture of both. They combine GIS modelling and description logic for representation and schemes, modify and fuse algorithms, and ultimately introduce a navigation architecture. GIS and ontology are used to constitute digital representation of dynamic data. The proposed framework does not consider neither vertical navigation nor moving obstacles.

Yang et al. [74] propose a GIS platform in which the GIS database is modified. The authors introduce properties such as road width, lane number, lane info, and if-traffic to be able to describe the environment of the Unmanned Ground Vehicle (UGV). In addition, they redefine road models and turning strategy to generate a cost map navigating system for UGV navigation in urban environments.

Fernández-Caramés et al. [75] introduce a method for integration of indoor localization approach and GIS for the purpose of real-time navigation. They employ GIS to analyze indoor spatial data and develop a method that detects a door within indoor environment with data fusion of laser and vision sensors. Extended Kalman Filter is used for path finding.

Mirats Tur et al. [76] have developed a map-based navigation system in urban environments using GIS. The proposed system enables a robot or a team of robots to navigate within urban environments with prior assumption that an understandable navigation map is available. In this system, robots can connect to the map and navigate based on it. The authors highlighte communication protocols and cooperation issues as the important aspects of the work.

Sun et al. [77] have proposed GLANS (GIS Based Large-Scale Autonomous Navigation System) for robot navigation in urban settings. They argue that current simultaneous localization and mapping (SLAM) techniques cannot be utilized for large-scale environments. In this method, a GIS database suggests a topological path on which the mobile robot can navigate, detect obstacles and consequently modify the path. Moreover, the adjustment results can be shared with other mobile robots so that the navigation and localization process is optimized. Their method is independent of the Global Positioning System (GPS).

Park et al. [78] have developed a GIS-based method to analyze trafficability of terrain for autonomous robot navigation. In this method, GIS is employed to analyze the possibility of having a piece of terrain under traffic of unmanned ground vehicles by generating grid maps. The GIS database analyzes the spatial data of a given environment and assigns a cost to each grid. Once all the grids are assigned with a cost value, a path can be generated to navigate the mobile robot.

Rackliffe et al. [79] have developed a GIS-based approach with which Unmanned Aerial Vehicle (UAV) can be landed and Unmanned Ground Vehicle (UGV) can be navigated. In this method, they integrate GIS with sensor data of the vehicle in urban settings.

The literature review conducted on robot navigation using GIS technology indicated that algorithms and the implementation play a key role in this regard.

(III) The majority of the research on robot navigation with Geo-referenced locations focuses on algorithms and computational issues. However, there are some uncertainties associated with a given space that should be considered. Construction sites, for instance, are dynamic and are associated with many uncertainties. Dealing with uncertainties, is one issue that cannot be addressed by predetermined algorithms so that other approaches should be included.

(IV) Zaki and Dunnigan [73] argue that algorithms applicable to path planning are different from the ones for motion planning. They define “path planning algorithms” as “seeking the most appropriate path to a given point”, and “motion planning algorithms” as “robot’s actual movement.” Thus, they classify motion-planning algorithms into eight categories namely, (1) “Bug Algorithms,” “Roadmap,” (2) “Cell Decomposition,” (3) “Potential Fields,” (4) “Sampling-based motion planning,” (5) “Kalman filtering,” (6) “Heuristic Approaches” and, (7) “Mathematical programming.” The common characteristics of all the above-mentioned algorithms is that they are not mutually exclusive, thus combinable.

Moreover, path planning algorithms are divided into five categories namely, (1) “sampling-based algorithms,” (2) “node-based optimal-based algorithms,” (3) “mathematical model based algorithms,” (4) “bio-inspired algorithms,” and (5) “multi-fusion based algorithms” [73].

#### 4.2.3 BIM and GIS (In Respect to Construction Automation)

The main objective of this section is to identify the requirements of BIM and GIS integration for the purpose of construction robot navigation and positioning. To attain this goal, first, the tools and methods for integration of BIM and GIS are presented. Then, a comparison of the different methods and tools will determine whether one of them is appropriate for the future purposes of this research, or a novel approach should be developed to assist construction robot navigation and positioning.

Hwang et al. [80] have created a roadmap to develop a prototype of interoperable framework to facilitate BIM and GIS integration. In this direction, they employ IFC format of a BIM model to integrate it into GIS environment.

Liu et al. [81] explore BIM as a technology facilitating collaborations between construction stakeholders and management of building components data. They bring IFC into consideration as interoperable data format of BIM containing spatial information of building components. They also perceive GIS as a platform to provide further spatial analysis on the information provided by IFC. The authors focus on identifying the requirements for “a generic 3D indoor framework” and identify four of them to be relevant for indoor spatial analysis, namely [81]: “Generation of a vector map,” “Management of data,” “Analysis of environment,” and “Management of safety”.

Irizary and Karan [82] employ GIS to conduct spatial data analysis to find the best location and number of cranes on construction sites. To do this, they need semantic information with regard to the building elements, and they find BIM as a response to this need. To overcome the challenges of the integration of BIM and GIS, they combine an “optimal algorithm”, GIS, and BIM to create a model, optimizing the location and the number of tower cranes [82].

Zhu et al. [83] have developed an open-source approach (OSA) to integrate BIM and GIS using IFC and shapefile format respectively. They utilize IFC-Tree as the spatial structure of IFC to export data into shapefile format through developing and implementing Automatic Multipatch Generation (AMG) algorithm. Their work needs to be improved in terms of efficiency so their next contribution is built upon.

Zhu et al. [84] introduce an enhanced open-source approach (E-OSA) to integrate geometric data derived from IFC into shapefile in order to contribute to BIM and GIS integration. The authors improve the efficiency of their previous contribution which is open-source approach (OSA). In this enhanced approach, Brep, swept solid, mapped representation and clipping are successfully transformed into Brep within a shapefile format using an algorithm. It is also discussed that CityGML and Shapefile as the most prominent data exchange formats with their pros and cons [84].

Wang et al. [12] consider BIM as the digital representation of a shared database of construction projects to enable construction practitioners collaborate throughout the project lifecycle. The authors take GIS into account as geographical, cartographical, and remote sensing technology, which comprises spatial data and classify key applications of BIM and GIS integration into (1) integration of data, (2) projects' lifecycle applications (3) management of energy, and (4) management of urban environments. Additionally, data integration is identified as the fundamental and the most challenging step in this regard.

Hong et al. [85] have studied the correlation of IFC and CityGML as the most prominent data format with regard to BIM and GIS respectively. They identify features of the two, prior to mapping the IFC to CityGML at various level of details (LoD), from LoD0 to LoD4. The authors consider their contribution as the foundation of BIM and GIS of indoor and outdoor environment [85].

Adouane et al. [86] have developed a model-based approach to facilitate IFC data conversion into CityGML. They encounter semantic and geometry as the main challenges in this regards. In this direction, they have also developed a series of additive algorithms to overcome the issues occurred in the project. Their work indicates that the semantical and geometrical issues occurring when converting IFC into CityGML, could be handled by a set of algorithms [86].

Zhu et al. [87] assess integration of BIM and GIS at data level. They conduct literature review on scholarly papers to investigate data models in terms of relevance and features, examine other potential data models for BIM and GIS integration, and provide roadmap for future works. BIM and GIS are considered as well-developed technologies where BIM is employed throughout a building lifecycle, while GIS mostly correlates with location issues and spatial data analysis in various domains. They have identified the challenges and the methods to integrate BIM and GIS.

Isikdag et al. [88] have developed BO-IDM based on building information for indoor navigation purposes. They determine the requirements for BIM and GIS integration and they attain this goal through simplifying BIM models [88]. Even though the proposed framework is practical, it shows important limitations such as removing a void for the sake of simplicity, thereby making it insufficient for the purposes of automation in construction.

Based on the scientific works mentioned in this section, the following conclusions can be drawn:

(V) BIM and GIS integration occurs at different levels. Researchers defined several levels of integration with regard to BIM and GIS integration so a common definition with consensus on it is not available. BIM and GIS could integrate mainly on two levels, which interrelate fundamental level and application level [89]. Fundamental level refers to data exchange and interoperability of BIM and GIS, while application level refers to developing new software tools to benefit from BIM and GIS advantages. Another classification comprises 5 categories namely, "schema-based," "service-based," "ontology-based," "processes-based," and "system-based" [90]. A third classification comprises of three levels namely, data, process, and application [91]. Data level incorporates extending current data schemas or modifying data formats to fit other software. Process level refers to cooperation of data schemas, while at the application level, new software is developed to incorporate BIM and GIS privileges. Although the aforementioned classifications define different levels of integration, much of the research attempts are being carried out on data level. In this direction, Zhu et al. [87] have extended the data level into two sub-levels, which are geometry level and semantic level. The former focuses on geometry transformation of data, whereas the latter concentrates on full attribute data translation.

(VI) Many researchers have identified various data exchange formats for both BIM and GIS. The former comprises less formats in terms of quantity compared to the latter. There is a consensus among the researchers, however, that IFC is the promising data schema representing BIM [12, 81–87]. BuildingSMART (formerly the International Alliance for Interoperability) developed IFC as an EXPRESS-based tool [92]. IFC uses three types of geometrical definitions to represent 3D models: boundary-representation (b-rep), constructive solid geometry (CSG), and sweep volumes [93]. B-rep uses the object's boundary surfaces to represent a 3D complex object [94], CSG applies a set of Boolean operators namely, union, intersection, and difference on primitive shapes such as spheres, cones, pyramids, or cylinders [95], and sweep volumes uses a path to extrude 2D objects in order to create solid shapes [87]. American Institute of Architects (AIA) defined IFC Levels of Development (LOD) from lowest to highest amount of information they contain. The five levels are LOD100, LOD200, LOD300, LOD400, and LOD500. The BIMForum have developed LOD350 in addition to the aforementioned levels as there was a need for a Level of development between LOD300 and LOD400 in order to detect/avoid clashes, layout, etc. [87]. BuildingSMART have also developed other IFC schemas such as XML-based IFC standard and ifcXML in addition to EXPRESS-based IFC standard [96] which can be used for BIM–GIS integration.

(VII) Contrary to the case with BIM, researchers have not reached a consensus regarding GIS data exchange format. City Geographic Markup Language (CityGML) and Shapefile are two primary formats in terms of data exchange schema in GIS. The Environmental System Research Institute (ESRI) has developed Shapefile as an open data schema containing attributes and spatial features [97]. On the other hand, CityGML is an XML-based standard. The Open Geospatial Consortium (OGC) has approved it as the standard open data schema representing 3D models of cities and landscapes [19]. Although Shapefile data schema is the native format of GIS and can be exported to non-GIS software tools such as Collaborative Design Activity (COLLADA), SketchUp, and 3D Studio Max [98], CityGML is more suitable for BIM and GIS integration. This is because Shapefile is a non-semantic data model while CityGML is. Moreover, CityGML can provide bidirectional data transformation for BIM and GIS integration while Shapefile only allows transforming data from BIM to GIS [84].

(VIII) CityGML is defined based on the Levels of Detail (LoD) provided in a 3D model from LoD0 to LoD4 [87]. CityGML also uses boundary representation (b-rep) to visualize 3D models and it allows users to extend it through application domain extension (ADE).

Figure 13 illustrates various levels of detail on a residential house. LoD0 is just the footprints of the house in 2 dimensional environments, while LoD1 represents in solid shapes with a flat roof. LoD2 becomes more advanced in terms of showing details compared to LoD1. LoD3 and LoD4, both, demonstrate the openings of the building but LoD4 incorporates interior spaces and components such as interior walls, and doors.

## 5 Discussion

The current study is a systematic literature review (SLR) combining scientometric analysis and qualitative analysis. The former is used to investigate a large dataset of articles on BIM and GIS integration, which is difficult to conduct with conventional methods, and the latter is utilized to deeply explore the field with relation to robot navigation for construction sites. The literature review methodology adopts a systematic approach in order to be able to investigate the field comprehensively. It extends earlier review works and examines the domain of BIM–GIS integration from a new—automation in construction—perspective in order to address the existing limitations and to reduce complexity.

This SLR testifies that the current solutions relying on BIM with developed localization methods show many limitations such as lack of vertical navigation (i.e. from one floor

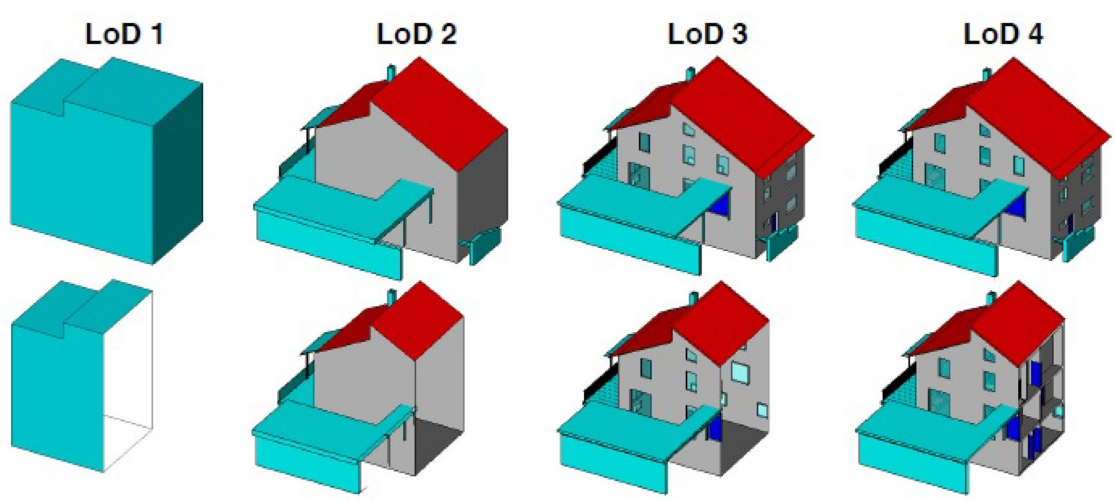



**Fig. 13** Levels of details on a residential house (*Source*: [99])

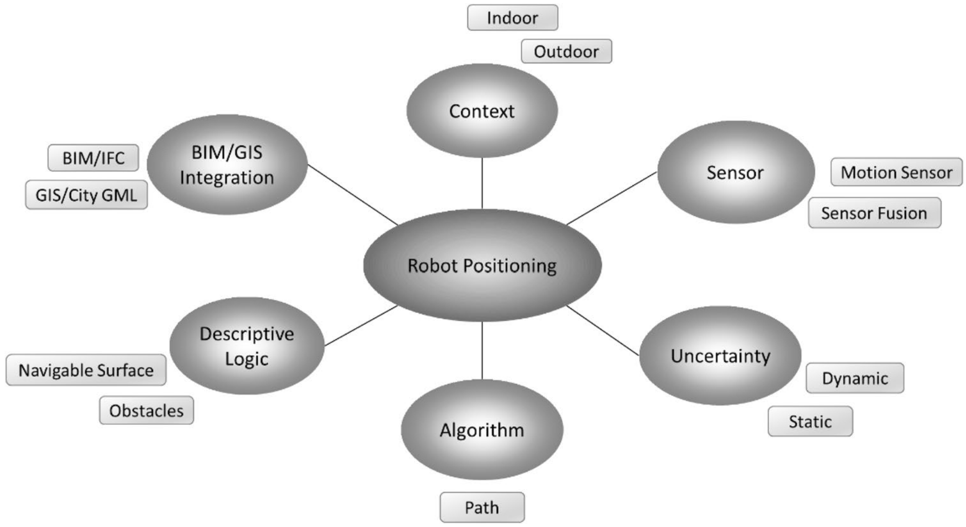



**Fig. 14** Requirements of BIM–GIS integration for robot navigation

to another floor), inaccuracy, not considering the dynamic nature of construction sites, etc. Therefore, more research needs to be performed in this regard or new approaches needs to be developed. The current study, which is part of a larger research project aimed to provide digital framework for robot navigation on construction sites, investigates the BIM–GIS domain to find its potential for improving robot navigation.

GIS, on the other hand, enables researchers to develop methods for robot navigation both for indoor and outdoor applications through applying various algorithms. The reported contributions are associated with high complexity and are unsatisfactory, as they do not consider construction sites uncertainties such as constant changes. Additional complexity comes from the analysis of data obtained from robot sensors. In this direction, complexity could be reduced exponentially through defining navigable surfaces in which building components are excluded.

BIM and GIS technologies are becoming omnipresent in construction projects and provide great benefits to the project stakeholders. However, due to their intrinsic differences, specifically in terms of focus, the integration of BIM and GIS is somewhat challenging and still under investigation. A number of research attempts are carried out to tackle navigation issues with either BIM or GIS for indoor environments, but they are still incompatible with construction sites' characteristics. BIM and GIS integration shows great potentials to be employed for robot navigation purposes as several research studies confirm it. GIS can be utilized to identify optimal path so that construction robots would be able to navigate and localize properly. BIM can also be used in this regard. BIM can provide a priori obstacle detection to robot through geometry and semantics of 3D models. Integration of BIM and GIS has the potential to considerably reduce the complexity of conventional navigation methods beside other opportunities it provides. Moreover, other methods should be incorporated to detect objects on construction sites, and react to its dynamic context.

Figure 14 illustrates the identified requirements for a digital framework for robots' positioning on construction sites. Having identified the requirements, our future research will seek to propose a novel approach to construction robots' navigation, integrated with BIM and GIS to cover the limitations of previous attempts and to decrease the complexity substantially.

## 6 Conclusion and Future Work

Studies have indicated that construction industry is suffering from low productivity, compared to other industries; also, scarceness of qualified workforce is foreseen in near future. Construction automation is introduced as one possible solution to these challenges. It is comprised of many aspects and practices but one of its functionalities is Digital Fabrication (Dfab). To enable construction robots to accomplish the assigned tasks perfectly, they need to be precisely positioned on the intended place. BIM and GIS have indicated great potential in this regard. Since BIM and GIS are already being used for other purposes in construction projects, relying on them for robots' navigation would reduce the complexity and the amount of time spent to implement other methods. However, BIM–GIS integration is challenging due to their different intrinsic focus. Hence, the current study adopts a Systematic Literature Review (SLR) to thoroughly review the research in the domain. In addition, scientometric analysis is used to investigate 236 articles. To deeper understand the challenges of the BIM–GIS integration in respect to robot navigation, qualitative analysis is carried out on the topics derived from keywords' co-occurrence method. Based on the qualitative analysis, challenges, gaps, and limitations of current solutions are investigated and the requirements to address limitations are determined. More importantly, this research aims to propose a novel approach using BIM and GIS integration for construction robots' navigation. Future work can also incorporate non-scholar sources such as texts and articles on websites in order to be investigated.

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**Availability of Data and Materials** The authors declare that they made sure that all data and materials as well as software application support their published claims and comply with field standards.

**Code Availability** All the software files used in the literature are available.

## Compliance with Ethical Standards

**Conflict of interest** The authors declare that they have no conflict of interest.

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