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Review

# Bibliometric analysis and review of Building Information Modelling literature published between 2005 and 2015

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A B S T R A C T

The use of Building Information Modelling (BIM) has increased in recent years, mostly due to the potential of the methodology for improving construction project performance and efficiency. With a view to achieving a better understanding of the research work on this subject, this paper conducts a bibliometric analysis and a review of existing literature on BIM focusing on the last decade. The authors selected the articles published in journals with an impact factor higher then 1.0, as well as the top 100 most cited articles. The search resulted on 381 articles, which were then categorised in order to systematise the research conducted over the years. The authors have not only analysed the existing literature but also highlighted new emerging fields in BIM research, being possible to identify Collaborative Environments and Interoperability, Sustainable Construction, BIM Adoption & Standardisation, and BIM Programming as the categories with the most significant growth in the last years. It was also observed that the most researched topics were related with the development of BIM tools, the study of BIM adoption worldwide, the energy simulation using BIM-based information and, more recently, with the semantic interoperability and ontology. On the other hand, the study on BIM at the academic level is very small, as well as parametric modelling and quantity take-off.



**Contents**



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# 1. Introduction

The construction industry currently generates 9% of gross domestic product (GDP) and provides 20 million jobs in Europe [1], and is responsible for 40% of energy consumption and 38% of $CO_2$ emissions [2]. The building sector is probably the single largest contributor to resource depletion, greenhouse gas (GHG) emissions and energy consumption [3]. In response to this demanding reality, it has become important to improve the energy performance and resource efficiency of buildings, infrastructures and construction in general. To achieve this goal, the Architecture, Engineering, and Construction (AEC) sector will need to promote the use of collaborative-based and rich information methodologies, such as BIM.

The term "*Building Information Model*" first appeared in 1992, in "*Modelling multiple views on buildings*" article, published in Automation and Construction journal [4]. In this article, the authors proposed a new approach for modelling building information based on multiple aspects (e.g. spatial design, building structure, and energy). Since then, the research on BIM methodology has been growing significantly and new applications are being found. In the early phases of BIM research, most articles were published either in Architecture magazines [5–7] or in conferences, covering the novelty of BIM methodology/technology and how challenging it would be to adopt it.

Currently, BIM refers to the use of a shared digital representation of a built object to facilitate the design, construction, and operation processes and to form a reliable basis for decision making [8]. It is not only a method that foster closer cooperation between all the various technical teams involved in the different stages of a construction project's lifecycle [9], but also integrates the information inputs from all teams involved in a project. Recent research shows that the BIM methodology improves the flow of information between the parties involved in a project and encourages new design solutions. It also reduces the amount of time and money expended on a project, through highly accurate cost estimation, clash detection and other mechanisms [10,11]. Recognising these advantages, most contractors that started to use BIM in their projects do not intend to perform traditional methods again, as BIM increased their productivity and greatly decreased the requests for information and rework [10].

With the aim of providing the readers with sufficient knowledge of the current literature on BIM, we review herein the existing research in BIM. While there are a number of reviews of BIM literature already published [12–32], these either focus on specific aspects of BIM application instead of providing an overall picture of it or different selection criteria are used. So, this paper performs a bibliometric analysis of published research in the field of BIM and then a comprehensive review. It is chronologically organised, giving the readers a better understanding of the evolution of BIM over the last ten years. After the Introduction, the rest of the paper is structured as follows: Section 2 describes the research methodology in detail; Section 3 groups the papers into categories based on a bibliometric analysis; Section 4 discusses the contents of selected papers and identifies trends and research gaps revealed in the literature; and Section 5 presents the conclusions.

## 1.1. Originality of the review

Between 2006 and 2015 several literature reviews on BIM were published. In 2009, Eastman et al. [17] reviewed rule checking systems, as it was deemed as an emerging field in 2009, and argued that the advent of BIM tools and IFC would enable an automatic rule checking, as it was verified later. Two years later Jung and Joo [14] studied the literature in the fields of computer-integrated construction (CIC) and BIM, with the purpose of developing a BIM framework for real-world projects developed by companies. Love et al. [12] examined BIM literature in the area of design errors and also presented a systemic model for reducing design errors, concluding that little empirical research had been carried out in this field of study. Cerovsek [13] focused on the technological dimension of BIM literature and on BIM implementation in projects for new buildings, in contrast to Volk et al. [16], who focused on recent research on BIM for existing buildings. Zhou et al. [18] surveyed the state-of-the-art on construction safety and digital design, evidencing BIM as one of the studied fields, similar to the study of Skibniewski [31]. Despite the focus was not the BIM methodology, the authors analysed a few articles that used BIM tools for safety analysis during construction planning (4D BIM). Ding et al. [15] studied the existing BIM applications in the construction industry and proposed a BIM application framework to expand from 3D to nD as a result, similar to other studies [19,20]. A more systematic analysis of BIM literature was conducted by Yalcinkaya and Singh [27], which resulted in the compilation of published articles between 2004 and 2014. Despite the useful identification of BIM research areas, the respective discussion is more focused on the scope of a few studies within each research area than actually analysing the contents of the articles.

Other reviews focused on the different fields of BIM application, as structural design [21], infrastructure industry [29], as-built data collection and analysis [22,24,25,28,32], where technologies as photogrammetry and laser scanning were deeply studied, building performance simulation in early phases of the project [26], and sustainability [23,30].

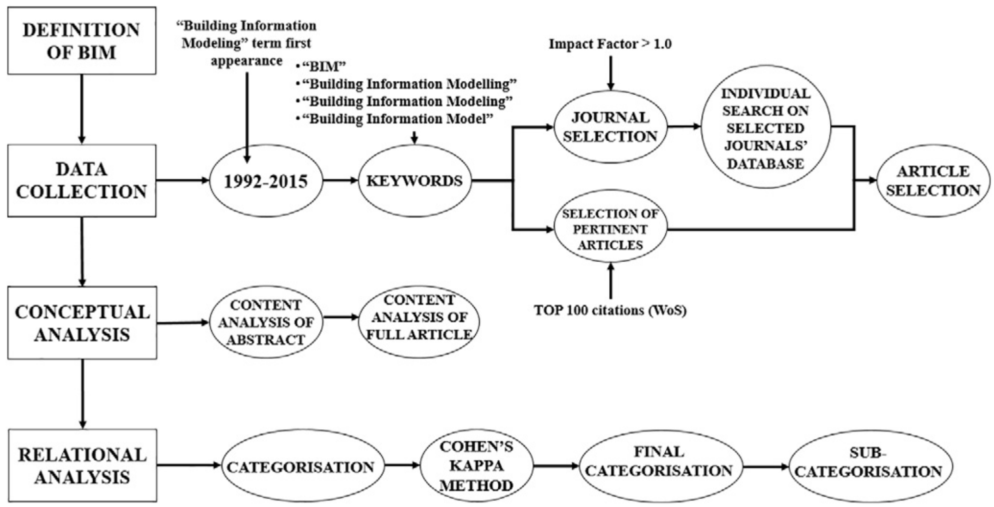


**Fig. 1.** Research methodology (bibliometric analysis).

In contrast to most of previous literature reviews, that focused on single aspects of BIM, this review contributes with a more systematic and updated analysis of all research on BIM. It not only studies a wide range of publications, but also examines papers published by recognised journals within this field. Throughout the review, BIM methodology will be categorised to simplify the understanding of the literature and permit a better analysis of trends and gaps in the research.

## 2. Methodology

Our paper analyses and classifies the research on BIM until 2015 by applying the quantitative method of bibliometric analysis. This bibliometric analysis consists of six main steps (Fig. 1): (i) keyword search in the *Web of Science* database; (ii) selection of journals that have an impact factor higher than 1.0; (iii) individual search in the database of the journals selected in the previous step; (iv) exclusion of duplicates and articles that do not discuss BIM; (v) selection of the 100 most cited articles; and (vi) categorisation of articles based on contents.

In the first step of our bibliometric analysis we conducted a keyword search in the *Web of Science* database using the keywords: (i) "BIM"; (ii) "Building Information Modelling"; (iii) "Building Information Modeling"; and (iv) "Building Information Model". We then refined the search in the database to only include scientific articles written in English and from the engineering and computer related fields, which resulted in 577 articles. Afterwards, we selected 399 articles that were published in journals with an impact factor greater than 1.0 (i.e. journals with articles published in the last two years and that have been cited one time, on average). However, even though Web of Science is acknowledged as the leading citation database with high quality and multidisciplinary research, it has some limitations as a search tool, mainly because it searches the terms only in the title/abstract/keywords of the articles. Considering this limitation, we conducted a new search in the databases of the journals selected in the previous step, as it performs a thorough search in the full article. This individual search resulted in 1.005 articles. After the exclusion of duplicated articles, and the ones that did not discussed BIM (from WoS database and the journals' database), only 369 articles fit our criteria. Then, we conducted a search (in the Web of Science) to identify the most cited articles in the BIM literature, in order to cover the most influencing articles in this field. By doing this, not only do we have a criterion based on journals' quality (Impact Factor) but also a criterion that is based on articles' influence in the literature (TOP 100 citation). As a result, 12 more papers were included (as the other 88 were published in journals with an Impact Factor higher than 1.0). As a result, we are going to analyse 381 papers in this review. Of the 381, 21 are literature reviews on BIM and were already discussed previously. Accordingly, they were not included in the Content analysis section that grouped the remaining 360 papers.

Although the first paper was published in 1992, entitled "*Modelling multiple views on buildings*" [4], only in 2006 the literature started to be more focused and assertive in relation to BIM research and development [33,34]. Therefore, we decided to review the last decade (from 2006 to 2015) in order to cover the most important phases of BIM research, tool development and implementation.

Based on a grounded approach, the categorisation process was carried out by each author in an independent way. Rather than categorising the literature based on existing research themes or areas (present in other studies), we proposed our own categories built on the articles' contents. After the categorisation process, we brought together our categories in order to reduce it to a single categorisation framework. For that purpose, we compared the independent categories using Cohen's Kappa method [35]. As Cohen's Kappa coefficient obtained in the first round was not sufficient, we conducted another categorisation round, which allowed to converge the process. Finally, a high degree of reliability was finally found at the second time, with Cohen's Kappa coefficient being 87%.

## 3. Bibliometric analysis outcomes

The bibliometric analysis shows that over the last decade there has been an increase in published papers on BIM from 4 in 2006 to 106 in 2015 (Fig. 2 and Table 1). It is also interesting to note that only 8,3% of the 381 articles were published up until 2011, which means that the last five years were particularly productive. Over the ten-year period under review, and according to our selection criteria, the Automation

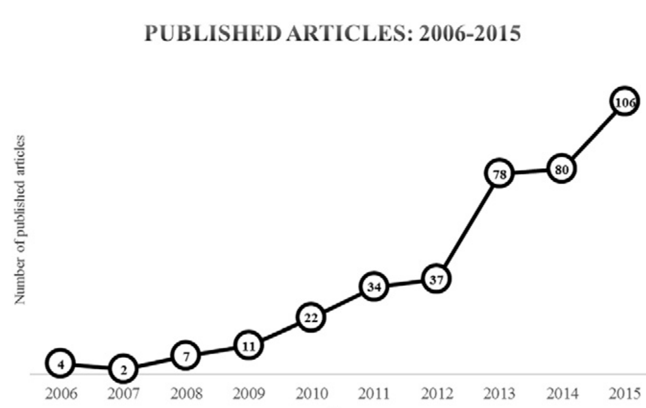


**Fig. 2.** BIM papers published over the last decade.

and Construction Journal published the majority of papers in the field of BIM (177), followed by the Advanced Engineering Informatics Journal (47) and the Journal of Computing in Civil Engineering (39).

Our bibliometric analysis also showed that, according to Table 2, 59 of the 100 most cited articles were published in the Automation and Construction journal, followed by Advanced Engineering Informatics (14) and Journal of Construction Engineering and Management (8).

Based on the content analysis, the papers were grouped into several categories according to specific major categories, defined as explained in the Methodology section (Fig. 3):

— BIM Adoption and Standardisation;
— BIM and Spatial Information;
— BIM Programming;
— Collaborative Environments and Interoperability;
— Construction Management;
— Facilities Management and Safety Analysis;
— Image Processing, Laser Scanning and Augmented Reality;
— Sustainable Construction;
— and BIM Reviews.

According to the categories mentioned above, it was possible to identify which research areas are more appealing to academic peers, based on top 100 citation (Table 3). Those research areas contain studies that covers "BIM Adoption and Standardisation", "BIM Programming", "Image Processing, Laser Scanning" and "Augmented Reality", and "Collaborative Environments and Interoperability". Similarly, the categories with higher number of published papers are also the same ones with more cited studies, with the exception of Sustainable Construction. While this analysis does not necessarily identify new trends or gaps in the BIM literature, as it will be discussed in the next section, it shows which topics were more interesting to the researchers during this last decade.

## 4. Content analysis

In order to discuss the results and provide a more qualitative analysis of the papers, we proposed a sub-categorisation structure, which was defined based on a content analysis of the articles and a consensus discussion. In the sub-categories descriptions, we have opted to describe and analyse the most representative and distinguished articles

**Table 1**
BIM papers published over the last decade (journal list).

| Journals | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Advanced Engineering Informatics | 0 | 0 | 3 | 2 | 1 | 7 | 5 | 10 | 6 | 13 | 47 |
| Advances in Engineering Software | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 2 | 2 |
| Applied Energy | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 2 | 0 | 3 |
| Applied Mathematical Modelling | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 |
| Archives of Computational Methods in Engineering | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 2 | 2 |
| Automation in Construction | 3 | 2 | 3 | 4 | 13 | 19 | 14 | 30 | 42 | 47 | 177 |
| Building and Environment | 0 | 0 | 0 | 0 | 1 | 1 | 2 | 1 | 1 | 4 | 10 |
| Building Research and Information | 0 | 0 | 0 | 1 | 0 | 0 | 1 | 2 | 0 | 1 | 5 |
| Building Simulation | 0 | 0 | 0 | 0 | 0 | 2 | 0 | 2 | 0 | 0 | 4 |
| Carbon Management | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 1 |
| Computer Journal | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 1 |
| Computer-Aided Civil and Infrastructure Engineering | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 2 | 2 | 4 |
| Computer-Aided Design | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 0 | 0 | 3 |
| Computers Environment and Urban Systems | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 3 |
| Computers in Industry | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 3 | 2 | 7 |
| Construction and Building Materials | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 1 |
| Disaster Advances | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 1 |
| Energy and Buildings | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 7 | 3 | 12 |
| Energy Efficiency | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 1 |
| Energy Policy | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 1 |
| Environmental Science & Technology | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 |
| Expert Systems with Applications | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 1 |
| Ieee Transactions on Intelligent Transportation Systems | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 |
| Ieee Transactions on Services Computing | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 |
| International Journal of Computer Integrated Manufacturing | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 1 |
| International Journal of Digital Earth | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 1 |
| International Journal of Geographical Information Science | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 1 |
| International Journal of Project Management | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 1 | 2 |
| Isprs Journal of Photogrammetry and Remote Sensing | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 1 |
| Journal of Civil Engineering and Management | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 3 | 3 | 2 | 9 |
| Journal of Cleaner Production | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 |
| Journal of Computing in Civil Engineering | 1 | 0 | 0 | 2 | 2 | 1 | 5 | 11 | 8 | 9 | 39 |
| Journal of Construction Engineering and Management | 0 | 0 | 1 | 1 | 2 | 0 | 2 | 2 | 0 | 0 | 8 |
| Journal of Intelligent & Fuzzy Systems | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 |
| Journal of Intelligent & Robotic Systems | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 4 | 4 |
| Journal of Management in Engineering | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 1 |
| Journal of Professional Issues in Engineering Education and Practice | 0 | 0 | 0 | 0 | 2 | 1 | 0 | 0 | 0 | 0 | 3 |
| Photogrammetric Record | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 |
| Project Management Journal | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 1 | 2 |
| Renewable & Sustainable Energy Reviews | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 1 |
| Research in Engineering Design | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 0 | 2 |
| Resources Conservation and Recycling | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 2 | 2 |
| Safety Science | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 1 | 2 |
| Simulation Modelling Practice and Theory | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 |
| Software and Systems Modelling | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 1 |
| Solar Energy | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 1 |
| Sustainable Cities and Society | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 2 | 1 | 1 | 4 |
| Visual Computer | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 1 |
| Waste Management | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 1 |
| Total | 4 | 2 | 7 | 11 | 22 | 34 | 37 | 78 | 80 | 106 | 381 |

**Table 2**
TOP 100 citations.

| Journals | Number of articles | Number of citations |
|---|---|---|
| Advanced Engineering Informatics | 14 | 384 |
| Applied Energy | 1 | 33 |
| Automation in Construction | 59 | 1698 |
| Building and Environment | 2 | 63 |
| Building Simulation | 1 | 21 |
| Computer-Aided Design | 2 | 21 |
| Computers Environment and Urban Systems | 1 | 11 |
| Energy and Buildings | 1 | 17 |
| Journal of Computing in Civil Engineering | 5 | 78 |
| Journal of Construction Engineering and Management | 8 | 195 |
| Journal of Management in Engineering | 1 | 37 |
| Journal of Professional Issues in Engineering Education and Practice | 3 | 44 |
| Research in Engineering Design | 1 | 18 |
| Software and Systems Modelling | 1 | 13 |
| Total | 100 | 2637 |

**Table 3**
Number of articles and citations by category (TOP 100 articles).

| Categories | Number of articles | Number of citations |
|---|---|---|
| BIM Adoption and Standardisation | 25 | 739 |
| BIM and Spatial Information | 4 | 92 |
| BIM Programming | 15 | 416 |
| Collaborative Environments and Interoperability | 17 | 360 |
| Construction Management | 7 | 156 |
| Facilities management and Safety Analysis | 4 | 98 |
| Image Processing, Laser Scanning and Augmented Reality | 15 | 365 |
| BIM Reviews | 6 | 227 |
| Sustainable Construction | 7 | 184 |
| Total | 100 | 2637 |

of the respective sub-category based on their citation and pertinence to their field. So, after analysing the full content of 381 papers, we conducted a critical analysis and description of 200 papers.

### 4.1. Category: Collaborative Environments and Interoperability

**Collaborative Environments and Interoperability** (Table 4) is the category with the most papers published, mainly in the past three years. Also, 33% of its papers were published last year, registering the highest growth rate of all categories in this review. An interesting result is the seemingly low volume of papers that address the collaborative environment aspect of BIM, despite this being referred to as one of the best aspects of BIM. Our review of the literature in these fields reveals that several authors made reference to a number of IFC limitations, despite the advantages of an open format tool. With a view to resolving certain issues, it is expected that new studies in the field of IFC will follow in the near future, mainly focusing on semantic interoperability. Other subcategory identified by the authors concerns information and knowledge exchange between BIM tools, highlighting the potential of BIM as an information repository. Another recent topic is the research on Semantic BIM and Ontology, which is increasingly drawing attention of scholars. Studies on this topic quintuplicated only in the last year, being proof of its importance for the research on taxonomies and data exchange between different platforms. Thus, Collaborative Environments & Interoperability encompasses the following sub-categories: (i) Interoperability & IFC; (ii) Semantic BIM & Ontology; (iii) Collaborative Environments; and (iv) Knowledge & Information Management.

#### 4.1.1. Sub-category: Interoperability & IFC

The sub-category that is most studied in this category is **Interoperability & IFC**, with a number of authors testing the interoperability between BIM tools for different applications. One of the most detected issue on this subject was the IFC capability to support information exchange. For instance, Sacks et al. [36] conducted an experiment (Rosewood experiment), which purpose was to analyse the workflow between design and construction in the domain of architectural precast façade, contributing for the development of an Information Delivery Manual (IDM) draft for this domain as well. The authors found that IFC $2 \times 3$ schema lacks entities and property sets required for precast concrete data exchanges, claiming that future work should be done in the IFC schema to address this issue. Loss in translation of semantic meaning for the data exchanged was pointed out as a major difficulty in the experiment, due to the inability of some applications to read some information within objects. Similarly, a more recent article studied the use of IFC schema for the reinforced concrete domain, in order to identify which properties and interrelationships the IFC schema are missing if one wanted to support earthquake design [37].

Other authors, as Venugopal et al. [38], have looked at IFC limitations. These authors studied the idea of model view definition (MVD) as an object-oriented mechanism for adding semantic meanings in model views, concluding that IFC language lacks a logical mathematical theory and has a limited expression range. In their research, Steel et al. [39] studied the interoperability when exchanging IFC-based models amongst different BIM tools. As in [36], the authors evidenced that IFC still faces semantic interoperability challenges, which will tend to

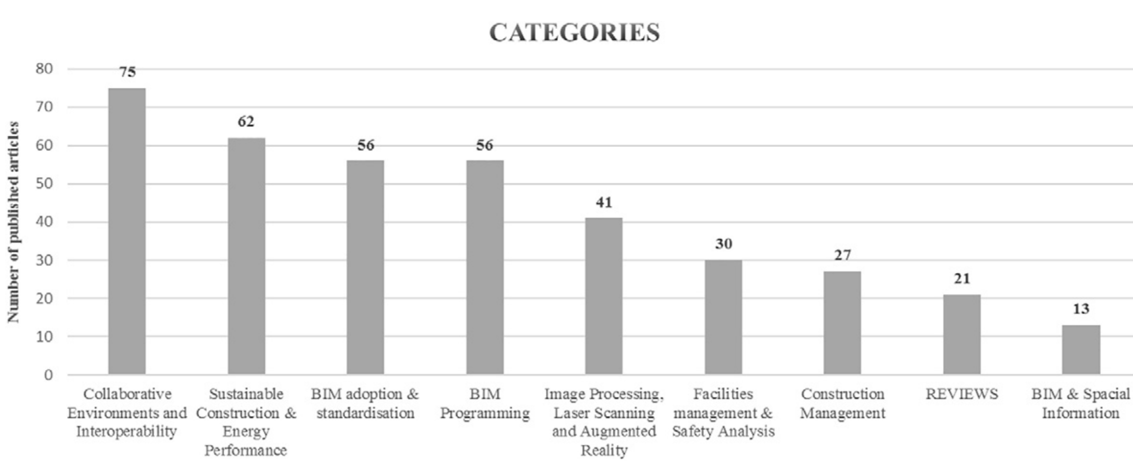


**Fig. 3.** BIM categories.

**Table 4**
Collaborative Environments and Interoperability category.

| Category and sub-categories | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | Total | % |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Collaborative Environments and Interoperability | 1 | 2 | 0 | 2 | 7 | 7 | 8 | 16 | 8 | 24 | 75 | 19,7% |
| Interoperability & IFC | 1 | 2 | 0 | 1 | 2 | 1 | 3 | 5 | 4 | 5 | 24 | 6,3% |
| Semantic BIM & Ontology | 0 | 0 | 0 | 1 | 0 | 2 | 0 | 5 | 2 | 13 | 23 | 6,0% |
| Collaborative Environments | 0 | 0 | 0 | 0 | 3 | 1 | 3 | 3 | 0 | 4 | 14 | 3,7% |
| Knowledge & Information Management | 0 | 0 | 0 | 0 | 2 | 3 | 2 | 3 | 2 | 2 | 14 | 3,7% |

increase as more domains are added to BIM studies. Other authors also referred the same issues regarding the effectiveness of interoperability [40].

BIM query language research is another topic considered in this sub-category, as it has much to do with IFC manipulation. As in the study carried out by Daum and Borrmann [41], Mazairac et al. [42] developed a framework for an open query language for BIM (BIMQL) for IFC model data management, resorting to bimserver.org platform. However, while Daum and Borrmann only assesses topological information pertaining to BIM models, Mazairac et al. are more generic. Nevertheless, there are certain limitations to [42], such as the restricted natural language mapping in the buildingSMART data dictionary that difficult the search for model parts (e.g. construction elements or quantities) by their natural language terms, lack of automation and scarcity of shortcuts available for the development of queries.

Other works related to IFC are those focused in data extraction from IFC models. An interesting example is the article developed by Fu et al. [33], which discussed how the different aspects of a building project could be implemented in BIM. For that purpose, IFC was used as data repository for all nD-driven analysis. As an outcome, it was developed an IFC-viewer that serves as the interface for the nD modelling tools, allowing the users to visualise the data within the IFC file. With a different approach, Isikdag et al. [43] used the information contained in IFC files to populate a novel methodology, the BIM-oriented modelling (BO-IDM), to ease indoor navigation. This new approach resulted in an improved and semantically rich 3D visualisation of indoor environment. Other authors have also used IFC files for indoor navigation, as Lin et al. [44]. However, while BO-IDM was the used method in [43], in [44] the authors used path planning with fast marching method, with IFC serving as an input for geometric and semantic information.

*4.1.2. Sub-category: Semantic BIM & Ontology*

The next identified sub-category in Collaborative Environments and Interoperability category covers the study on **BIM semantics and ontology**. While this topic remained unnoticed until recently, researchers started to focus on solving issues as semantic interoperability to improve the communication between different systems. We believe that the recent interest was encouraged by the increasing adoption of BIM throughout the world, by the increase of existing standards, and by the development of BIM data dictionaries. As more tools and standards emerge, it becomes even more important to achieve higher levels of semantic interoperability. It is the study of the semantic interoperability that will potentiate synergies between BIM and other fields and improve the existing ones. In their study, Pauwels et al. [45] argued that the use of semantic web languages can enhance IFC for building performance monitoring, demonstrating their findings with a test case for acoustic performance. Some of the issues of IFC schema identified by the authors were the lack of mathematically rigorous logic and the multiple ways to describe the same information, which could be improved with the use of semantic web. Further studies on semantic information were also conducted recently, namely a new graph data model (GDM) to extract topological and geometric information of IFC files, representing the topological relationships between 3D objects in models [46]. Semantic web language was also used in other works, which is believed to improve the interoperability between BIM and its synergies [47].

More related with the study of ontologies, Rezgui et al. [48] argued that Web Ontology Language (OWL) can address some of the issues of IFC. The authors believe that ontologies enable a richer conceptualisation of all domains in the construction industry, when compared to product data standards. So, a roadmap for the purpose of semantic service-based e-Construction was proposed in order to assist the industry to move from product data standards to semantic services. Another ontological approach was discussed by Lee et al. [49], which proposed an ontological inference process for an automatic cost estimation. The added value by using discipline-oriented ontology is that subjectivity's errors due to the misinterpretation of designers are reduced, as construction work items are automatically inferred. A more recent article developed by Venugopal et al. [50] proposed a novel integrated ontological framework to improve data sharing throughout construction industry domains, showing that the existing IFC schema should be restructured. This study revealed that ontologies are able to define a more logical semantic structure to the building elements than the existing IFC schema.

*4.1.3. Sub-category: Collaborative Environments*

There is no BIM without collaboration, which can be noticed throughout this review. So, another sub-category we considered is the **Collaborative Environments** aspect of BIM. In this sense, works covered in this sub-category focus on the benefits of BIM regarding team collaboration. For instance, Isikdag and Underwood [51] proposed two design patterns for formalisation of the Model-View-Controller (MVC) architecture in order to facilitate model-based synchronous collaboration through the entire lifecycle of a building. This was later continued by [52], now focusing on model-based web services. The authors argued that effective collaboration can be achieved only through effectual coordination and communication, and that the MVC proposed in [51] enables different specialised technical areas to work within their own views, while in [52] the interaction between BIMs and web techniques such as AJAX, SOAP and REST was studied. Similar to [51], Lee and Jeong [53] developed a prototype for a filter-based communication model that enabled different technical teams to participate in the project with higher levels of shared understanding, each accessing the necessary information that was converted into their own representation using user-defined ontologies. Another study that focused on designer and user communication was developed by Shen et al. [54], with users simulating their activities in new buildings by using BIM models, for pre-occupancy assessment. By doing so, future occupants will be able to contribute for the design of buildings more oriented towards their necessities.

Collaborative-based platforms/networks are another important facilitator for communication amongst teams, with Singh et al. [55] and Grilo et al. [56] developing interesting works in this matter. While in [55] a theoretical framework for using the BIM-server as a multi-disciplinary collaboration platform was proposed, categorising the features and technical requirements, in [56] a Business Interoperability Quotient Measurement Model (BIQMM) was developed which, combined with a multi-criteria decision-making tool, analysed business interoperability for BIM-based projects, enriching the selection processes solely on the basis of technical parameters. Another research was conducted by Ajam et al. [57], which developed an augmented process and information model to support data exchange between web-collaborative extranets (WCEs) and Project Integrated Databases (PIDs) for the tendering stage, being a new development in the field of ICT applications. The used of augmented reality to improve the collaboration amongst teams was also studied by Lin et al. [58], where a stationary system named BIM table was developed. By using this system, the involved parties can connect their tablets to the BIM table in order to discuss the construction planning and coordination, sharing only the information they deem necessary. Further study in the field of ICT was done by Moum [59], which assessed the benefits of using 3D object models and applied a descriptive and multi-level framework for exploring the impact of ICT on the architectural design process, while Shen et al. [60] developed a User Pre-Occupancy Evaluation Method (UPOEM) to improve communication between designer and client. However, the UPOEM only provides basic architectural information on office buildings.

#### 4.1.4. Sub-category: Knowledge & Information Management

Articles that focus on the exchange and management of information and knowledge within BIM environment are covered in this sub-category, the **Knowledge & Information Management**. Concerned with the information exchange requirements, Eastman et al. [61] proposed procedures for information delivery manuals (IDM), capturing detailed level information requirements from end users at the IDM phase of specification to anticipate MVD specification issues. Aware of the results of [61], Lee et al. [62] proposed an extended Process to Product Modelling (xPPM) to overcome IDM's issues, improving exchange requirements and functional parts as a result.

The quality of information exchange between coupled software packages (ability to work in unison) was assessed by Fröbel et al. [63], which took into account diverse sources of mapping errors, resulting in global quality values and indicators. In the field of lifecycle information management, Motamedi et al. [64] proposed the use of Radio Frequency Identification (RFID) tags that are permanently attached to specific elements to provide lifecycle information, in ifcXML format, allowing the involved stakeholders to store and hand over useful data to other users. In the same field, Jiao et al. [65] presented a cloud approach for data management through a unified BIM and business social networking services (BSNS) federation, enabling data sharing through individuals, project teams and enterprises throughout the lifespan of a construction project. It was also highlighted the challenges of Big Data in the field of information management and how cloud services could be a solution for the high volume of data. Researching on information flow as well, Čuš-Babič et al. [66] proposed an automatic information mapping to improve project progress monitoring, detailed planning, and management of material flows.

Regarding knowledge sharing, Lin [67] proposed a new methodology, the Construction BIM-based Knowledge Management (CBIMKM) system, which improved the effectiveness of knowledge sharing in the 3D environment by means of a 3D CAD-based knowledge map. Lin used a questionnaire to evaluate CBIMKM, in which automatic knowledge correction, knowledge management and easy identification of knowledge and experience were recognised as the main advantages of this system. High hardware requirements, time expenditure and difficulty in knowledge editing were highlighted as barriers.

### 4.2. Category: Sustainable Construction

**Sustainable Construction** (Table 5) is the second largest category, with one of the highest growth rate in the last years. This domain is increasingly becoming one of the most crucial targets for building in the EU, with sustainable performance and energy efficiency at the forefront of this trend. The analysis of energy consumption is a field that always concerned researchers of the construction industry. Thus, the integration of energy simulation with BIM tools was a predictable outcome, resulting in a sub-category with several studies. The sustainability aspect of BIM is also one of the categories with the highest growth rate in the last years. This may have to do with the international commitment to reduce GHG emissions and mitigate the effects of climate change. The researchers identified the potential of BIM methodology to tackle these issues and increase transparency in the whole construction process, not only for new buildings but also for existing ones. The EUPPD [68] also recognised BIM's huge potential for resource and time management, and used in conjunction with state-of-the art knowledge and software for energy performance and LCA, BIM will be a key element in the reduction of resource and energy wastage. The Building Performance field is also a new trend in terms of study and research, with the aim of improving the sustainability of the AEC sector by monitoring the interior conditions of buildings and promoting green material usage. BIM-LCA integration is being recently recognised, despite the difficulties of integrating these methodologies, as well as interoperability issues between the software used. The sub-categories that we have identified are: (i) Energy Performance; (ii) Sustainable Performance; and (iii) Building Performance.

#### 4.2.1. Sub-category: Energy Performance

The sub-category that we first identified is the **Energy Performance**, which covers studies on Photovoltaics (PVs), automation of energy analysis, and also the study of the impact of human behaviour on energy consumption. In order to assist energy managers throughout the lifecycle of a building, Costa et al. [69] proposed a novel integrated toolkit that could be used for building renovation optimisation and comparison of different alternatives. However, due to a number of compatibility issues, this product still has not been made ready for commercial use. Other article that considered BIM for building energy renovation was written by Larsen et al. [70], which analysed the role of scanning technologies in energy retrofit projects. The digital workflow analysed by the authors due to the use of prefabricated timber-framed elements on energy performance retrofit projects allowed them to conclude that these type of elements generates less waste and less assembly effort on-site. Another approach to reducing energy consumption was studied by Eguaras-Martínez et al. [71], in which human behaviour was considered in the building simulation. According to the authors it is possible to save up to 30% of total energy consumption if schedules are correctly used and that value would be even greater if used with BIM methodology. An original article in the field of thermal analysis was authored by Wang et al. [72], with the authors developing a hybrid light detection and ranging (LIDAR) system that is used to collect point cloud and temperature data from existing buildings. By using a laser scanner and an infrared camera, this novel system can then be used for retrofitting purposes and to generate an as-built BIM model, improving the energy performance of buildings.

**Table 5**
Sustainable Construction category.

| Category and sub-categories | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | Total | % |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Sustainable Construction | 0 | 0 | 0 | 1 | 0 | 8 | 4 | 13 | 21 | 15 | 62 | 16,3% |
| Energy Performance | 0 | 0 | 0 | 1 | 0 | 4 | 2 | 7 | 11 | 4 | 29 | 7,6% |
| Sustainable Performance | 0 | 0 | 0 | 0 | 0 | 3 | 0 | 4 | 5 | 8 | 20 | 5,2% |
| Building Performance | 0 | 0 | 0 | 0 | 0 | 1 | 2 | 2 | 5 | 3 | 13 | 3,4% |

Studying the use of IFC on energy simulation, Gupta et al. [73] proposed a conceptual framework for renewable energy simulation tool development. Based on that framework, the authors also developed an IFC-based prototype and compared it with other PV simulation tools, obtaining a low deviation percentage. Ahn et al. [74] developed an IFC–IDF interface to convert geometric data in the IFC to IDF (EnergyPlus file) and discussed the benefits and limitations of both full automated interface (FAI) and semi-automated interface (SAI). SAI was considered more transparent and more reliable than FAI, and to offer greater control over the input values and types of energy-saving systems. A similar study was conducted by Welle et al. [75]. The authors proposed a methodology, ThermalOpt, that automatically integrates BIM (IFC files) with energy simulation tools (EnergyPlus) and daylighting simulation tool (Radiance). The BIM tool generates the IFC file that is automatically used as an input in the remaining tools through developed plug-ins, the IFC2ThermalSim and ThermalSim. As a result, ThermalOpt enables designers to simulate a number of design alternatives, with improved design process speed, accuracy, and consistency. However, the computational time to process the analysis of large buildings is considered a limitation of this methodology.

#### *4.2.2. Sub-category: Sustainable Performance*

Another sub-category identified is the **Sustainable Performance**, which includes several environmental aspects involved in construction such as Carbon Footprint, Green Certification and Life Cycle Assessment (LCA). As far as the field of Carbon Footprint study is concerned, Bank et al. [76] integrated a BIM model with a decision-making tool to enhance the measurement, prediction, and optimisation of sustainable building material performance. The tool not only assists in the creation of certification schemes but also supports decision-making processes in the early design stages of the building with a view to reducing the carbon footprint. Iddon and Firth [77] developed a BIM-based tool to estimate both embodied and operational carbon footprint, where they determined that embodied carbon was responsible for 20–26% of the total carbon emissions. Space heating was considered to be the main contributor to carbon emissions during the lifecycle of a building, indicating that a greater insulation would decrease operational carbon. However, the authors concluded that the embodied carbon increases as the operational carbon decreases.

In the field of green certification, Azhar et al. [78] undertook exploratory research to determine the applicability of BIM in the Leadership in Energy and Environmental Design (LEED®) certification process. The authors concluded that BIM can be used not only to achieve 17 LEED® credits, but also to contribute to the generation of documents that support LEED® credits. Building on Azhar et al. [78], Wong and Kuan [79] implemented the Hong Kong BEAM Plus system with a BIM-based sustainability analysis. BIM was also used together with a ranking system to monitor Indoor Environmental Quality (IEQ) in underground stations, in the Marzouk and Abdelaty [80] study. The proposed framework can measure air temperature and particulate matter (PM) concentration levels, as well as rank maintenance actions in the underground network.

A methodology that is gaining momentum is the Life Cycle Assessment (LCA), an international recognised environmental methodology that assess the environmental impact of the full life cycle of a product [81] and supported by the European Commission [1]. In this sense, Wu et al. [82] developed a comprehensive review on the LCA of concrete, highlighting BIM as a good tool for quantifying the impacts of the concrete throughout the lifecycle of the building. With a more educational approach, in 2011 Stadel et al. [83] combined BIM with LCA methods at an engineering course, examining Green Building Studio (GBS) and Integrated Environmental Solutions' Virtual Environment (IESVE), both Revit's plug-in. Although the authors considered those tools to be straightforwardly learned, the obtained results are inconsistent between them. The authors also believe that BIM-LCA integration can enhance the student's knowledge in the field of sustainable design, raising the awareness for the environmental impacts of a project's life cycle. Basbagill et al. [84] combined BIM-based software with LCA and Energy analysis software, using sensitivity analysis to identify which elements contributed most to the impact of a building. The authors concluded that the elements of a building that can reduce environmental impact the most are cladding, piles, partitions, flooring surfaces, floor structural assembly, column and beam structure assembly, and window assembly. Notwithstanding the innovative nature of this paper, replicating this framework will require the use of a considerable number of programs: DProfiller for BIM modelling, eQUEST for energy simulation, SimaProf for LCA analysis, as well as Athena EcoCalculator and CostLab in order to provide MRR information, Excel to perform simple mathematical operations, and, finally, ModelCenter to perform the sensitivity analysis. The same methodology was used in a later article of the same authors but with a different purpose [85]. In this article, the authors proposed a multi-objective approach to evaluate building designs, demonstrating the importance of conceptual design in the life cycle impact and cost of a building. By doing so, it was possible to select more environmental and economic friendly solutions, proving the usefulness of this approach. A similar study was done by Jrade and Jalaei, which aimed to obtain the environmental impacts of a new building at the conceptual stage [86]. The authors used the BIM model to generate and export a quantity take-off which was used in Athena Impact estimator (LCA tool) to perform the LCA study. However, as in [84,85] the lack of automation is a limitation of this study. A more recent study, published in 2015, covered life cycle thinking, LCA methodology and LEED system, having a more conceptual approach [87]. The authors used a case study to investigate the energy use of the same building in different locations, analysing the energy, economic and environmental performance of that building. They concluded that the same building in different countries have considerable different results, demonstrating that LEED system must be adapted if used in locations outside USA.

Recent works on sustainable performance are focusing on multi-objective optimisations, automatic certification, and waste minimization. For instance, a recent and interesting work coupled life cycle cost (LCC), ecological footprint (based on the agricultural potential of the land), and $CO_2$ emissions [88], resulting in a tool that assesses multiple design alternatives. Nonetheless, the developed tool only allows users to define the project's information (e.g. material type for the whole project), instead of reading the object's information. This option is understandable, as the authors aim was solely to develop a tool that could assist structural engineers.

#### *4.2.3. Sub-category: Building Performance*

The last sub-category of Sustainable Construction category is the **Building Performance**, which covers studies in the field of daylighting simulation, decision-making processes, and thermal behaviour of buildings. An interesting work in the domain of daylighting simulation was conducted by Kota et al. [89], which integrated a BIM tool, Revit, with Radiance and DAYSIM (daylighting simulation tools). The authors intended to throw light on the benefits and challenges resulting from this integration with their study and concluded that, while BIM lacks some information required for simulating daylight analysis, it nevertheless has the possibility of incorporating the necessary information. A similar study was done by Díaz-Vilariño et al. [90], which used as-built BIM models as an input of daylighting simulation tool. A set of laser scanners were used to generate the as-built BIM model, using the gbXML schema. Afterward, the BIM file was imported in Ecotect software, which performed the daylighting simulation.

Envisioning the environmental potential of BIM, Cheng and Ma [91] integrated a BIM-based system to manage waste due to demolition and renovation. The tool they developed serves not only to estimate the waste resulting from demolition and renovation, but also to calculate disposal charging fees and the requirements in terms of waste-loading trucks. Focusing on the thermal comfort, Marzouk and Abdelaty [92] studied an underground station using wireless sensors and BIM to monitor thermal conditions inside the station. While the sensors network was used to measure air temperature and humidity levels, BIM was used as a visualisation tool for those readings. This way, operators will have a tool to identify spaces with more deficient thermal conditions and implement corrective measures. A more recent study developed by Liu et al. [93] applied particle swarm optimization (PSO) algorithm to optimise a building's performance, based on life cycle costing (LCC) and life cycle carbon emissions (LCCE). An advantage of such optimisation is the possibility to solve multi-objective problems, as the LCC and LCCE minimization, as well as quickly perform multiple design solutions.

### 4.3. Category: BIM Adoption and Standardisation

**BIM Adoption and Standardisation** (Table 6) is the category with the third highest number of published papers, being an area that has been explored since the early phases of BIM research. It registered a significant increase in the number of published papers in the last three years due to growing interest in adopting BIM, either voluntarily or out of necessity. A research topic that we identified is the automation of rule checking, where national rules and standards are incorporated in the BIM models, saving time in the identification of irregularities. Surprisingly, there are few papers studying existing BIM standards/protocols and comparing them. This shows that, in the period under review, there has been a lack of interest in thoroughly studying this important aspect of harmonising BIM standards, at a time in which the AEC sector is becoming increasingly more global. Also, in this category was identified another research focus, the assessment of the adoption of BIM at national and at enterprise level. However, the authors identified a gap in the literature with regard to the assessment of BIM adoption in a whole region (e.g., at the European level) with the same indicators, as opposed to in a single country (where comparative studies are carried out using a common survey methodology and framework). Finally, it is also worth noting that another identified sub-category, the BIM Training & Education, accounts for only three published papers, what we consider to be another gap in the BIM literature. Either this type of interest is more covered by lower impact journals and proceedings or scholars are more interested in the practical side of BIM methodology. However, this field could be an opportunity to promote interest in BIM amongst young students and overcome the resilience to BIM in university engineering/architectural courses. Finally, the last sub-category incorporates studies that focus on the benefits due to the adoption of BIM, as well as ROI studies. As a result, BIM Adoption and Standardisation sub-categories were: (i) Rule Checking & Standards; (ii) BIM Benefits & ROI; (iii) BIM Adoption; and (iv) BIM Training & Education.

#### 4.3.1. Sub-category: Rules Checking & Standards

A topic that is gaining momentum in these last years, despite its first study being published in 2008, is the **Rules Checking & Standards**, with several studies covering the automation of rules checking and analysis of standards. Regarding the latter, Howard and Björk [94] developed a framework that group the existing BIM standards according to their application on building projects. The study showed that northern European countries, such as Finland and Norway, and Singapore have been more willing to promote the use of IFC than the USA, and that international organisations, such as ISO, have an important role to play in the success of IFC implementation. Further studies on IFC standards were done by Zhiliang et al. [95], which developed an IFC-based information model to test the implementation of the IFC standard for construction cost estimation for tendering in China, concluding that the current version of IFC cannot yet support direct data exchange with applications used in China. Also, Choi et al. [96] developed an automated BIM-based evacuation regulation checking system for high-rise and complex buildings, the InSightBIM-Evacuation, reducing the time spent on the regulation checking process. Another interesting study was developed by Zhang et al. [97], which created an automated rule-based checking system for fall protection in a BIM model, in which Occupational Safety and Health Administration (OSHA) rules were successfully incorporated into the system. More recent studies in this specific subject are focusing on the use of object-oriented modelling (through IFC schema) to incorporate national rules within the project [98], with several issues remaining unsolved as the lack of semantic information within the model.

#### 4.3.2. Sub-category: BIM Benefits & ROI

In the second sub-category, **BIM Benefits Assessment and Return on Investment**, a number of studies have focused on the benefits of using BIM in projects and BIM ROI analysis. Both Barlish and Sullivan [99] and Chien et al. [100] published papers on the subject using the Case Study research method. While the former developed a framework model to determine the value of BIM, the latter studied the risk factors associated with BIM adoption using a questionnaire survey. These papers provide a clear picture of BIM benefits, as well as the inherent risks, with the lack of standardisation and the lack of personnel training appearing to be a hindrance to total exploitation of BIM benefits (e.g., design and construction costs). Continuing the work of Barlish and Sullivan [99], a new conceptual framework for asset owners to measure the benefits of implementing BIM was later proposed by Love et al. [101]. Some work has also been carried out to assess the cost-benefit ratio and BIM ROI, with Giel and Issa [102] obtaining a huge ROI variation of 16 to 1654% as a result of the adoption of BIM by the company studied, and Lee et al. [103] obtaining a ROI between 22% and 335% based only on the avoidance costs due to project delays, when BIM is used. However, Love et al. [104] were more sceptical and conservative, arguing that the ROI values obtained by Giel and Issa [102] could be overinflated and that the lack of a standard approach for collecting data used in the ROI analysis could have a negative effect on the exactness of the results. Love et al. [104] concluded that ROI is an incomplete tool for fully evaluating the benefits of BIM implementation.

#### 4.3.3. Sub-category: BIM Adoption

Another important sub-category that we identified, and of major importance to the understanding of BIM dissemination and implementation challenges, is **BIM Adoption**. Within this sub-category authors studied the challenges of adopting BIM at national and at organisation level and how it could be promoted through procurement. The BIM Implementation sub-category is of extreme importance, as the studies reveal not only “global barriers”, but also cultural aspects that influence the success of BIM adoption.

In relation to the barriers and challenges of BIM adoption at national level, Rezgui et al. [105] did a wide study in the UK, through a qualitative approach based on workshops and a focus group. Another study of BIM adoption in the UK was developed by Eadie et al. [106], which surveyed 92 BIM users, using a questionnaire to assess the impacts of BIM on their

**Table 6**
BIM Adoption and Standardisation category.

| Category and sub-categories | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | Total | % |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| BIM Adoption and Standardisation | 0 | 0 | 2 | 2 | 7 | 5 | 4 | 15 | 8 | 13 | 56 | 14,7% |
| Rule Checking & Standards | 0 | 0 | 1 | 0 | 1 | 1 | 0 | 2 | 1 | 4 | 10 | 2,6% |
| BIM Benefits & ROI | 0 | 0 | 1 | 0 | 0 | 0 | 2 | 4 | 5 | 3 | 15 | 3,9% |
| BIM Adoption | 0 | 0 | 0 | 2 | 5 | 3 | 2 | 9 | 2 | 5 | 28 | 7,3% |
| BIM Training & Education | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 1 | 3 | 0,8% |

daily activities, with the collaborative environment and management process behind BIM being the most important aspects. While in the former case, the authors proposed a governance approach for BIM management and developed a roadmap for BIM adoption structured in three maturity stages, in the latter case, the authors developed a ranking system for the financial benefits of BIM adoption. Both studies concluded that, notwithstanding the benefits of BIM, it was necessary to make significant investments in software, equipment and training to facilitate implementation by SMEs (small and medium-sized enterprises).

The adoption of BIM has been studied in several countries. For instance, Linderoth [107] and Samuelson and Björk [108] studied BIM adoption in Sweden by using questionnaires, semi-structured interviews, participant observations and participation in meetings. Both authors found that BIM adoption is still in its early stages, but some aspects, such as cost reduction thanks to the use of BIM in projects, contractual agreement for compulsory use of BIM, regulation tools, etc., would benefit from the adoption of BIM. Other authors studied BIM adoption in Australia, as Gu and London [109], Kraatz and Hampson [110], and Forsythe et al. [111]. Although these studies lacked the scope and amount of quantitative data of the aforementioned studies, they showed that even Australian market leaders have a different perception of BIM and are uncertain of BIM adoption throughout the industry, with the AEC sector having limited use of BIM methodology and technology. In China, the adoption of BIM was studied by Xu et al. [112], using a questionnaire based on hypotheses built by an initial semi-structured interview with BIM experts. In addition to the conclusions already mentioned above, Xu's study also revealed that Chinese BIM users feel that existing BIM tools reflect foreign concepts more than their own, resulting in an additional barrier. Furthermore, some respondents have not fully grasped the BIM concept and what differentiates it from ordinary CAD tools, believing that BIM is not worth the implementation costs. However, other studies revealed different conclusions for other countries [113,114], demonstrating that BIM implementation success might also depend on cultural aspects as well. The authors surveyed both professionals and students in order to find out their interests on BIM, which showed that it is thought that BIM can aid in the field of sustainable construction, information management and integrated project delivery (IPD). The respondents also said that interoperability, lack of legislation, and organisation's attitude towards innovation are amongst the most challenging barriers that BIM will have to face, being confirmed by Watson's study [115]. Another study also showed that facilities management organisations that implemented BIM are using it mostly for energy management and maintenance purposes [116] and that building components' location (e.g. equipment) and real-time data collection are areas with potential application.

At the organisational level, BIM implementation play a key role, as demonstrated in the last paragraph and by Dossick and Neff study [117], which showed that organisational aspects between involved parties can hinder the collaboration amongst them. However, if successfully implemented within an organisation, BIM allows to achieve better results as argued by Leite et al. [118]. In their study, it was demonstrated that professionals proficient in BIM are able to model high levels of detail (LoD) without necessarily having more modelling work than with lower LoDs, leading to a more compressive analysis of the project. A very interesting article that covered BIM adoption in organisations was developed by Succar [119]. In his study, Succar reviewed existing international guidelines in order to produce a "BIM Framework", allowing industry stakeholders and academics to understand the requirements of BIM implementation. By proposing a multi-dimensional knowledge model that covers BIM fields (fields of activities), BIM Stages (maturity levels), and BIM Lenses (knowledge domains), the author structured the processes and domains within BIM environment. Another study on BIM implementation within organisations was conducted by Taylor and Bernstein [120], which combined qualitative and quantitative data of 26 firms that use BIM in order to identify different practice paradigms in project networks, concluding that as project experience increases, the firm-level BIM practice paradigm evolves as well. They also found that those firms that have progressed further along the practice paradigm trajectory are also those that are willing to share BIM files across the project networks, in contrast to firms in the early stages. Also, in Porwal and Hewage's [121] study, a BIM-partnering public procurement framework was proposed, laying the ground work for the introduction of BIM into the existing public procurement system. Another contribution for BIM-based procurement processes was done by a framework developed by Ren et al. [122], which integrates BIM with electronic commerce (e-commerce), aiding in quantity take-off and cost estimation tasks that could be used for tendering purposes.

#### *4.3.4. Sub-category: BIM Training & Education*

Amongst the 381 analysed papers, only three studies focused at **BIM in the context of training/education courses**. In their study, Peterson et al. demonstrated how BIM-based project management tools contributed to the development of more realistic project-based class assignments, thus bridging the gap between academic problems and real-world problems in the field of project management [123]. Sacks and Barak's article studied the outcomes of the creation of a BIM course in the university, with students acquiring better spatial visualisation of the projects (mainly in orthographic views) and being able to complete design projects much faster than with CAD tools. The authors also argue that BIM course should not be an extension of CAD courses, but one with its own identity, believing that students do not necessarily need to learn CAD before or after the BIM course [124]. A more recent work surveyed the progression of computing in the AEC related courses, considering universities from across the world (i.e. USA, Europe, Asia, and Australia) [125]. In this study, the American Society of Civil Engineers (ASCE) conducted an online survey to identify the evolution in computational knowledge and skills in the AEC courses (architecture, engineering, and construction management). It was demonstrated by this study that computing skills have gained an increased importance within AEC courses, while computational knowledge is not deemed as important as the computing skills. However, the respondents pointed out that the current curricula are still not enough to suppress the actual needs of the construction industry, showing that further improvements should be made in the AEC courses.

### *4.4. Category: BIM Programming*

Most papers in **BIM Programming** category (Table 7) deal with the area of BIM tool development. Even though this field began to be explored in 2006, it is still developing, which seems to indicate that, while it is not a new trend, it still has a lot of potential. Several articles in this category focused on Parametric Modelling, as the appearance of new applications are stimulating object-oriented modelling to incorporate all the required information (e.g. intelligent objects). Other studies focused on the development of BIM-based tools, constituting the largest sub-category in this review, with a total of 39 papers. The interest in this topic is certainly due to the process automation, which reduces as much as possible the tasks that professionals have to perform when developing new tools and testing new possibilities. This specific field is also closely connected with distinct activities, such as construction management, structural analysis, sustainability, etc. The Cloud Computing sub-category is also a relevant research field, as the development of projects is today conducted at a distance and collaboratively, meaning that the exchange of information and files must be as swift as possible. As a result, this category includes the following sub-categories: (i) Parametric Modelling; (ii) BIM Tool Development; and (iii) Cloud Computing.

#### *4.4.1. Sub-category: Parametric Modelling*

The first sub-category that we considered is **Parametric Modelling**, with authors studying the benefits of information manipulation of BIM objects. Early studies on parametric modelling were done by Lee et al. [34], which proposed a building object behaviour (BOB) notation and

**Table 7**
BIM Programming category.

| Category and sub-categories | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | Total | % |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| BIM Programming | 3 | 0 | 1 | 4 | 4 | 4 | 6 | 10 | 10 | 14 | 56 | 14,7% |
| Parametric Modelling | 1 | 0 | 0 | 0 | 0 | 1 | 1 | 3 | 0 | 1 | 7 | 1,8% |
| BIM Tool Development | 2 | 0 | 1 | 4 | 2 | 2 | 4 | 5 | 8 | 11 | 39 | 10,2% |
| Cloud Computing | 0 | 0 | 0 | 0 | 2 | 1 | 1 | 2 | 2 | 2 | 10 | 2,6% |

description method in the area of precast concrete construction that could be used as a guide for implementing parametric objects. Building on Lee et al.'s work, Cavieres et al. [126] accomplished automatic geometric modelling, not only by developing a parametric modelling tool for early-stage design, but also by adapting the BOB method to concrete masonry design. A similar study was developed by Lee and Ha [127], which proposed a costumer interactive BIM (CIBIM), a 3D parametric modelling tool, that allows clients to easily visualise and model a building's solution according to their own desires. Despite the advantages of this tool, as error reduction and disposal of unnecessary models, additional time and effort is required at early phases of the project.

*4.4.2. Sub-category: BIM Tool Development*

Another identified sub-category, with papers dating from 2006, focused on the **development of BIM tools** for the optimisation and processes automation. According to Welle et al. [128] the improvement in BIM-based tools through optimisation methods would benefit the automation of processes, as observed in their proposed methodology "BIM-based Daylight Profiler for simulation" (BDP4SIM), which simulates climate-based daylighting, and the Revit plug-in based on evolutionary computing developed by Rafiq and Rustell [129]. Another automated building design analysis was achieved in Sanguinetti et al.'s article [130], where a novel system architecture was proposed to improve architectural design. In their study, the need for manual input of information (e.g. energy consumption and preliminary cost) was significantly reduced, as that information is automatically obtained through post-processing of building models, consequently reducing designers' effort when testing different solutions.

Within this sub-category, some authors have also explored the visualisation capabilities of BIM models, developing some visualisation BIM tools. For instance, in 2009 Sacks et al. [131] it was developed two prototypes based on BIM's visualisation potential, improving safety planning and workers' coordination. The authors argue that BIM-based visualisation interfaces are a great solution to improve workers' communication and tasks planning. Based on the results of this article, Sacks et al. [132] implemented a BIM-based construction management system, KanBIM, to support on-site production planning. This innovative system allows the construction teams to visualise the construction of the product and its process through large on-site touch screens, supporting decision making processes and real-time evaluation of tasks. Building on [132], Davies and Harty [133] developed a similar tool, SiteBIM, to assist construction operations. However, unlike the large touch screens used in [132], tablets were the chosen interfaces to support workers. Another original article that enriched the visualisation capacity of BIM was developed by Yan et al. also [134], through the integration of BIM with gaming. As an outcome, the users are able to interact with a virtual model in order to evaluate how different buildings solutions can have an impact on occupants (e.g. accessibility design), having a strong pedagogical value when used by students.

Other authors narrowed BIM tools applications to support specific activities or processes such as reinforced concrete, glass reinforced concrete, and temporary structures, as well as specific tools for facilities managers (FM). The specifications for a tool that could assist the construction process of cast-in-place reinforced concrete was proposed by Barak et al. [135], in which the authors identified the necessary information to support the design and construction activities of all involved parties. With regard to FM-based tools, some interesting applications have been developed such as the "Serious Human Rescue Game", by Rüppel and Schatz [136], which explores human behaviour during a fire emergency evacuation. Also, Vanlande et al. [137] developed a method to collect and combine lifecycle information on a building, resulting in a collaborative internet platform called Active3D. This platform serves to store and exchange documents and handle IFC files during the lifecycle of a building. However, it is not suitable for FM during building operation phase. Motamedi et al. [138] used RFID tags for the indoor locating of assets in the operational phase of buildings, without requiring a fixed Real-Time Location System (RTLS) infrastructure. An original synergy with BIM was achieved by Thompson and Bank [139], which used a BIM model to populate a System Dynamics (SD) model for analysing a building exposed to a bioterrorist attack. This BIM-SD model is able to compare different building solutions to determine the best possible performance in case of such situation. It is argued by the authors that the integration of SD with BIM can improve the synergies with other simulation programs as well, as it offers the possibility to integrate all separate models into a single decision-making process.

*4.4.3. Sub-category: Cloud Computing*

The last sub-category that we identified is the **Cloud Computing**, with articles studying the benefits of internet-based computing integration with BIM applications. This sub-category emerged in 2010, with Grilo and Jardim-Gonçalves [9,140–142] studying how BIM and Cloud Computing could improve/advance interoperable electronic procurement, resulting in the SOA4BIM framework and the Cloud-marketplace concept. In 2012, Redmond et al. [143] conducted a set of interviews with users of cloud computing integrated with BIM, which showed that the development of a super-schema is needed in order to read various BIM formats. However, issues such as privacy and security must be properly addressed before the Cloud BIM information exchange mechanism, which would enhance the collaboration between different specialities, is created. Chong et al. [144] also concluded that cloud computing applications could enhance the communication and information flow during the project life cycle. As compared to the standard modelling workflow, Chen and Hou [145] developed an online platform for inter-disciplinary collaboration and proposed a hybrid client–server and peer-to-peer (P2P) network to enable it, resulting in increased modelling efficiency and time savings. More recent studies on cloud computing are considering real-time data collection for processes monitoring [146] and performance tests [147].

*4.5. Category: Image Processing, Laser Scanning, and Augmented Reality*

The **Image Processing, Laser Scanning, and Augmented Reality** (Table 8) category provides some insight into the research work carried out in the fields related to image and 3D capturing, processing and improvement. As we have seen, most of the papers in this category are from the last three years, meaning that this is a very recent area of study. One of the identified sub-categories with the highest grown and number of published papers is the Laser Scanning, a technology able to aid in the monitoring of construction tasks and generate as-built models. Other sub-category that require state of the art technology, is the integration of BIM with Augmented Reality (AR), combining the real world with virtual objects (partial immersion), and with Virtual Reality (VR), where the user visualise a virtual world that is not real (total immersion), through special glasses. This field is interrelated

**Table 8**
Image Processing, Laser Scanning, and Augmented Reality category.

| Category and sub-categories | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | Total | % |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Image Processing, Laser Scanning and Augmented Reality | 0 | 0 | 0 | 1 | 2 | 2 | 3 | 10 | 11 | 12 | 41 | 10,8% |
| Image Processing | 0 | 0 | 0 | 1 | 0 | 1 | 1 | 1 | 2 | 2 | 8 | 2,1% |
| Laser Scanning | 0 | 0 | 0 | 0 | 2 | 0 | 1 | 5 | 5 | 9 | 22 | 5,8% |
| AR-based Framework/Application | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 4 | 4 | 1 | 11 | 2,9% |

with other fields within BIM literature that can make use of the visualisation potential of the BIM model, such as Facilities management (e.g. visualise elements behind existing walls). As such, it is expected to be further explored in the near future. Finally, Image Processing is the last sub-category that we identified, with researchers using on-site photos to verify actual as-built conditions. The sub-categories are the following: (i) Laser Scanning; (ii) AR-based Framework/Application; and (iii) Image Processing.

*4.5.1. Sub-category: Image Processing*

The first sub-category that we identified is the **Image Processing**. In this field, by using an object-based approach to monitoring detailed interior construction progress, Roh et al. [148] compared an as-planned 3D BIM models with as-built photographs, providing the user with realistic insight into the interior construction process. Focusing on the incorporating laser scanning into drilling processes, Akula et al. [149] used point cloud data from 3D imaging technologies to automatically identify safe zones for drilling. With a different focus, both Klein et al. [150] and Motamedi et al. [151] integrated image processing with Facilities Management. Klein et al. [150] used photogrammetric image processing to document and verify actual as-built conditions using BIM. However, the image-based survey did not meet the FM quality assurance standards due to errors in the identification of as-built model dimensions. In the Motamedi et al.'s article [151] it was proposed an FM Visual Analytics System (FMVAS), an integration of Computerised Maintenance Management System (CMMS) with BIM that harnesses the potential of knowledge-assisted BIM-based VA for a failure root cause detection scenario (e.g. thermal conditions) using the cognitive and perceptual reasoning of FM technicians. Despite the differing approaches and results, both authors used the visualisation capabilities of BIM to assess the quality of the construction, demonstrating how useful it can be in facilities management. Also, other authors focused on the automated progress monitoring from unordered photo collections [152, 153]. While in [152] the authors used a vision-based method for material classification from several photos of construction site, registering an accuracy of 97.1%, in [153] Golparvar-Fard et al. used the results of a similar method to improve the progress monitoring of the construction by using a 3D viewer that highlighted all observed deviations. Also, a 4D as-built and as-planned model was automatically generated in [153], being the first study that incorporates both models with unordered daily photographs.

*4.5.2. Sub-category: Laser Scanning*

The articles that focus on the automatic BIM model generation based on the point cloud by using 3D laser scanning technology were grouped in the **Laser Scanning** sub-category. In this sense, Brilakis et al. [154] were amongst the first researchers to study this field, automatizing as-built modelling through video and laser scanning data. In the proposed frameworks, the built environment is scanned, generating images and point clouds. Then, videogrammetry is used to identify objects coordinates, spatial correlation is used to generate the 3D surfaces out of the point clouds, and the object recognition is made through image analysis tools. In this last part, image tools were connected to an external database that contained several potential objects that could be present in the built environment. As a result, the proposed framework successfully generated an as-built model by employing laser scanning technology. However, the authors highlighted that the current framework still needed considerable improvements in the field of semantic information. Similarly, Xiong et al. [155] automatically converted 3D point data from laser scanning systems into a rich information model, while Tang et al. [156] developed an automatic process to generate as-built BIMs, taking into account geometric modelling, object recognition and object relationship modelling, as in [154]. In Tang et al.'s article it was also explored and evaluated the main methods/techniques that could potentiate the as-built model creation, which demonstrated the need for higher automation in it. An as-built model was also developed in Lagüela et al.'s work [157] through the semi-automated processing of laser scanning point cloud for the purpose of thermal characterisation.

Recognising the added value of laser scanning technology, Mahdjoubi et al. [158] argued that a new market could be opened up for real estate companies based on the development of digital models incorporating energy performance information. Nevertheless, the cost of, and insufficient knowledge on, 3D Laser scanning technology is still a constraint in most cases, despite the benefits for health monitoring, such as automatic detection of a building's condition. Another article that covered the earned value of laser scanning technology was developed by Turkan et al. [159]. The authors conducted an experiment where recognised objects were automatically transformed into their earned values, using project cost accounts and object quantities on spreadsheets. It was shown by their experiment that this automatic transformation can improve the accuracy of progress monitoring of 4D BIMs. The same authors improved the system on a more recent paper [160].

Still in the Laser Scanning sub-category, another special field that was explored is the Terrestrial Laser Scanning (TLS), which uses TLS technology to generate 3D point clouds to create BIM models. Despite the apparently small range of application for BIM-TLS integration, these studies focused on a diverse range of aspects of construction. While Mill et al. [161] used TLS (a point cloud) to create a BIM model as the basis of a digital management model for façade damage detection, Jung et al. [162] argued that a new TLS approach should be used for the generation of indoor structure through point cloud, resulting in data-size reduction of 5% while productivity and reliability increased. Bosché [163] and Anil et al. [164] also analysed productivity gains comparing a 3D as-built model with a 3D as-planned model and concluding that it is possible to identify many more errors in less time. On the other hand, Bosché and Guenet [165] developed an approach to automatic surface flatness control using BIM-TLS integration, by matching each point of the point cloud to the corresponding object in the BIM model. Notwithstanding, several challenges were identified in relation to BIM-TLS integration, such as the quality of the databases used and automatic extraction of planes from point clouds.

*4.5.3. Sub-category: AR-based Framework/Application*

The last sub-category that we identified is the **AR-based Framework/Applications**, with some authors exploring the BIM-AR integration for on-site information retrieval, enhancement of construction defect management, visualisation techniques, etc. In this field, Wang et al. [166,167] first developed a conceptual framework that integrates BIM with AR in which technologies such as RFID, laser pointing, sensors and motion tracking are able to increase the effectiveness of BIM-AR integration. However, while the framework in [166] lacked empirical testing to assess its effectiveness in as-built environments, in [167] mobile device-based AR (e.g., iPad, iPhone, tablet) tested this framework in a real environment, on activities such as inspection, data acquisition for recording construction surveys and collaborative and information-sharing platforms. A similar study was conducted by Yeh et al. [168], where a device called iHelmet provided users with information related with drawings. Not only this system allowed users to achieve the correct answer faster but also improved the understanding of the construction drawings. Meža et al. [169] also studied how BIM can feed information into AR-based systems resulting in a mobile AR system, which was tested in a real case study. Both Meža et al. [169] and Wang et al. [166,167] found that BIM-AR integration systems should include a more comprehensive 4D and 5D dimension BIM model and that the lack of standardisation of information and communication technology (ICT) tools is an issue that must be tackled. Similar to [169], Lee and Akin [170] developed an AR-based system (AROMA-FF) to support operation and maintenance (O&M) activities. Sensor-based technology delivers input for this system, providing O&M workers with real-time geometry and specification data of equipment, as well as maintenance history. However, when obtaining sensor-based data there is no noteworthy difference between the new system and conventional systems. Other limitations were found, as the compulsory use of keyboard and mouse, non-feasibility of deploying sensors for all equipment and objects within the facility, and is not compatible with smart phones. Another study that integrated AR with BIM was conducted by Park et al. [171], which developed a conceptual system framework for proactive construction defect management that integrates AR with BIM, seeking to reduce defect occurrence during the construction process. However, this framework faced some issues as there was a lack of a defect management information tool for BIM-based software and there were errors in the AR-based markers.

### *4.6. Category: Facilities Management and Safety Analysis*

**Facilities Management (FM) and Safety Analysis** (Table 9) is one of the categories with the lowest number of papers. However, in the past two years it has attracted the interest of several researchers. Researchers are currently trying to automatically identify hazard situations and integrate them with BIM-based tools, in order to improve FM operations, as well as develop frameworks to integrate building management and BIM. These two fields are clearly a new trend in BIM research and show great potential. Our qualitative analysis of this category led to the definition of the following sub-categories: (i) Safety Management; and (ii) Building Management and Maintenance.

#### *4.6.1. Sub-category: Safety Management*

One area that has caught the interest of a growing number of researchers in recent years is **Safety Management** for buildings. In this sub-category, Fire safety analysis is of major importance. In this sense, Abolghasemzadeh [172] considered the behavioural responses of occupants in the event of a fire in a building, with a view to calculating the most suitable escape route using an egress analysis. The originality of this study was that it considered the occupants' familiarity with the building and acquaintance with escape routes. Li et al. [173] developed a BIM-centred algorithm, Environment-Aware radio frequency beacon deployment algorithm for Sequence Based Localization (EASBL), for locating first responders and trapped occupants in fire emergency scenarios. BIM was used to supply geometric information as an input to the EASBL as well as a graphical interface for user interaction. However, despite the satisfactory results, the computational efficiency, or the lack thereof, in processing building geometries was one of the limitations of this study.

A number of studies also looked at the use of automatic processes for safety analysis, fall prevention, and confined space safety. For instance, Hu and Zhang [174] and Zhang and Hu [175] published two articles that analysed the structural safety during construction works by proposing a new approach that integrated 4D BIM and safety analysis. This new dynamic approach enables construction managers to dynamically analyse and avoid possible collisions due to changes in the construction schedules, being successfully tested in three real pilot cases. Park and Kim [176] have also worked on safety analysis, however, instead of considering 4D BIM as in [174,175] the authors have integrated BIM with augmented reality and location tracking technologies. This novel visualisation-based system can improve risk identification and real-time communication amongst workers, and also work as a safety educational tool. Although users recognised this innovative system potential, they still have identified some limitations, mainly in the communication between workers and in the tracking devices' accuracy. A more recent study also uses location tracking technologies for safety planning [177], with the authors observing the same problem of limited accuracy of GPS. However, in [177] the authors focused more on the visualisation and resolution of potential conflicts while in [176] the authors also studied the communication between workers. A novel aspect in [177] was the use of air drones to collect as-built photos of construction site to aid in the identification of spatial constraints. Another original article was designed by Wang et al. [178], which integrated BIM with firefly algorithm (FA) to improve tower crane layout planning, allowing construction managers to automatically generate, simulate and visualise the cranes' location. This system not only avoids human errors as identifies possible collision courses between cranes or with construction elements. Its feasibility was proven by a case study, with the system identifying a collision between a crane and a beam, which would reduce the construction productivity or even create hazardous situations. Focusing on confined space safety, Riaz et al. [179] integrated BIM and sensor technology to reduce safety hazards in confined spaces, resulting in the Confined Space Monitoring System (CoSMoS). CoSMoS not only monitors the oxygen and temperature levels, but also highlights and enables alerts in problem areas using Revit. The advantage of this system is that it can be used during both the construction and operation phases, gathering data throughout a building's lifecycle. Nevertheless, false alarms can occur if the sensing subsystem reader is far from the wireless sensor, and battery lifetime in the sensors is also an issue that needs to be addressed.

#### *4.6.2. Sub-category: Building Management and Maintenance*

The other identified sub-category is **Building Management and Maintenance**, which is the subject of a number of papers covering maintenance processes and automatic processes to support building management. The management of built environment represents a key role in the most recent studies in BIM literature, as operational costs (e.g. energy consumption, maintenance, waste treatment, etc.) are far higher than construction costs only. In this field, Motawa and Almarshad [180] developed an interesting work, where data of building maintenance operations is collected and used to identify how a building condition is worsening, leading to the development of better preventive actions. The methodology used by the authors is based on the integration of BIM, to collect relevant information, and Case-Based Reasoning (CBR), to collect knowledge, as BIM tools alone are not able to fully

**Table 9**
Facilities Management and Safety Analysis category.

| Category and sub-categories | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | Total | % |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Facilities management and Safety Analysis | 0 | 0 | 0 | 0 | 0 | 2 | 3 | 5 | 9 | 11 | 30 | 7,9% |
| Safety Management | 0 | 0 | 0 | 0 | 0 | 2 | 2 | 3 | 6 | 9 | 22 | 5,8% |
| Building Management and Maintenance | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 2 | 3 | 2 | 8 | 2,1% |

understand the knowledge acquired from such operations. By integrating both methods, maintenance teams will not only learn from historic data but also from previous experience, paving the way for "Building Knowledge Modelling". Another work was described in Lucas et al.'s article [181], which proposed a BIM-based framework for healthcare facilities to capture and store FM information during the operation and maintenance phases, as well as a classification system. Lu and Olofsson [182] proposed the integration of Discrete Event Simulation (DES) with a BIM model. In the BIM-DES framework, while BIM provided product and process information to DES, DES evaluated the construction performances, providing feedback to the BIM model at the end of the process. Another system was proposed by Zhang et al. [183], which developed a system that uses RFID sensors to monitor the deformation of structures, automatically highlighting in the BIM model an element whose safety limits have been surpassed.

### 4.7. Category: Construction Management

Registering consistent growth in recent years, the **Construction Management** category (Table 10) has attracted increasing attention lately, except in 2015. Schedule Management has attracted the increasing attention of BIM researchers and designers, unveiling the potential of BIM with regard to the optimisation of schedules and in their visualisation, especially if Genetic Algorithms are used. The use of GAs can also generate new opportunities for multi-objective optimisation of construction schedules, resource usage and cost of assembly. However, very few studies focused on the Quantity Take-off capacity of BIM tools or even in the use of BIM in Cost Estimation processes. This category is made up of the following sub-categories: (i) Schedule Management; (ii) Quantity Take-off; and (iii) Cost Estimation.

#### 4.7.1. Sub-category: Schedule Management

The earlier studies focused mainly on the area of **Schedule Management**, with authors focusing on schedule improvements through BIM-based frameworks and applications, optimisation methods, and benefits of automation. The first study that focused on the 4D aspect of BIM was published in 2008, by Goedert and Meadati [184]. The authors have used both CAD and BIM tools to develop a 3D model and incorporate the information/documents of the construction processes. However, in 2008 the 4D modelling of BIM tools were very limited, with the authors point out that not only have they spent more time in creating the 3D model than with standard 2D tools, but also that BIM tools were unable to display the 4D environment without additional programming. More recently, Song et al. [185] proposed a BIM-based framework for managing construction planning and scheduling based on 3D geometric data and process data that served as input data for the creation of a construction schedule. This 4D simulation also compared different construction schedules, choosing the most optimal one. Chen et al. [186] also proposed a BIM-based framework to achieve a near-optimum schedule plan in accordance with project objectives and constraints, resulting in the N-Dimensional project Scheduling and Management system (NDSM). Two other teams integrated genetic algorithms (GAs) in Schedule Management: Moon et al. [187] and Faghihi et al. [188]. While, in the former case, the schedule-workspace interference was optimised based on a location-constraint GA and BIM, thus minimising the frequency of parallel work, in the latter case, a methodology was proposed for information retrieval from the BIM and fed to a GA, with a view to automatically generating a construction schedule. Developing the automation of tasks, Kim and Son [189] and Kim et al. [190] both used BIM models to automatically generate construction schedules, however, despite both articles have similar aims, the used approach is different. While in [190] the authors used 3D data collected in-site (by using remote-sensing technology) and then imported that data to a BIM tool, in [189] the authors imported the BIM model information into external scheduling software (MS Project). Regarding the advantages of using 4D BIM applications for quality control, Chen and Luo [191] explored the integration of 4D BIM with product, organisation and process (POP) data structure. Data consistency, easy understanding of quality defects and identification of zones that required quality inspections are some of the main advantages of this approach.

#### 4.7.2. Sub-category: Quantity Take-off

Another sub-category that we considered is the **Quantity Take-off**, encompassing works that use BIM to withdraw quantity maps automatically. In this sense, Babič et al. [192] used BIM as a link between an enterprise resource planning (ERP) information system and construction object-related information, for the purpose of monitoring and managing material flow for automatic calculation of material quantities. However, the model for that study included only the main building elements, with BIM being used in a limited environment for the purpose of information system integration. A wider study has been conducted by Said and El-Rayes [193] who developed an automated multi-objective construction logistics optimisation system (AMCLOS) to retrieve project spatial and temporal data from existing scheduling and BIM files, supporting contractors in integrating and planning material supply and site decisions. Lastly, Monteiro and Martins [194] focused on a more specific challenge, the potential limitations of BIM to answer distinct quantity take-off specifications, concluding that it is possible to adapt the model according to the specifications demanded.

#### 4.7.3. Sub-category: Cost Estimation

The last sub-category is **Cost Estimation**, with some authors developing automatic tools or processes for building cost estimation (5D BIM). For instance, Cheung et al. [195] proposed a multi-attribute-based tool for cost estimation in their study, implemented on Google SketchUp as a plug-in, which assesses functionality, economics and performance of buildings. Another interesting article was developed by Hartmann et al. [196], which used two BIM tools, one for cost estimation while the other was for risk management, in order to contribute for the dissemination of BIM implementation within organisations. By doing so, the authors demonstrated the feasibility of integrating both tools and the benefits of using BIM technology for construction management. The benefits of using 5D BIM for construction management was also explored by Popov et al. [197]. The authors developed a methodology for project management in the 5D environment based on the study of BIM applications and Virtual Project Development (VPD), supporting the calculation of resources, cost estimation, schedule management, etc. Focusing more on the tendering stages of a project, Ma et al. [198] proposed a semi-automatic IFC-based information model for tendering for building projects (TBP), which reduced estimators' workload and possible errors.

**Table 10**
Construction Management category.

| Category and sub-categories | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | Total | % |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Construction Management | 0 | 0 | 3 | 0 | 2 | 0 | 6 | 6 | 7 | 3 | 27 | 7,1% |
| Schedule Management | 0 | 0 | 3 | 0 | 0 | 0 | 3 | 4 | 5 | 3 | 18 | 4,7% |
| Quantity Take-off | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 1 | 1 | 0 | 3 | 0,8% |
| Cost Estimation | 0 | 0 | 0 | 0 | 1 | 0 | 3 | 1 | 1 | 0 | 6 | 1,6% |

**Table 11**
BIM and Spatial Information category.

| Category and sub-categories | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | Total | % |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| BIM and Spatial Information | 0 | 0 | 1 | 0 | 0 | 3 | 2 | 3 | 2 | 2 | 13 | 3,4% |
| Geographical Information System (GIS) | 0 | 0 | 1 | 0 | 0 | 2 | 0 | 1 | 1 | 2 | 7 | 1,8% |
| Space Syntax | 0 | 0 | 0 | 0 | 0 | 1 | 2 | 2 | 1 | 0 | 6 | 1,6% |

### *4.8. Category: BIM and Spatial Information*

**BIM and Spatial Information** (Table 11) is the category that has the fewest papers in this literature review. Generally speaking, this category has remained constant over time, with BIM-GIS integration being the first subject to be studied. It was only later that the Space Syntax field began to attract greater research interest. However, the total number of papers published in this category (13) reveals a lack of interest on the part of academia. Nevertheless, the use of BIM with GIS and Space Syntax can offer great advantages in urban planning and construction operations with low levels of visibility, representing opportunities for future developments in this field. Researchers are starting to notice GIS's potential in early stages of BIM projects or in renovation projects, as it provides detailed geographical information of the asset location considering as well its surroundings, which could have an influence in a building's performance (e.g. shading analysis). The sub-categories identified were based around two major subjects: (i) Geographical Information System (GIS); and (ii) Space Syntax.

#### *4.8.1. Sub-category: Geographical Information System (GIS)*

The first field to be explored in this category by researchers was the integration of BIM with **Geographical Information System (GIS)**, with authors using BIM-GIS for a range of purposes. For instance, Isikdag et al. [199] assessed the implementation of an IFC-based BIM model in geospatial context with a view to improving the fire response operations and site location of a project, making use of the high level of geometric and semantic data of BIM models. With a different focus, Elbeltagi and Dawood [200] developed a BIM-GIS-based visualisation system to monitor construction performance, enabling nD visualisation of the construction progress by incorporating as-built site photographs. A similar approach was used by Bansal [201], which used a 4D GIS for space planning. In his study, Bansal argued that BIM tools still faces considerable challenges as geospatial analysis modelling of topography, and believed that more work must be done in order to effectively integrate BIM with GIS. However, more recent studies seemed to solved some challenges. In 2013, Irizarry et al. [202] used BIM-GIS integration in an original way, allowing designers to visualise the materials' supply chain by using a plug-in developed in Revit. In this study, the BIM model generates the quantity take-off, identifying which materials will be necessary in the construction site. Then the tool exports that information into a GIS module which will pinpoint the location of nearby suppliers and then estimate the cost and duration of the construction. As a result, BIM-GIS integration not only identifies the optimal solution for logistic costs but also detect the motive for materials delays. However, according to the authors, BIM-GIS integration still have some semantic interoperability issues. Later, Mignard and Nicolle [203] proposed a new approach called SIGA3D, built on the ACTIVe3D platform developed in [137], integrating BIM with GIS for urban facility management. This approach led to the creation of an Urban Information Model (UIM), which allowed for the modelling of information on a city on a platform for urban facility management, SIGA3D.

#### *4.8.2. Sub-category: Space Syntax*

The other sub-category that we identified is **Space Syntax**, a domain that makes use of spatial configurations to predict movement patterns and human behaviour. In this domain, Lee et al. [204] developed a tower crane navigation system that provides 3D information on a building, its surroundings and the lifted object in real time using sensors and a BIM model. Not only was this system tested on a construction site for 71 days, it was also a great support for tower crane operators during blind lifts. Other studies have been conducted by Jeong and Ban [205] and Langenhan et al. [206], who employed graph theory in order to recognise the extracted information from semantic BIMs and measure spatial configurations based on Space Syntax theory. However, for these approaches to be implemented optimally, IFC models must be well designed.

## 5. Conclusions

As seen in Section 3, BIM research has consistently grown in recent years, with more than 90% of the papers being published in the last five years of the period under review, meaning that the last five years were particularly productive in terms of BIM research publications. Furthermore, we have observed that early published papers were much simpler and more general (conceptual) than the current published papers, which are very specific and focused on the application of new methods and tools (using case study methodology). Despite the higher number of published papers in the last years, the quality and complexity of recent papers are substantially high, meaning that BIM field is reaching advanced levels of maturity.

Based on the bibliometric analysis and categorisation process, it was observed is that even though Collaborative Environments and Interoperability is the category with the most papers published, it was the BIM adoption and standardisation category that had the most cited articles (28%), being followed by BIM Programming (16%) and Image Processing, Laser Scanning and Augmented Reality (14%). In regard to sub-categories, the articles that scholars cited the most covered the study of BIM adoption, development of tools, application of laser scanning technology and reviews on BIM literature. Regarding the most cited scientific journals, Automation in Construction was the journal with the highest number of published articles on the top 100 most cited, with a total of 59 articles.

After we carefully analysed the content of the 381 articles and categorised them, the BIM categories that had the highest number of published papers were: (i) Collaborative Environments and Interoperability; (ii) Sustainable Construction; (iii) BIM adoption and standardisation; (iv) and BIM Programming. Accordingly, these four categories can be considered the main BIM research trends, with the Collaborative Environments and Interoperability having the highest growth rate in the last year, mainly pushed by studies on Semantic BIM and Ontology. However, “Facilities Management and Safety Analysis” and “Image Processing, Laser Scanning and Augmented Reality” can also be considered hot topics in BIM literature, as most of the papers on these areas were published in the last three years of the studied period.

Our analysis of existing BIM literature revealed that the subjects that can be considered as new trends or as having potential are: the development of BIM-based tools; Semantic BIM & Ontology; Rule Checking & Standards; Laser Scanning technologies; Schedule Management; Safety Management; Energy Performance; and Sustainable Performance. Despite the considerable amount of literature on BIM tools development (39), researchers are expected to continue to explore new synergies with BIM, as BIM-based tools will always be required to automate most of the processes. Also, Interoperability & IFC will continue to be studied in the near future, as the interoperability and potential of new software/tools will need to be carefully assessed. Another topic that incorporates the knowledge in tool development and interoperability is the study on semantics and ontology, which only in the last year resulted in 10 published papers, being the sub-category that had the highest growth rate.

However, a number of gaps were identified in BIM literature as well, namely: analysis and comparison of international/national BIM standards; assessment of BIM adoption over Europe; and BIM training and education papers that focus on BIM implementation at the academic level. Also, fields such as BIM-GIS, space syntax, and quantity take-off are not receiving much attention from researchers. Nevertheless, we believe that BIM-GIS integration can offer new opportunities in urban planning and construction operations with low visibility.

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