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A combined scientometric and conventional literature review to grasp the entire BIM knowledge and its integration with energy simulation

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Abstract

This paper presents an up to date overview of the principal research topics and research trends within the Building Information Model (BIM) research domain. It also offers a detailed review of the integration of BIM and Building Energy Performance Simulation (BEPS). The different strategies to improve interoperability are reviewed together with the various applications of such an integration (BIM with BEPS) in the literature.

Firstly, a scientometric analysis which allows identifying research patterns and emerging trends in a specific research domain is performed to categorise the large number of articles constituting BIM literature into several clusters, each representing a particular topic. The main research topic in each cluster, together with the chronological progress and evolution of each cluster are summarized through a literature review of the selected highly cited articles.

Secondly, an analysis of the different aspects relevant to the integration of BIM with BEPS is performed to highlight the evolution of the interoperability between BIM and energy simulation tools. Subsequently, a review of the different applications of such integration (BIM with BEPS) is performed to identify potential knowledge gaps.

This study highlights six main BIM research topics focusing on BIM adoption and benefits, BIM-aided management, progress monitoring and as-built modelling, interoperability, life cycle analysis and energy simulation. It also emphasises the lack of well-established strategies to ensure the interoperability between BIM and energy simulation tools. Furthermore, this study reports on the poor integration of BIM and BEPS for building system and control modelling as well as its limited application during the operational phase.

Keywords: Building Information Model (BIM), Building Energy Performance Simulation (BEPS), Scientometric analysis

1. Introduction

The recent years have seen a fast development of the digital representation of buildings referred to as Building Information Model (BIM). The concept of BIM stems from a need for improved collaboration and information exchange within the Architecture Engineering and Construction (AEC) industry. It is commonly recognised as a digital representation of a facility and is built upon a set of parametric visual objects (3D) that include geometric information as well as functional, semantic and topological information related to the different processes and applications involved during buildings' life cycle [1]. BIM acts as a complex, continually evolving, collaborative and centralised database among the various stakeholders (architects, engineers, consultants, contractors, etc.) contributing to better and well-informed decisions, time savings and cost reduction [2]. Although collaborative, technological and legal challenges need to be addressed [3], BIM adoption has the potential to improve building design, construction coordination, productivity, facility management, cost estimate accuracy while reducing clashes (up to 10%), omissions, construction time (up to 7%) and overall project cost [4].

Regulations and standards are implemented to promote and support the integration of BIM in construction projects. They are defined to precisely describe how BIM should be used and executed by the different stakeholders to ensure both the realisation and the maximisation of BIM benefits [5]. Regulations and standards can be at the national, state or city level and vary according to countries and contexts [6]; but generally cover topics such as interoperability, the role of BIM manager, collaboration, Designers' qualifications, BIM functions, level of development, operation and maintenance, BIM execution plan and fees [5].

In 2015, Cheng et al. [7] identified 47 BIM standards in the USA, of which 17 from government bodies and 30 proposed by non-profit organisations. As an example, in 2003, the General Services of Administration (GSA) released a guideline that imposes the use of BIM in some aspects of the construction project [6]. Similarly, as of 2015, 34 BIM standards were identified in Europe [7]; 18 of them being from the United Kingdom (UK) which is one of the first European countries to mandate the use

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Nomenclature

BIM: Building Information Model.
WOS: Web Of Science.
AEC: Architecture Engineering Construction.
CEN: European Committee for Standardization.
IFC: Industry Foundation Classes.
LEED: Leadership in Energy and Environmental Design.
MVD: Model View Definition.
BEPS: Building Energy Performance Simulation.
BCA: Building and Construction Authority
GSA: General Services of Administration.
ISO: International Organization for Standardization.
FGI: Focus Group Interview.
IDM: Information Delivery Manual.

of BIM especially in public sector projects. Likewise, this interests towards the use of BIM is translated by the increasing number of regulations in Asia. As an example, in Singapore, considered as the leading Asiatic country regarding BIM regulations [7], the Building and Construction Authority (BCA) mandated the use of BIM for all projects with a gross floor area above 5000 m^2 [8]. Finally, there are several international standardisation bodies such as the CEN TC442 which focuses on the standardisation of structured semantic information for the built environment; the ISO/TC59 which works on the organisation of information about construction works, and finally the buildingSMART association which provides solution to enhance information exchange between software applications in the construction industry [9].

Within this general framework of BIM, early research trends focus on enhancing building design, construction planning or cost estimation. However, the use of BIM has been later enlarged to other functions such as Building Energy Performance Simulation (BEPS). The integration of BIM with energy simulation consists of aligning BIM information with data requirements of the energy simulation tool. More specifically, it consists of automatically implementing energy simulation tool input using information from BIM [10]. The combination of BIM with BEPS can efficiently support design decisions, thus producing energy efficient and eco-friendly buildings.

As a result, a review of BIM in general and the integration of BIM with BEPS is an interesting tool to grasp the current BIM research and the state of the art of the integration of BIM and energy simulation. Such a combined review provides (1) insight into potential future research, current challenges and capabilities of BIM in general with (2) a closer view into its union with energy simulation.

Literature review studies are often performed to understand the extent of existing knowledge in a certain domain (e.g. BIM). For instance, Zhou et al. [11] investigate the potential of building's visual representation to address the diverse safety issues during construction. Tang et al. [12] reviewed different approaches that allow to document the differences between the design and the actual building (as-is condition) for the development of an as-built BIM. Volk et al. [13] reviewed the different approaches for the creation of a BIM for existing buildings. They stress the need to automate data acquisition as well as the necessity of an improved BIM management. Although appropriate and providing a thorough analysis, these studies often focus on a particular BIM aspect (e.g. Safety, existing buildings) and do not provide an overall view of the entire domain knowledge (BIM) and current research trends. This is understandable regarding the extensive body of literature related to BIM and its applications. An attempt to describe the entire BIM knowledge using the traditional (manual) study review process is potentially subjective since the study is drawn from a fraction of the existing papers and might fail to represent the entire domain knowledge [14, 15].

In recent years, scientometric reviews have been adopted to quantitatively assess the progress of a specific research area (e.g. BIM). For instance, Wei et al. [16] use scientometric analysis to identify the main research interests and focus over time of the Geographic Information System (GIS) knowledge domain. They specifically identify research patterns and trends in GIS. Similarly, Chen et al. [17] use scientometric analysis approaches to detect the academic landscape of the nanobiopharmaceutical research domain while Yu et al. [18] provide an overview of the aggregation operator research area.

The core of scientific literature related to a specific domain represents a comprehensive definition and representation of the past and actual knowledge of this specific topic. Consequently, the possibility to comprehensively and quantitatively analyse such literature resources in a generic way can yield valuable information about the specific interest in the field and provide a broad view on the topic and its current status and relevance.

A scientometric review relies on a statistical analysis of the relationships between different scientific contributions (papers) from which statistical indexes that indicate research patterns and emerging trends are calculated. In the present context, a scientometric review will allow to provide the ”big picture” of the different applications and the use of BIM worldwide. Another advantage of a scientometric analysis is the possibility to examine a changing focus over time: the primary research interests over the past few years but more importantly the future needs and development [19]. In that regard, scientometric analysis allows to identify when and how a specific topic started to attract researchers' attention, what are the most active subtopic and which developments have occurred from then to the current state of the art. It could then serve as a guide to identify and analyse the most relevant papers.

In 2015, Yalcinkaya et al. [14] applied latent semantic analysis to identify the research pattern in BIM from the BIM-related academic articles published between 2004 and 2014. Journal papers that contain the search terms "BIM" or "Building Information Model" Or "Building Information Modelling" in their title, abstract or keywords are retrieved from various databases (e.g. google scholar, Web Of Science, Scopus) and then referred to as the core dataset. In total, their analysis is based on 975 journal papers (core dataset) and identified twelve main BIM related research areas such as implementation and adoption issues, energy performance and simulation or safety management. However, their study excluded the expanded dataset which includes all articles that cite at least one article of the core dataset. Such expansion is motivated by the fact that an article that cites another article belonging to the core dataset might be relevant to the topic. In addition, the expanded dataset makes it possible to explore a broader view of the domain [15].

Later in 2017, He et al. [20] have analysed BIM related research published between 2007 and 2015. However, they focus mainly on papers that deal with managerial issues in the adoption and implementation of BIM and exclude documents that focus on technical development, practical matters and standardisation and other technical problems. As a result, they focus on 126 peer-reviewed journal papers (conference proceedings being excluded) that fit their analysis criteria. Similarly to the study in Ref. [14], the expanded data set was excluded also from this analysis.

In 2017, Zhao et al. [21] conducted a scientometric review of the global development of BIM research published between 2005 and 2016. They also use "BIM" or "Building Information Model" as keywords and retrieve the information from the Web of Science (WoS) database. However, the expanded dataset was excluded, and the core dataset did not include conference proceedings although the latter can reflect the current and recent interest of the community in BIM research.

The previously cited scientometric studies provide a good understanding and a general overview of BIM research before 2016. However, they mainly focus on the interpretation of the different scientometric indexes. In addition, an updated analysis that integrates new contributions and the expanded dataset (both peer-reviewed publications in journals and conference proceedings) up to 2018 needs to be performed to pinpoint recent trends. An overview of the integration of BIM and energy simulation for the different life-cycle stages is another missing aspect in the current literature.

In light of the previous considerations, the present study uses scientometric analysis to provide an up to date general overview of BIM knowledge domain. More specifically, figure 1 shows the overarching structure of the study presented in this paper. First, a scientometric analysis approach (especially Document Co-citation Analysis (DCA), further explained in section 2.1) is used to break down BIM research domain into several clusters that define the main research areas in BIM (see figure 1.A). Secondly, the topic addressed in a specific cluster is identified. Typically, an automated algorithm determines the recurrent words and terms within each cluster to deduce the topic addressed in the cluster. This approach allows obtaining a high-level view of the main problem addressed each cluster. However, for a more detailed and better grasp of the topic, a traditional review of the highly cited papers in each cluster identified is performed in this study (see figure 1.B). As a result, this paper combines scientometric analysis with a traditional literature review to better describe the main research interest and focus of BIM. Third (see figure 1.C), the focus is set on the integration of BIM and energy simulation where a more in-depth literature review provides information on the status of the coupling between BIM and BEPS.
Consequently, this paper consists of two main sections (see figure 1).

In section 2 (see figure 1), a brief summary of the scientometric method is given. Subsequently, a scientometric review of BIM articles between 1990 and (May) 2018 is performed. Peer-reviewed journal papers and conference proceedings are included in the dataset. The focus is set on the identification of the principal research domains and landmark contributions as well as the identification of the research trends that emerge between 2016 and 2018. In addition, a summary of the chronological evolution of the different BIM research domains is presented based on selected articles chosen from the highly cited ones.

Section 3 (see figure 1) reports on a review of the existing body of literature related to the integration of BIM with BEPS. Emphasis is put on the main issues of such an integration and the different solutions and strategies described in the literature. Also, the potential applications of such a combination are identified.

2. Overview of BIM related research topics

2.1. Methodology: Scientometric analysis

Advance and development in a specific research domain are illustrated by the constantly growing body of its scientific literature. This aggregation of literature describes different developments and innovation that occur over time and it embeds potentially valuable information that can be mined to explain the current emerging trends [16, 22]. Based on their citation performance, scientific articles can be categorised into two types: classic and transient. Classic articles are the most important – bedrock– and pertinent articles of the research domain and are characterized by their continuous frequent citations. Transient articles, on the other hand, are highly cited within a short period of time and indicate emerging thematic trends during that period [23, 19, 24, 17].

A scientometric review identifies and analyses the evolution of the research over time. It is a quantitative approach that relies on large-scale bibliographical data to assess the development of the research domain through different qualitative indexes. Two main types of indexes are encountered in a scientometric review: co-occurrence analysis and burst detection.

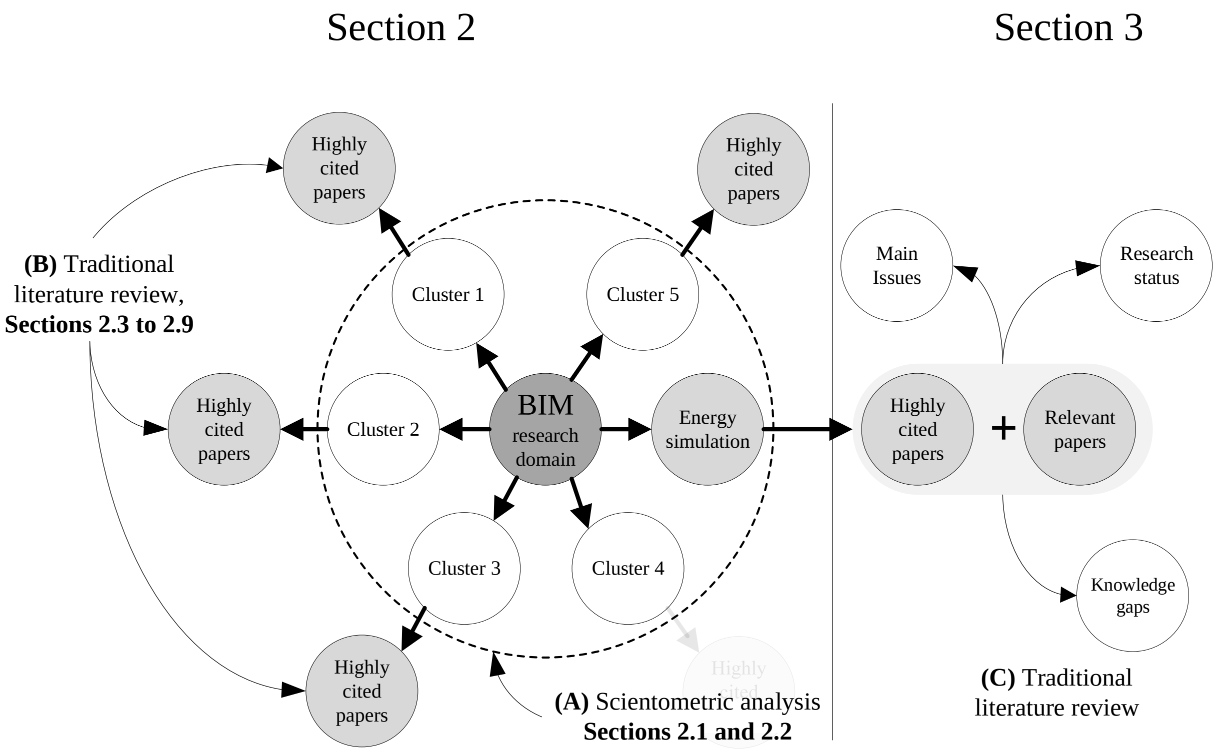

Figure 1: Overview of the structure of the paper explaining the combination of scientometric analysis with traditional literature review

Co-occurrence analysis. A co-occurrence analysis assumes that two components (e.g. two journal articles) that appear in a third context are related. The frequency of the co-occurrence gives an indication of the correlation between the two components [22, 25]. As an example, the fact that two journal articles are cited in a third one might suggest that they are somewhat related. If both initial journal papers are co-cited in several other papers then they might address the same topic. The more the two previous articles are cited together, the more they are potentially scientifically related. A co-occurrence analysis applied to journal citation is referred to as document co-citation analysis.

A document co-citation analysis (DCA) assesses the scientific proximity of different articles by measuring the co-citation frequency of two articles in the later literature. The higher the frequency, the stronger the relationship. This results in a document co-citation network in which nodes are formed from the different co-cited articles, and an edge is created when other articles cite them (e.g. see figure 2 for an example of such a network) [26]. When a certain group of articles is frequently cited in combination with each other, they potentially address a specific topic of the global research domain and can later be categorised as a cluster (e.g. see table 1) [26]. The number of combined articles defines the size of the cluster to which they belong. The cluster analysis gives an overview of the evolution of the most important research topics within the considered research domain and allows identifying the development of the latent and prominent research interests (classic article) throughout the years [24, 20].

The general topic that is addressed in a cluster is identified by an automated cluster labelling process. It uses a word profiling approach to extract the most representative term or word from the keywords, title or abstract of the articles constituting the cluster [19, 16, 27]. However, in this study, a manual literature review of the most cited papers is adopted to better capture the topic of a cluster.

Burst detection. A burst represents a sharp, but however time-limited, interest towards a specific component (e.g. journal article). As an example, a high burst of citations of a particular document over a particular time period indicates the general interest towards this document during this period. Consequently, burst detection can be used as an indicator of the most active and attractive area of research during a period but it can also serve to identify emerging research trends [24, 28]. As stated earlier, a citation burst of a certain article indicates a particular interest towards this article and its content and can provide insight on the general interest regarding this research field [20, 26, 24].

2.2. *Tool and application*

Driven by this interest in identifying the underlying foundations and trends of a research, several scientometric tools such as Vosviewer [61], Bibexcel[62], Science of SCience tool (SCi2) or Citespace [19], have been developed within the last few years. CiteSpace is known to be a very powerful and comprehensive tool [16] and has already been applied in previous

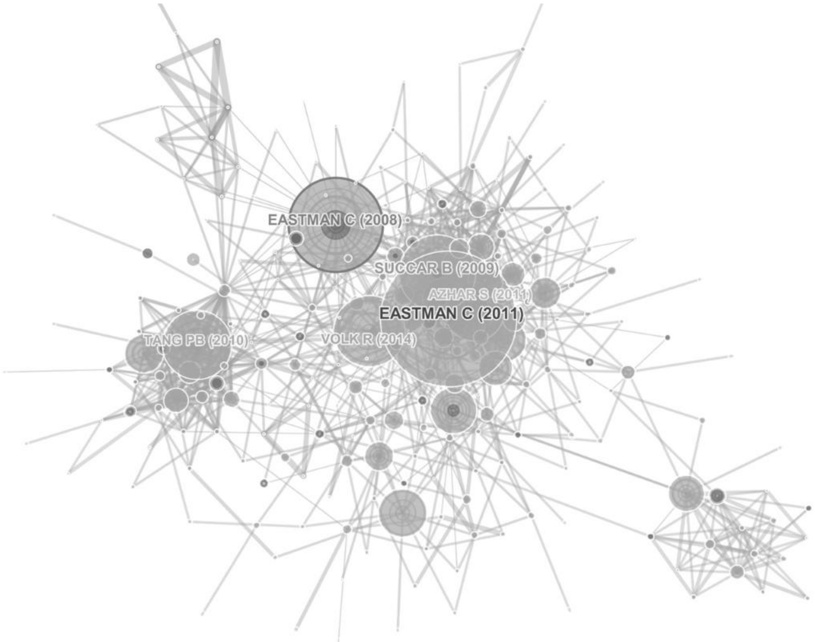

Figure 2: Document co-citation network obtained from the analysis of the 6988 records

studies that tackle topics ranging from nano-biopharmaceutical [17] to geographic information system (GIS) [16].

Citespace [19] is a Java-based application that can create a co-occurrence network (e.g. Document Co-citation network) with a built-in clustering algorithm. It can identify the hidden connections between the different scientific contributions and has an advanced network visualisation feature that includes cluster visualisation, timeline view and timezone view. It also possesses all the features and characteristics required to compute the different indexes previously presented, which has further motivated the choice to its use in this study.

Citespace is compatible with the Web Of Science (WoS) database. The keywords ”BIM” or ”Building Information Model$” or ”Building Information Model$ing” ($ represents one or no character) were introduced into WoS search engine to identify all the BIM-related scientific contributions. This resulted in a core dataset of 2662 articles (including peer-reviewed papers and conference proceedings) and an expanded dataset of 4326 articles leading to a total of 6988 items. These records were imported into Citespace for document co-citation analysis as well as citation burst analysis.

Figure 2 shows the resulting document co-citation network obtained from the analysis of these 6988 articles. A large node corresponds to a high co-citation frequency while a darker node pinpoints an article that has a citation burst. As an example, the BIM handbook from Eastman et al. (2011) [63] is one if not the most pertinent scientific contribution in BIM research. The network is then clustered, resulting in six main research topics as presented in table 1. A review of the different articles constituting each cluster allows to identify the following topics.

1. Cluster 0: BIM benefits and adoption
2. Cluster 1: Management
3. Cluster 2: Progress monitoring and as-built modelling
4. Cluster 3: Interoperability
5. Cluster 4: Embodied carbon and life cycle analysis
6. Cluster 5: Energy performance analysis.

These topics will be further developed in section 2.3 to 2.8 using the representative literature (in table 1) which consists of the most cited articles in each cluster. This study assumes that analysing the most relevant papers can provide a broad overview and state of the art of the topic. However, identifying knowledge gaps for each cluster is out of the scope of the present work.

Table 2 presents the papers that experienced a citation burst, i.e. most often cited from 2016 up to May 2018. These highly cited papers are identified by a built-in algorithm within CiteSpace, based on the metadata from the Web Of Science (WOS) database. These papers with citation bursts will be integrated in section 2.3 to 2.8 to highlight trending research in BIM.

2.3. Cluster 0: BIM benefits and adoption

This cluster is the most prominent and essential. It deals with two general subtopics which are the adoption and the benefits of BIM. Both aspects are interrelated since a broad adoption of BIM depends on a clear and well-defined quantification of its advantages. This section gives an overview of the landmark papers and presents the different strategies developed for a successful adoption of BIM.

Table 1: Main clusters obtained from the Citespace clustering methodology. Presentation of selected highly cited references

Cluster	Topic	Subtopics and representative literature
#0	BIM benefits and adoption	Demonstrating BIM benefits (Azhar [29], Eadie et al. [30], Barlish et al. [31]); BIM adoption strategy (Howard et al. in 2008 [32], Gu et al. [33], Arayci et al. [34], Porwal et al. [35], Hartmann et al. [36], Becerik-Gerber et al. [37], Miettinen et al. [1])
#1	Management	Supply management (Irizarry et al. [38]); Defect and quality management (Park et al. [39], Chen et al. [40], Motamedi et al. [41]); Safety management (Zhang et al. [42], Zhang et al. [43], Isikdag et al [44], Li et al. [45]) ; waste management (Cheng et al. [46]).
#2	Progress monitoring and as-built modelling	Progress monitoring (Turkan et al. [47], Kim et al. [48]); As-built modelling (Tang et al. [49], Xiong et al. [50], Patraucean et al. [51], Bosche et al. [52]).
#3	Interoperability	Yang et al. [53], Gielingh et al. [54], Becerik-Gerber et al. [55], Sacks et al. [56]
#4	Embodied carbon or life cycle analysis (LCA)	Iddon et al. [57], Basbagill et al. [58]
#5	Energy simulation	Sclueter et al.[59], Welle et al. [60]

Table 2: List of the articles having a strong citation burst between 2015 and 2018

Authors	Title	Cluster
Iddon et al. [57]	Embodied and operational energy for new-build housing : A case study of construction methods in the UK	#4
Ma et al. [64]	Existing building retrofits : Methodology and state-of-the-art	#2
Klein et al. [65]	Imaged-based verification of as-built documentation of operational buildings	#2
Bosche et al. [52]	The value of integrating Scan to BIM and Scan vs BIM techniques for construction monitoring using laser scanning and BIM : The case of cylindrical MEP components	#2
Cabeza et al. [66]	Life cycle assessment (LCA) and life cycle energy analysis (LCEA) of buildings and the building sector : A review	#4
Patraucean et al. [51]	State of research in automatic as-built modelling	#2
Ortiz et al. [67]	Sustainability in the construction industry : A review of recent developments based on LCA	#4
Miettinen et al. [1]	Beyond the BIM utopia : Approaches to the development and implementation of building information modelling	#0
Motamedi et al. [41]	Knowledge-assisted BIM-based visual analytics for failure root cause detection in facilities management	#1
Chen et al. [40]	A BIM-based construction quality management model and its applications	#1
Murphy et al. [68]	Historic Building Information Modelling Adding intelligence to laser and image based surveys of European classical architecture	#2
Li et al. [45]	A BIM centered indoor localization algorithm to support building fire emergency response operations	#1
Ding et al. [69]	Building Information Modelling (BIM) application framework : The process of expanding from 3D to computable nD	#0
Groger et al. [70]	CityGML Interoperable semantic 3D city models	
Sebastian et al. [71]	Changing roles of the clients, architects and contractors through BIM	#1
Kang et al. [72]	A study on software architecture for effective BIM / GIS-based facility management data integration	#1

Demonstrating BIM benefits. The adoption of BIM has encountered reluctance and scepticism from the AEC industry despite the different reported benefits from its use. In 2011, Azhar [29] evaluated the various trends, benefits, challenges and risks in BIM application. He exposed the expected benefits of BIM such as the improved (3D) visualisation, cost estimation and clash detection. Based on a survey, he defines the state of BIM use and found that it is mainly used by architects for preliminary and detailed design; although its application can be extended to other disciplines. Utilising data obtained from ten specific case studies, Azhar [29] demonstrates that BIM improves collaboration and potentially leads to cost reduction, better profitability and time management. Quantitatively, and based on the case studies considered, he stated that the use of BIM specifically to conduct design, feasibility analysis, Facility Management (FM) and preconstruction services can result in an average Return On Investment (ROI) of 634%. As a specific example, he reported that the cost of BIM integration during the Aquarium Hilton project [29] was estimated at 90000 USD with a net benefit of 710000 USD, altogether resulting in an ROI of 780%.

Although, most (surveyed) BIM users are convinced by the potential benefits, a vast majority of contractors still relies on traditional drawings, primarily because of the difficulty to leave the established work practice. Also, technological limitations such as limited interoperability and lack of explicit quantification of BIM benefits still hamper its use.

Because the benefits of BIM were not demonstrated and quantified, owners and contractors lack indexes to support the decision of its integration into their workflow. They require a quantitative proof of the real efficiency of BIM before adopting it. Existing qualitative evaluations that were performed on specific case studies are difficult to compare. This gap of knowledge has driven the investigation of the quantitative benefits of BIM in a more thorough way. For instance, Eadie et al. [30] quantified the financial effects of BIM use. They ranked the main BIM characteristics in terms of their (potential) economic benefits and gains. They found that the potential of BIM to improve collaboration among the different stakeholders has the highest financial impact. The management aspect is ranked second while the financial impact of a 3D visualisation has the least economic value. Also, they found that – at that time – BIM was mainly used during the preliminary design and design stages and less during the operational stage. In the same context, Barlish et al. [31] proposed an empirical method that compares Non-BIM with BIM project and aims to measure the impact of BIM. Specifically, they focus on return metrics (change orders, schedule and request for information) and investment metrics (design and contractor costs). In one of their case studies, they recorded a saving of 42% from change orders, a decrease of 50% of the request for information and a project duration reduced by 33% based on the standard duration. However, the design investment increased by about 30% due to the implementation of BIM. On average, they concluded total savings of 2%. Also on a more general scale, Bryde et al. [73] explore and synthesise the advantages of BIM use. They compile data from 35 case studies available in the literature and concluded that cost reduction was one of the main benefits of BIM beside the improvement of the project delivery time, quality, coordination and collaboration among the different stakeholders. Although technical challenges such as software issues and interoperability together with managerial issues need to be solved, they clearly pinpoint the advantages and benefits that can be drawn from the use of BIM.

BIM adoption strategies. Demonstration and quantification of the benefits alone are not sufficient to accelerate the adoption of BIM. Lack of awareness, slow change in the established work practice, complexity of BIM standards and the data exchange format IFC (Industry Foundation Classes), together with insufficiently defined roles and responsibility in a BIM project constitute a significant obstacle in the adoption of BIM in a construction project; not to mention the resistance to change and reluctance towards the transition from traditional 2D drawings to BIM. Also, BIM adoption requires additional training for people, new hardware resources and a redefinition of the roles of the different stakeholders. These issues have prompted the identification of strategies that have the potential to promote BIM use. In 2008, Howard et al. [32] performed a qualitative survey based on the perception and opinions of several experts on BIM and its open-format standard IFC. As results, the different experts pointed out that the application of BIM does not fit in the established work practice. Also, the experts recognised the need for BIM standards such as IFC but acknowledged that it is rarely applied in practice due to its complexity. They suggest to hide BIM complexity behind a technological implementation. Later, Gu et al. [33], use Focus Group Interviews (FGI) to define the understanding of BIM and their expectation for the different disciplines involved in a construction project and to better picture the reasons for a slow BIM adoption rate. They conclude that the perception of BIM varies from one discipline to another. As an example, they found that architects see BIM as an extension of conventional CAD software while project managers identify BIM more as a process that integrates CAD and other analysis that are required for the project. Also, they highlight the need to improve the current work practices and the necessity of specific roles such as a BIM manager. As a conclusion, they report that a broad adoption of BIM would require to address both technical and non-technical issues.

Arayci et al. [34] identify the need for a significant change in the current construction process and the attribution of the roles. Consequently, they determine a better practice for the adoption of BIM through a knowledge transfer partnership between small and medium architect firms and the University of Salford. They then concluded that a successful BIM adoption relies on a bottom-up approach in which people and staff are gradually introduced to BIM, thus reducing the potential reluctance to change. In the same context, Porwal et al. [35] propose a BIM partnering framework which aimed at facilitating BIM adoption by using its potential to improve the collaboration between the various stakeholders. They conclude that their framework has the potential to address the different challenges (e.g. ownership challenges). Hartmann et al. [36] in 2012 proposed the technology pull approach in contrast with the conventional technology push (top down) method often developed in literature. The technology pull approach consists of aligning BIM features with the existing construction process and identifying the main points where BIM can be of significant benefit. During the empirical experiments performed, BIM experts work in close collaboration with project teams of several contractors to demonstrate the potential of BIM in the company's current construction process. They (BIM experts and project teams) conclude that the capability to automatically extract quantity data from BIM facilitates and potentially automates the cost estimation process, not to mention the significant time saved by such automated process. In addition, they also note that the use of BIM permits to update the estimated cost automatically. Their approach confirms the efficiency of a bottom-up approach and should be developed at the same time as the conventional top-down approach. Moreover, the introduction of BIM as an academic discipline can be considered as another aspect that contributes to its adoption. In 2012, Becerik-Gerber et al. [37] proposed an innovative collaborative (BIM) course simulating a real-life construction project. The course is found to provide an excellent overview to BIM-based collaboration as most of the students learn how to coordinate the information exchange through BIM.

Despite the different studies demonstrating the various benefits of BIM, Miettinen et al. [1] still pinpointed the disparity between the theoretical promises of BIM (which they referred to as BIM utopia) and the practical reality. For example, they pointed out the highly advertised interoperability capability of BIM which turned out to be difficult to achieve in practice. Their work analyses theoretical BIM promises and how the different practical issues were addressed within literature. Their study also questions the advertised BIM benefits compared to what it really delivers. As a conclusion, suggestions are made that a more application oriented research approach for BIM is required to favour its effective application. This paper [1] presents a high citation burst indicating that the research community is actively investigating in this direction to reduce the gap between theoretical benefits of BIM and the reality.

Supporting that evidence, the work by Ding et al. [69] which pinpoints the main weaknesses of BIM is also one of the most cited papers up until now. It suggests that achieving a full BIM adoption in the AEC industry constitutes one of the main challenges until now.

2.4. Cluster 1: Management

This cluster covers a broad range of management issues in the construction process that can be solved or at least reduced by using BIM. The integration of BIM can be beneficial for a broad range of management issues such as safety, waste, supply, defects and maintenance.

Supply management. An example of improved management strategy driven by BIM is the study for which Irizarry et al. [38] combine GIS and BIM –for quantity takeoff– to support and enhance the planning for the dispatch of the construction materials from the supply point to the construction site. They aimed at reducing the waste of resources due to poor management of such a supply chain. As a result, they conclude that the combination of BIM and GIS enables the project management to identify the optimal transportation path and warehousing minimising logistic costs. Their approach limits delayed delivery and provides accurate information on the cause of potential problems.

Defect and quality management. During the construction phase, rework can cost up to 4% of the contract value depending on the building typology [74]. Park et al. [39] propose a conceptual proactive mechanism for rework management that demonstrates another potential use of BIM. Also, construction quality control is another aspect that benefits from BIM integration [40]. As an example, Chen et al. [40] propose a 4D BIM (3D + time) approach for quality management. Their goal is to ensure consistency between construction and design intent, to monitor the construction progress and to improve collaboration between the different actors. Their study constitutes a first step towards the application of BIM for quality management and is among the most cited papers until now (see table 2), indicating the current interest of BIM researcher towards this specific aspect.

During the operational phase, facility management needs to identify the causes of technical problems. This task is usually undertaken using a collection of historical data (e.g. sensor data) combined with traditional drawings. This approach is time-consuming and less intuitive as emphasised by Motamedi et al. [41] who develop a method that combines maintenance and management information with the 3D visualisation feature of BIM. A colour coding is used to visualise components' information from which defective components are identified. This work is also among the most cited work potentially indicating its importance in the BIM research area (see table 2).

Safety management. Although the building construction process has significantly evolved, loss of life and injuries, as well as damages, are still frequent and unacceptable. A safe work environment requires an extensive safety planning including identification of potentially dangerous situations and appropriate safety measures. Consequently, Zhang et al. [42] proposed a 4D management approach combining 3D visualisation with activity schedules (time) that consists of three main parts built on top of a BIM software application. They found that BIM integration enables to foresee and avoid collisions. Later, Zhang et al. [43] proposed an automated rule-based safety planning for fall protection. Existing safety guidelines and regulations are formulated into a set of rules and integrated into an existing BIM tool. The study demonstrates the possibility to automate the identification of safety hazards through BIM.

On top of that, safety measures during the operational stage can also greatly benefit from BIM. For instance, improved indoor navigation is vital for emergency response, improved delivery as well as maintenance and management in large buildings. The ability to navigate and quickly identify the different paths is critical for a prompt, safe and successful intervention (e.g. maintenance). In this context, Isikdag et al [44] proposed their "BO-IDM" model –based on IFC– to facilitate indoor navigation by combining 3D visualisation with semantic information. Its application proved that the proposed model is suitable for indoor navigation based on the combination of semantic information and 3D visualization. Additionally BO-IDM facilitates the detection of the different utilities scattered in the building. Similarly, Li et al. [45] have specifically focused on developing a BIM-based approach that enables quick and accurate detection of people in case of a fire emergency in the building. In such a case, indoor navigation is vital to locate and retrieve people trapped in the building. An uninformed search plan in an unknown environment can, not only jeopardise the success of the operation, but also put in danger the life of members of the rescue team. Consequently, Li et al. [45] designed an environment-aware radio frequency beacon deployment algorithm for Sequence-Based Localization (SBL) that uses BIM as input to provide both the geometrical information and the visualisation for user interaction. The evaluation of the tool on two simulated fire emergency scenarios reveals the high accuracy and robustness of their approach. This work is a highly cited paper (see table 2) indicating the interest of the research community towards this specific topic.

Waste management. Considering the constant increase of construction and demolition waste, which is often poorly managed and disposed, it is essential to estimate the quantity and type of waste throughout all life-cycle stages from construction through renovation to demolition. This emphasises the need for better and sustainable waste management in construction and demolition. In this context, Cheng et al. [46] developed a BIM-based tool that extracts information from BIM and performs a waste estimation. They rely on the Autodesk Revit^{TM} API to obtain an estimate of the waste. Their tool demonstrates another application and the potential of BIM for waste management.

2.5. Cluster 2: Progress monitoring and as-Built modelling

This cluster gives an overview of the potential of BIM for different aspects of management during the construction and operation of a building. It describes the use of different remote sensing technologies (e.g. laser scanner) for construction progress monitoring and as-built BIM modelling (e.g. BIM reconstruction from point clouds).

Construction progress monitoring. A successful construction project requires an efficient progress measurement method and evaluation. Progress measurement consists of continuously monitoring the construction progress and comparing it with the expected planning. Early identification of disparities between the schedule and the progress of the as-built structure allows to promptly address the deviations, thus reducing the potential cost due to late rework. Also, it might accelerate the project acceptance. Among the landmark studies in this field, Turkan et al. [47] developed an automated progress tracking system which compares 3D data from laser scans with the BIM. Although they obtained promising results, they emphasise the need for a more rigorous scanning schedule to improve the outcomes. Similarly, Kim et al. [48] developed a construction progress measurement that uses the design BIM with actual schedule information and 3D data obtained from remote sensing. They align the as-built information (e.g. from remote sensing) with the as-planned model, then compare the as-built data with the BIM and finally update the as-built status. They validated their approach on an actual construction site and proved its potential to improve progress measurement methods in general.

As-built modelling. Changes during construction steming from different built errors or undocumented rectifications result in a difference between the as-built facility and the as-design model. This prompts a need within the AEC industry to verify and compare the as-built with the as-designed status (the design BIM). Laser scanning is one of the most used approaches to capture the as-is condition of a facility. Point cloud data resulting from the scanning process is converted into a 3D, semantically rich BIM in a process known as SCAN-to-BIM. In 2010, Tang et al. [49] presented the state of the art of as-built BIM creation and the different approaches to automate this process. They emphasise various challenges that still need to be addressed. Specifically, they underline the focus of existing studies on straightforward aspects of a building (e.g. planar surfaces) although real buildings are a combination of more complex shapes. In addition, existing algorithms are developed in an unrealistic, occlusion-free environment. Most of the approaches are case dependent and involve a significant amount of manual processing. Later (in 2013), Xiong et al. [50] automate the scan-to-BIM process using an algorithm that can distinguish clutter and occlusion (e.g. Furniture in the room). They present a seminal study towards scan-to-BIM automation but emphasise more on the future challenges such as the need for recognition of openings and their type.

This combination of remote sensing and BIM is still among the most active BIM research areas, since among the papers that have a high citation burst until now (2018), four of them (see table 2) address this specific topic. For instance, Patraucean et al. [51] provide an overview of the as-built modelling process focusing on the geometric part. They provide an overview of the different point cloud data collection approaches, data processing methods, modelling of as-built BIM with or without as-designed BIM, as well as a method that can generate an as-built model for MEP components. They acknowledge the significant progress in the last few years and emphasise the need to consolidate existing technologies. Also, they stress the need for better and more robust object recognition approaches. Similarly, Bosche et al. [52] recognize this overall progress and further emphasise that object recognition and identification remains one of the main challenges. However, their work constitutes a landmark paper since it extends scan-to-BIM and progress monitoring to MEP components. Specifically, they propose an approach that automatically recognises and identifies MEP objects with circular cross-sections such as pipes from the point cloud data. This automated recognition enables to quickly detect the deviation between the as-built and the as-designed MEP. Although encouraging results have been found, the state that further study is required to generalize their approach.

This cluster presented the different applications of BIM reconstruction for progress monitoring and as-built modelling. It highlights the evolution of the research in this specific topic and identify the need to improve the existing approach to be more robust and applicable in real buildings.

2.6. *Cluster 3: Interoperability*

The ability to seamlessly exchange information contained in a BIM between different software applications is critical in a collaborative environment such as a construction project. This interoperability makes the information understandable to different BIM applications and provides the possibility to share digital information among the various disciplines, further reducing the use of traditional documents. However, lack of interoperability arises when semantic data has multiple definitions across the different disciplines or when incompatible proprietary information models are used by the various actors.

Although the use of a standardised data model such as IFC constitutes a solution, it presents a recurrent inconsistency and lack of semantic (entity and property set) which results in information loss, hampering its use as the main data model for exchange. Consequently, the development of strategies to improve BIM interoperability, more specifically the open-BIM data model IFC constitutes one of the issues in BIM and it attracts a large research interest. For instance, among the landmarks and most cited study on the subject, Yang et al. [53] (in 2006) developed a seminal and first step approach that integrates a building design domain ontology, object-oriented modelling and a proposal to extend the IFC standard and thus improve its interoperability. They demonstrate that their approach can support the data exchange throughout the construction process in general. Later in 2008, Gielingh et al. [54] pointed out that the use of exchange standard data models has been weak in general in industry. They identified the main reason of the poor adoption of exchange formats, especially the STEP ISO 10303 standard, from which the IFC standard has been derived. The need to invest in new hardware devices (e.g. computer) or software tools (e.g. BIM authoring tools) are among the main reasons. Legal aspects can also hinder its application since an electronic format might not have legal importance because it is difficult to access for a judge (in contrast to a paper-based version) and could be easy to falsify. Overall, they notice that the industry, in general, is not yet ready to adopt the change. Also, its adoption requires that all the actors and software applications adopt the same standard. Later on, in 2010, a survey conducted by Becerik-Gerber et al. [55] still emphasise that interoperability has been identified as one of the crucial aspects of BIM that need to be addressed and resolved. The same year, Sacks et al. [56] conducted the Rosewood experiment which aimed at identifying new collaboration workflows that take advantage of BIM benefits. They recognise the exchange capabilities of the existing BIM tools. But more importantly, they define new (IFC) entities and objects as well as property sets that are needed to support the exchange in an aspect of the construction process. Specifically, they focus on ensuring the collaboration for the design of architectural pre-cast concrete façades. Their experiment demonstrated the ability of exchanging pre-cast concrete information using existing BIM and emphasised the different challenges and issues that need to be addressed to achieve a seamless data exchange. They highlight the need for a BIM standard that details the information required to enable data exchange in a specific process (e.g. precast concrete design, energy simulation); i.e. identifying the IFC entities and property sets that comprehensively define the data exchanged during this process. Their experiment constitutes one of the early steps towards the implementation of the Information Delivery Manual (IDM) methodology (ISO 29481-1) making it possible to define a subset of IFC required to exchange specific information at a specific point in the process, the so-called Model View Definition (MVD). The combination of IDM and MVDs with the current version 4 of IFC improves the interoperability and it is currently the main path to follow to achieve interoperability in BIM.

2.7. *Cluster 4: Reduction of embodied energy*

The reduction of the emission of greenhouse gases and especially CO_2 constitutes one of the current worldwide challenges. Throughout their entire life cycle, buildings use a significant amount of energy and are responsible for a large part of greenhouse gases emission. The amount of GHG (embodied carbon) that results from the production of building materials and all the processes involved in the construction is significant, often equating the energy and gases emitted during the operational phase (operational carbon). However, considering the difficulties in manually computing these different impacts, researchers have investigated the potential benefits of BIM integration for life cycle assessment. For instance, Iddon et al. [57] developed a BIM tool capable of computing embodied and operational carbon for a newly built facility. Specifically, information from the BIM is used to implement a calculation model and compute the energy used associated with heating, and lighting (from which the operational carbon is derived). While the embodied carbon associated with each material used in the construction and represented in the BIM is retrieved from a database to compute the embodied carbon. They determined that the reduction of the operational carbon tends to increase the embodied carbon, reinforcing the results obtained in previous studies. Similarly, Basbagill et al. [58] developed a BIM-based framework that helps to understand the impact of decisions related to building components. Choosing materials with low embodied carbon already in the early design is key to significantly reduce the building's carbon footprint. Also, the framework of their study permits to automatically or semi-automatically provide environmental impact feedback to the building design team at that stage. As a result, they observed that the choice of materials and their thickness are the most significant parameters that increase the embodied energy of a building. As presented in table 2, this study [58] is one of the landmark articles on the application of BIM for building life cycle assessment indicating the current keen interest towards this topic.

2.8. *Cluster 5: Energy simulation*

The last cluster investigates the integration of BIM with energy simulation. In a widely cited article, Schlueter et al. [59] argue on the necessity to use energy simulation from the early stage of the design. They also highlight –at that time– the lack of tools that couple advanced CAD tools such as BIM with energy calculation. Consequently, they developed a prototype of a tool that relies on the Application Programming Interface (API) of a proprietary software application (Autodesk Revit 2008) to couple BIM and a static energy and exergy calculation. The little variation in term of energy calculation results between an existing tool and their prototype, combined with the facilitated model input constitute one of the first demonstrations of the benefit of BIM for energy simulation. This topic will be thoroughly discussed in section 3.

2.9. Epilogue

This review identified six main research topics (see table 1) and provided a detailed general view on the evolution of the different strategies developed within each item using the information provided in highly cited articles. Based on the citation burst (see table 2), the topic of BIM-aided management, as well as as-built modelling approach, are among the currently highly investigated.

In general, the reluctance to change and a lack of quantitative proof of BIM benefits combined with poor interoperability result in an overall reluctance towards BIM adoption. Consequently, a large part of the BIM literature reports on several studies that demonstrate the benefits of BIM and improved interoperability but also proposes novel strategies that would facilitate the transition from the established work practice towards BIM-based processes. Besides, researchers present innovative procedures that integrate BIM to improve or even automate existing, inefficient workflows. As shown throughout this section, BIM can be of great importance for different applications ranging from the early design to the operational phase.

3. Review of the integration of BEPS into a BIM-based workflow

Building energy simulations play a crucial role in reducing the overall energy use in the built environment. Simulation models can be static (steady-state) or dynamic (sub-hourly time step) and are used to quantify the performance of a design and evaluate its environmental impact as well as financial impacts [75]. Consequently, most of the green building certification standards (e.g. LEED: Leadership in Energy and Environmental Design) are attributed based also on energy simulation output. However, the currently available energy simulation tools require an important effort for manual input and a thorough knowledge of the specific software interface resulting in a limited use of energy simulation during design. Typically, an energy simulation is performed only after the initial architectural design. It is conducted by an energy simulation expert who has to manually introduce the information and create the building energy model based on drawings, reports and data sheets. This poses the problem of duplicated information and errors not to mention the significant amount of time required for model implementation. Additionally, in case of incomplete data, the energy expert has to provide temporary or default values based on his expertise and knowledge. These assumptions are in many cases not communicated or documented. The outcome of an energy simulation is dependent on modellers judgement and experience and can vary from an energy expert to another. The integration of building energy simulation into a BIM-based workflow will help to remove the time consuming and error prone manual configuration, leaving room for a broader use of building energy simulation during the entire design stage and beyond. Also, it has the potential to provide documentation and standardisation of the energy performance simulation modelling.

Several challenges and limitations have to be overcome to achieve a full integration of BIM and BEPS. This section presents an overview as well as a description of the evolution of different approaches that are adopted in the body of scientific literature to address the main BIM to BEPS integration issue: Interoperability (see section 3.1). In section 3.2 an overview of the primary applications of integrated BIM-BEPS is provided to pinpoint the different knowledge gaps and typical application domains that could benefit from such integration.

A manual literature review is performed using a selected set of scientific contributions from the Web of Science (WoS) database. The combination of the keywords TS=(”BIM” OR ”Building Information Model$” OR ”Building Information Model$ing”) with TS=(”BES” OR ”BEPS” OR ”Energy simulation” OR ”Building energy simulation”) has been introduced in the search engine and has prompted 111 relevant scientific contributions. A further manual screening has been performed to identify the off topic contributions. The review presented in this section stems from 70 scientific publications in journals and conference proceedings.

3.1. BIM to BEPS Interoperability

Software interoperability is the ability of two or more software applications to exchange information seamlessly. In a BIM-based energy simulation, it is the possibility to fulfil the energy simulation requirements and flawlessly transfer data from a BIM tool to an energy performance simulation program (e.g. EnergyPlus [76] or DOE-2 [77]). In 1999, Bazjanac et al. [78] demonstrated through different case studies the advantage of using BIM and achieving true interoperability for building energy simulation. They showed the high potential of attaining interoperability regarding cost, time savings as well as reducing duplicate data and errors in the energy simulation model implementation.

Although extensive research has been performed, true and total interoperability is still not achieved. Data loss, incompatibility, missing information as well as inconsistent translation from BIM to energy simulation programs are common problems [79, 80, 81]. For instance, Kim et al. [82] compared the differences between the results of a traditional, manual modelling and a BIM-based modelling to demonstrate the lack of interoperability. They concluded that even though the use of BIM in combination with the gbXML exchange format facilitates the implementation of the energy simulation model, missing information (in the gbXML format) combined with the use of default or temporary values causes significant differences between the results of the BIM-based and the traditional approach. More importantly, they found that HVAC system related information was among the assumptions that impacted the results the most.

Also, as demonstrated by Moon et al. [83], interoperability capabilities vary depending on the available tool. They [83] evaluated the interoperability for architectural data exchange using the gbXML format with several energy simulation tools (EnergyPlus [76], eQUEST [84], Ecotect [85], IES-VE [86]) and found that although all four tools were able to import all the geometrical information, eQuest showed the best interoperability. These two examples show the lack of interoperability and the need for a more stringent data exchange process between BIM and energy simulation. Consequently, solving or improving interoperability constitutes one of the primary research areas for BIM integration of BEPS.

In 2007 Yi et al. [87] identified three general approaches that were being used or developed –at that time– to address or improve interoperability:

1. An "integrated model" method that links several models through a common data model.
2. A "specific data sharing" method that uses a custom information model to exchange information.
3. A "generic data sharing" method that prioritises flexibility and aims at being compatible with the large majority of software applications.

They [87] emphasise that the third approach has the potential to achieve true interoperability. Later, in 2015, Asl et al. [88] further pointed out that the third approach through the use of the open standard IFC or the de-facto standard gbXML constitutes one of the main methods to address interoperability. However, the current interoperability issues have led to the development of different ad-hoc middleware solutions and custom translation tools. The following three main strategies have been identified:

1. Proprietary tool-chain
2. Middleware tool
3. Exchange requirement identification

Proprietary tool-chain. This first strategy uses proprietary software (in most cases the API of the BIM software) to perform the data exchange between the BIM and energy simulation. Although such an approach cannot be considered as a general interoperability solution, it presents some attractive points. It allows a seamless data transfer because the software's API is fully compatible with the proprietary data information model, yet not always exposing the entire internal data structure. Consequently, data loss and incompatibility are limited enabling the implementation of a fully operational workflow. For instance, Asl et al. [88] propose the building information modelling (BIM)-based performance optimisation (BPOpt) framework that aims at facilitating the identification of the different design options during the early design. BPOpt includes energy analysis using green building studio (DOE 2.2, [77]), daylighting analysis (using Autodesk rendering service) and a visualisation framework. To overcome the issue of interoperability between the different tools, they use Autodesk Revit's API for the data exchange process. Similarly, Jeong et al. [89] use the Autodesk Revit$^{\mathrm{TM}}$ [90] API coupled with the "Buildings" library for Modelica [91] to ensure seamless information exchange between BIM and simulation. As drawbacks, the information exchange entirely relies on a proprietary information model which is most often only compatible with tools from the same vendor and often also depends on a specific version of these tools. This combination limits the broad adoption of BIM-based energy simulation since the aforementioned applications are often too expensive for small companies or part-time users.

Middleware tool. This second strategy relies on publicly available data models such as IFC and gbXML. It addresses the different interoperability issues as well as the limitations of BIM software by developing various tools and middleware from which the information extracted from BIM can be checked and if necessary rectified and enriched. As an example, Karolaa et al. [92] (in 2002) reported on the development of the BSpro server which was used to facilitate the implementation of IFC-interoperable applications. It has been used as middleware in the IFCtoIDF tool developed by the Lawrence Berkeley National Laboratory (LBNL) [92]. Later, among other approaches, Cormier et al. [93, 94] developed the eveBIM tool, which in addition of being a BIM visualisation tool, provides the possibility to update missing properties directly in IFC (2X3). The eveBIM tool has also the capability to enrich building system information. In 2013, Kim et al. [95] propose another Ruby-based tool that can facilitate the information exchange (especially geometry exchange) between the Ifcxml format and the DOE 2.2 energy simulation analysis. Material properties and HVAC system data still need to be integrated manually into the model. Also, Cheng et al. [96] presented a web-based framework that facilitates to update and integrate potentially missing information in BIM. Similarly, Kim et al. [97] have developed a tool that can parse an IFC file, identify the name of the material and find their corresponding properties from a database to generate an input file for the DOE 2.2 simulation engine. Choi et al. [98] propose a workflow that includes the development of a material library and a tool that can retrieve material information and generate an IDF input for EnergyPlus [76]. A similar approach can be found in [99]). In the same category, O'Donnell et al. [100] propose the intermediate data model SimMODEL to bridge the gap between the BIM data model and simulation models. SimModel aligns the information of the BIM data model and the requirements of the energy simulation tools (initially for EnergyPlus).

The main limitation of middleware use is the reliance on another data source (other than the BIM) for building-related information. This can result in duplicate or out-dated data, increasing the risk of errors and mistakes. The intermediate format can also create additional restrictions for the information exchange, especially if it is designed for a specific simulation tool.

Exchange requirement. The last strategy aims at a BIM that contains all the required building related information for energy simulation. BIM (IFC) capabilities are extended so that the exchanged file satisfies the exchange requirements for the energy simulation. This strategy relies on the flexibility of the open-

BIM framework which includes the Information Delivery Manual (IDM) methodology with Model View Definitions (MVDs) from EN ISO 29481 and the data model itself (IFC as defined in EN ISO 16739). This approach can be considered as the most flexible one since it does not rely on a proprietary tool or format while having an IFC file directly compatible with the simulation exchange requirements avoids duplicate work and information. As early as 2007, Yi et al. [87] recognise the flexibility of IFC, especially due to the possibility to define custom Property Sets (Psets). Several studies proposed new IFC property sets to adapt the official IFC data schema to meet their specific exchange requirements. For instance, Welle et al. [60] assure the interoperability between IFC and their tool ThermalOpt by suggesting the possibility of using custom property sets combined with a set of modelling guidelines. Later, Gupta et al. [101] coupled BIM with renewable energy simulation analysis and suggested new property sets to ensure that the BIM contains all the information required for their study. Similarly, Cemesova et al. [102] address the interoperability issues between IFC and the Passive House Planning Package (PHPP). They identify the existing parts of IFC that partially cover their exchange requirement and introduce new entities and relationships to fulfil the exchange requirement for the PHPP. Recently, Maurer et al. [103] suggest new property sets for high-quality buildings to fit the exchange requirements of a specific application. Most of these approaches combine BIM modelling guidelines with some extensions of IFC to ensure that the new property sets and the required information are integrated and modelled correctly in the BIM (e.g. in [104]). This extension of IFC and implementation of guidelines can be formalized through the use of the IDM methodology. IDM allows identifying the exchange requirements in a specific domain to implement a set of guidelines and a Model View Definition (MVD). The MVD is a technical –computer understandable– definition of the exchange requirement and defines the different IFC entities that need to be exported. As a recent work (in 2018) in that sense, Pinheiro et al. [105] proposed a standardised approach that uses IDM and the MVD technology to capture and translate the exchange requirement for building energy performance simulation using EnergyPlus [76] or Modelica [106] (especially with the AixLib Modelica library). Their work contributed to the International Energy Agency Energy in Buildings and Communities (IEA EBC) Annex 60 and formed the base for the results of Activity 1.3 of Annex 60. They demonstrated through different case studies together with a bottom-up approach the possibility to use IFC MVD to define the exchange requirements for energy simulation. The focus is put on the exchange of geometry data and limited HVAC description and properties. Recently, Andriamamonjy et al. [107] have developed a similar approach based on IDM and MVD to enable a direct information exchange between IFC4 and Modelica. This approach ensures a complete transfer of information from geometry modelling as well as system and control models in the BIM to the simulation model. Although the standard and the different concepts are mature and proven, the main limitations of these strategies currently lies in the slow adoption of the necessary workflows and still insufficient compatibility of the different BIM software applications with IFC4 and custom MVDs.

Although we think that this last solution is the most promising one for the near future, up to now, there is no perfect solution to address all interoperability issues efficiently. Each of the different approaches has advantages and drawbacks. Nonetheless there are several standardisation works (e.g. CEN/TC 442) aim at improving interoperability.

3.2. BIM to BEPS application

Interoperability is one main research focus and solutions for this issue are vital to ensure the sustainable and widespread integration of BIM and BEPS in the AEC industry. Integrated BIM to BEPS approaches have already been applied in buildings. This section provides an overview of the principal BIM to BEPS applications, especially for design and operation of buildings.

3.2.1. Design process

A good design process is critical to achieve optimal building energy performance. Informed and well-supported design decisions are needed for different aspects of the building such as dimension, material or system. More importantly, a well-informed decision earlier in the design stage could ensure a significant reduction in energy use. Hamedani et al. [108] found that performing energy simulations early with an architectural BIM with a LOD (Level Of Detail) 200 can reduce by 19% the energy use in buildings. A Level of Development (LoD) defines the level of information at a given point during the different design stages. It increases as the design process progresses, and varies from LoD 100 to LoD 500 [109]. For instance, a BIM with a LoD 200 includes a basic geometry representation of a building while a BIM with a LoD 300 comprises a more detailed geometry and thermal characteristics [110].

However, Hamedani et al. [108] pinpoint the lack of energy simulation tools compatible with a low LOD, thus emphasising a technology gap. Finding solutions to fill that gap could be significantly beneficial for the building design in general. The following paragraphs highlight some important aspects in the design of very energy efficient buildings.

***Orientation*.** The identification of the right use of solar radiation is a crucial point in the design. A low solar contribution increases the use of heating and lighting systems, while an excess of solar gains can increase the need for cooling. Consequently, the orientation of the building is vital for adequate solar gains. Several studies have leveraged BIM to facilitate the evaluation of the impact of building orientation during design. For instance, Abanda et al. [111] use a tool-chain (Autodesk Revit - GbXml - Green Building Studio) to facilitate the assessment of the impact of building orientation in small-scale constructions. In the application to a three storeys detached house building, they found that savings of 17 056 kWh of electric energy and a reduction of gas use of 27 988 MJ resulting in cost savings of £878 can be achieved over a period of 30 years for well oriented typical British domestic dwellings. Similarly, Gupta et al. [101] developed a framework that uses BIM at the early design stage to find the optimal building orientation, location and roof tilt maximising PV performance. Even further, Kim et al. [112] combine the use of parametric BIM and visualisation with building energy simulation to study the impact of an elaborated kinetic faç ade on the heating and cooling load. They use Autodesk Revit as BIM tool to model the case study and calculate the sun path. Autodesk Green Building Studio is used as energy performance simulation tool. As a result, they found that a kinetic façade reduces the energy use by 4% compared to a facility with a static one. Beside the building orientation, studies [113, 114, 115] have investigated the integration of BIM and BEPS to accurately find the optimal window design, i.e. size, position, glazing properties and orientation. As an example, Kim et al. [115] studied 65 different scenarios with various window sizes and orientations using the combination of Autodesk Revit and Green building studio to assess the impact.

Certification. Beyond some specific aspects of buildings shown earlier, the benefits and potential of BIM-BEPS integration in diverse aspects of the detailed building design have been investigated. For instance, Kamel et al. [99] developed the Automated Building Energy Modelling and Assessment Tool (ABEMAT) that combines the use of gbXML, a corrective python script and a modified version of EnergyPlus to provide fine-grained energy simulation results, i.e. details of the heat transfer through specific building envelope components. They emphasise that their tool through the fine-grained results can benefit both building design and retrofit. Schlueter et al. [116] developed a tool-chain that links BIM with a Design Of Experiment (DOE) approach to allow a better understanding of the different design factors as well as their interaction. It gives a better picture of the design space and can benefit both design and retrofit. Besides, integrated BIM to BEPS can facilitate the building certification process. For instance, Akcay et al. [117] developed a toolchain that combines Autodesk Revit$^{\text{TM}}$ [90], the Sefaira performance analysis platform (use EnergyPlus simulation engine) [118] and a Microsoft Excel$^{\text{TM}}$ [119] macro to automate and optimise the obtention of points for LEED certification. Similarly, Cemesova et al. [102] used the openBIM format IFC to facilitate the accreditation for the PASSIVHAUS standard. Another aspect of the integration of BIM and energy simulation is the extension of its application to high-rise buildings. Pan et al. [120, 121] assess the obstacle in a BIM-based energy simulation in high rise buildings. They found that interoperability, as well as the high number of thermal zones in these buildings, constitute one of the main challenges.

Design exploration. The coupling of BIM and energy simulation alone, although facilitating the energy simulation analysis, does not guarantee an optimal building design. The possibility, to rapidly and thoroughly explore and compare the different design alternatives ensures a better informed decision. As a result, several studies have been directed towards the combination of a BIM-based energy simulation tool with an optimisation algorithm to facilitate the exploration of the design space. For instance, Welle et al. [60] reported on the development of the BIM-based tool referred to as ThermalOpt. They used IFC and different middleware tools combined with a genetic algorithm to identify the optimal architectural design of buildings. Similarly, Asl et al. [122] presented the Revit2GBSOpt tool which couples BIM with an optimisation tool and enables the exploration of the different design possibilities. They demonstrated, through a case study, that using BIM with an optimisation algorithm increases the design efficiency. Later, they integrated a multi-objective optimisation algorithm and developed the BPopt tool. In the same context, the work of Nour et al. [123] suggested an IFC java toolbox combined with a genetic algorithm optimisation to minimize the building life-cycle cost.

3.2.2. Building operation

Considering that it is a relatively recent concept, most of existing buildings do not possess a BIM. In the case they have, the chances are high that a disparity exists between the design BIM and the actual building. Consequently, researchers investigate the use of technologies from geomatics for BIM reconstruction to perform energy simulation for renovation and retrofit purposes. As an example, Wang et al. [75, 124] present and demonstrated an approach that links reconstructed BIM from point cloud data and energy simulation. They collected the geometry representation using 3D laser scanner and then generated a gbXML file to be used as input for an energy simulation engine. Recently, Patino-Cambeiro et al. [125] proposed a methodology that would allow assessing the energy performance of existing tertiary building by reconstructing BIM from information obtained from advanced geomatic technology (e.g. laser-scanning).

In addition, Dong et al. [126] investigated the integration of BIM-BES with fault detection and diagnosis (FDD) technics to optimise building energy consumption. Although the study demonstrates the usefulness of BIM-BES for the operational phase, their use is still not common practice and necessitates further research.

3.3. Epilogue

Most of the approaches presented earlier are applied only to the building fabric. Extensive and thorough studies have been performed to identify efficient ways of taking advantage of BIM to BEPS integration for the building envelope (orientation, simulation or iterative design strategies). In contrast, the use of BIM for the building systems and controls is much less investigated. Among the few studies that address the coupling of BIM with HVAC simulation, Bazjanac et al. [127] presented the IFC to HVAC utility that aimed at linking IFC and EnergyPlus by creating the IDF input file for EnergyPlus . They demonstrate a successful data exchange but also emphasise the incompatibilities between IFC and IDF. Later, to address this issue, O'Donnell et al. [100] propose SimModel as an intermediate data model between IFC and EnergyPLus to facilitate the data exchange. SimModel is currently used in the Symergy tool. Recently, Andriamamonjy et al. [107] have demonstrated the direct link between the IFC4 format and energy simulation by relying on IDM-MVD. Nonetheless, additional studies and software development are required to achieve a full ”industry ready” BIM-BEPS integration for building systems and control.

Another aspect that might hinder the integration of building system (and control) is the reliance on ”traditional simulation engines” such as DOE-2 (with Green Building Studio) or EnergyPlus. Traditional simulation engines possess some features that make them less intuitive and flexible especially for building systems and control modelling. Furthermore, their hourly simulation time-step is incompatible with the simulation of the fast response required for HVAC and control [128].

Consequently, studies have investigated the use of flexible and object-oriented modelling tools such as Modelica [129, 107, 130, 131, 132, 133] .

For instance, Kim et al. [129] developed an approach that relies on the Autodesk Revit API to couple BIM with the ”Buildings” library for Modelica [91]. However, they focus mainly on the building envelope. In the frame of the IEA Annex 60, activity 1.3 Cao et al. [130] developed an approach that integrates IFC and the Modelica AixLib library through the intermediate SimModel for HVAC modelling. Recently, Andriamamonjy et al. [107] have established a direct translation from IFC to Modelica for a coupled model of building envelope, system and controls.

Finally, one can note that the use of BIM to BEPS mainly aims at the detailed design stage. The works of Wang et al. [75] or Dong et al. [126] can still be considered as outliers compared to the general trend. Nonetheless, the integration of BIM and BES for building operation can be beneficial for different application such as Fault Detection and Diagnosis (FDD) and Model Predictive Control (MPC) since such combination can also facilitate their implementation. This emphasises the need for further research to close this knowledge gap.

4. Discussion

BIM in general. The scientometric analysis reveals six main research topics. They can be re-categorised into two main parts with two different but interrelated goals.

A first part (cluster 0 and 3) aims at solving the main issues limiting the broad use of BIM. Problems that stem from either technical limitations or reluctance to change well established, yet often inefficient workflows. A significant amount of studies propose strategies that can help the transition from the established work practice into BIM-based processes. This can be achieved through education, alignment with the existing processes and demonstration of the different benefits of BIM using representative case studies. The common aim is trying to motivate the various actors in the construction industry to adopt BIM in their projects, by showing the different BIM qualities and capabilities. A significant effort has been made to improve interoperability. In the long-term, effective interoperability has to enable seamless communication between the different stakeholders across all disciplines contributing to a project.

A second part (cluster 1, 2, 4 and 5) focuses more on developing different BIM integration strategies that are beneficial to a building throughout its lifecycle. Studies investigate strategies that automate tasks which were previously either entirely manual and often inefficient or non-existent. As an example, BIM is used to automate safety and supply management as presented in section 2.4. Although most of the studies are proof of concepts, they put in practice and emphasise through diverse case studies the real potential of BIM. These different studies can be used to influence sceptical people towards the real impact of BIM and prove the functions of this approach that go far beyond the ”fancy” 3D visualisation and rendering.

Driven by the overall potential benefits of BIM emphasised in this paper, the worldwide adoption of BIM-based workflows has increased over the past few years. As an example, Gocuk et al. [134] reported that the use of BIM is growing in large design firms in the US. This enthusiasm towards BIM stems from the alignment of BIM with the design tasks and a high potential to decrease costs and improve the project quality. A McGraw Hill Construction survey from 2012 already reported that the use of BIM in North America has surged from 49% in 2010 to 71% (in 2012) among the different building construction actors (Contractors, Architects and engineers) [135]. Similarly, a survey from 2015 from the same institution predicted that on average BIM users will increase by 95% worldwide within the next two years [136]. Likewise, another study from 2016, from the National Building Specification (NBS-UK) [137] also emphasised the high adoption rate of BIM in countries such as Denmark, Canada, UK and Japan. The report underscores the rise of BIM adoption from 39% in 2013 to 48 % in the UK and from 64% to 67% in Canada. On a more high-level scale, Jung et al. [138] report the overall status of BIM adoption in the six continents. They found that North America and Europe and Oceania are the most active continents for BIM adoption; followed by Asia and Africa.

BIM for energy simulation. Energy simulation is one of those applications that can significantly benefit from BIM. The latter offers the possibility to automate the time-consuming and error-prone manual creation of energy simulation models. However, as developed in section 3, issues such as lack of interoperability between BIM and energy simulation tools still hinder the broad application of such an integration. Although three main strategies (see section 3.1) have been indentified to improve the interoperability, we believe that the open-BIM framework (IDM-MVD-IFC4) is the most promising approach. It is software independent (open) and enables to adjust BIM to the requirements of any application (here energy simulation at different life-cycle stages). As a result, such an approach allows bringing BIM to a much broader application since much more information could be integrated into it. As an example, Andriamamonjy et al. [107] rely on the concept to generate a numerical model of building systems and control using BIM information. However, although the format (IFC) itself is software independent, its practical application relies on the compatibility of existing proprietary software applications with IFC. This constitutes the main bottleneck since the compatibility with IFC is not uniform, and the degree of compatibility varies from one software to another. Also, there is a need to include the capability to use custom MVDs for the IFC export from the existing BIM software applications. The progress towards more open-BIM regulation and standardisation can be an incentive for proprietary software vendors to focus more on the IFC format. Nonetheless, further studies and research are necessary to obtain a fully applicable and interoperable approach. Also, the integration of BIM and energy simulation was mainly used to facilitate the modelling of the building's outer shell.

So far, the integrated BIM-BEPS has been used primarily during design in various applications covering the identification of optimal building orientation to design exploration. A gap of knowledge still exists in the integration of BIM for building systems as well as control modelling. Although Andriamamonjy et al. [107] present an early contribution towards that step, further research is still needed. Also, the integration of BIM to BEPS for the operational phase is insufficiently investigated. BIM to BEPS can facilitate or even automate the development of strategies such as Fault Detection and Diagnosis (FDD) and Model Predictive Control (MPC).

5. Conclusion

This paper provides an overview of the focus of the BIM research domain as well as the research trends up to now. It presents an overview of the integration of BIM with BEPS in which the emphasis is set on the different strategies for improving interoperability and on the applications benefiting from such combination. Knowledge gaps and potential application domains are identified.

A scientometric analysis has been used to distinguish the research focus within the vast body of BIM literature. It categorises the different papers into quantifiable clusters, each of them addressing a specific BIM topic. Citation burst detection has been used to identify trending topics. Subsequently, a manual review of the highly cited and relevant articles in each cluster, as well as those with high citation burst, has been conducted to grasp the entire state of the art of BIM knowledge. Finally, the articles related to BIM to BEPS integration were retrieved and then reviewed. They were categorised based on how they address interoperability and which aspect of building design and operation they treat.

As a result, this study identified six main BIM research topics revolving around BIM adoption and benefits, BIM-aided management, progress monitoring and as-built modelling, interoperability, life cycle analysis and finally energy simulation. The clusters focusing on BIM-aided management, progress monitoring and as-built modelling are related to several papers that present a citation burst; indicating that these topics are among the main research focus until now. In contrast, BIM and energy simulation integration seems to attract fewer researchers compared to the other clusters.

The review of the current BIM to BEPS integration shows a lack of established and commonly accepted workflows to address interoperability.Most of the strategies presented have some advantages and some drawbacks, although we think that the use of the open-BIM framework (IDM-MVD) is the most promising long-term solution since it is based on open standards and allows to specifically adapt BIM to satisfy a specific exchange requirement. Most of the BIM to BEPS applications are used for the building envelope design which highlights a knowledge gap for the use of BIM to BEPS for building system and control as well as for its application during the operational phase (e.g. Fault Detection and Diagnosis or Model Predictive Control). Consequently, future research should focus on how BIM to BEPS could be integrated to facilitate the implementation of such strategies.

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