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Using BIM to improve building energy efficiency – A scientometric and systematic review

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ABSTRACT

The Architecture, Engineering, Construction, and Operations (AECO) sector is responsible for a great proportion of the global energy consumption and associated environmental impacts. On this front, and from a sustainability improvement perspective, the use of Building Information Modelling (BIM) capabilities could represent an opportunity to improve these impacts in all steps of a building's life. The main purpose of the current paper is to identify the areas in which BIM technology can or already is playing a role in improving building efficiency, helping AECO sector stakeholders in reducing environmental impacts. In the current paper, the impact of using BIM to enhance the building energy efficiency is explored through a scientometric analysis and a systematic literature review. There is a high interest among the scientific community in these fields, given the recent rise in publications and citation numbers. Moreover, there is a lack of interoperability between BIM and energy analysis tools, a high potential for integrating BIM with other technologies, such as thermography, Geographic Information Systems (GIS) and monitoring, and a very positive impact from the use of BIM in the optimisation of construction solutions which allow energy savings in the AECO sector.

Contents

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1. Introduction

Building Information Modelling (BIM) is a revolutionary technology that, when applied to the Architecture, Engineering, Construction and Operations (AECO) sector, could transform the way in which buildings are conceived, designed, built and maintained [1].

On the other hand, the AECO sector is currently responsible for a large part of the world's energy consumption [2] and, consequently, its daily operation produces several negative environmental impacts [3]. Therefore, the AECO sector is under great pressure to reduce the levels of polluting emissions [4] and is compelled to increase the energy efficiency of its current methods (materials, processes, equipment, buildings).

To achieve this challenging goal, BIM technology can play a very important role [5], from the design phase until the end-of-life phase, as it can, amongst others, allow comparisons between materials and solutions in the design stage [6–8] and renovation processes [9,10], evaluate the interior thermal comfort from BIM models [11,12], estimate energy needs, act as a platform for visualising analysis results [13,14] and aid in energy certification processes [15,16].

However, there is a lack of knowledge concerning the extent to which BIM technology is being used to improve energy efficiency in buildings. Therefore, a systematic literature review is needed, that comprises and organises all the information regarding the current methodologies and processes that enable energy efficiency gains through BIM modelling, including existing limitations and possible future developments.

Thus, the current paper focuses on this subject and intends to help AECO stakeholders in understanding all the ways in which BIM can be used as a tool to improve energy efficiency levels within the sector. With this goal in mind, the current paper is organised in five sections. Section 1 introduces the topic and

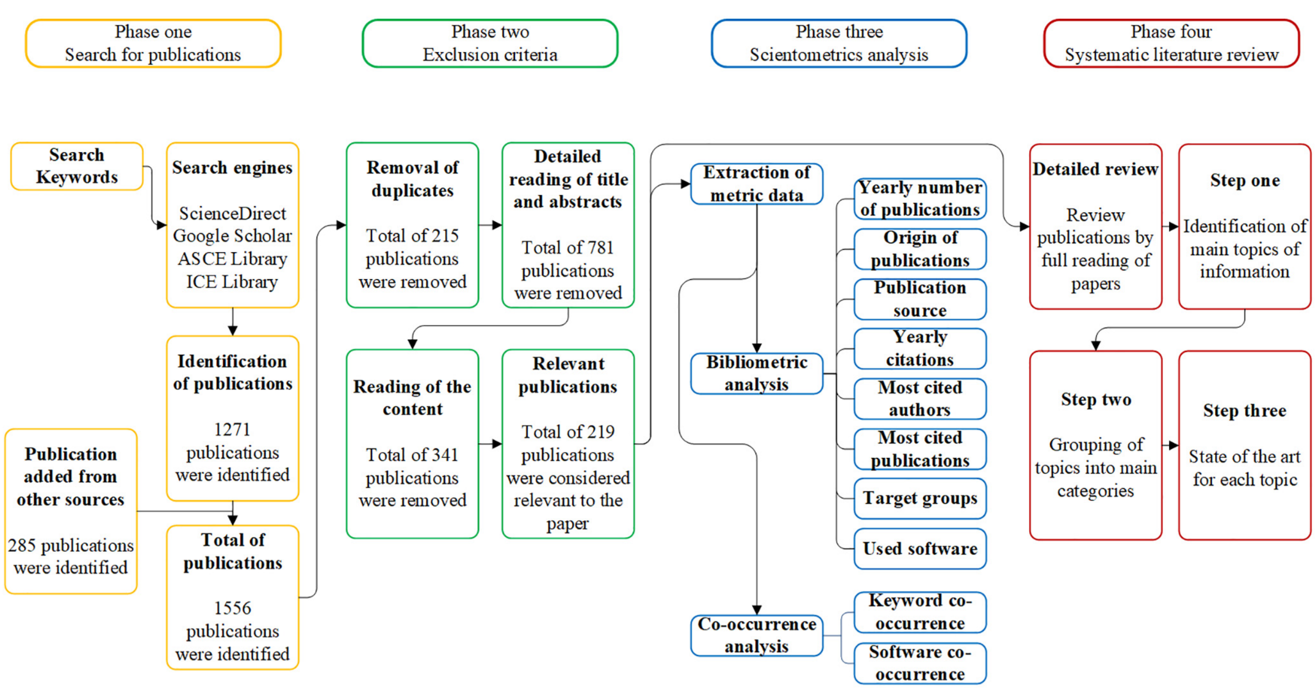

Fig. 1. Research Methodology

details its structure. Section 2 details the scientific methodology used in this research paper. Section 3 develops a scientometric analysis of the literature. Section 4 performs a systematic literature review regarding the use of BIM to improve building energy efficiency. Lastly, Section 5 presents the conclusions drawn in this paper.

2. Research methodology

A four-stage methodology was applied to develop the current paper, with the first being the search for publications, the second the definition and application of exclusion criteria, the third the elaboration of a scientometric analysis, and the last the execution of a systematic literature review. This methodology is detailed in Fig. 1.

2.1. Phase one: Search for publications

Systematic literature review guidelines describe at least three types of inclusion criteria [17], these being databases to search, keywords to use and type of publication to include.

Four databases were used in the search for publications: ScienceDirect, Google Scholar, the American Society of Civil Engineers Library and the Institution of Civil Engineers Library.

Regarding keywords, three different search terms were defined to gather the most relevant information related to BIM use to improve building energy efficiency:

i) "BIM" AND "Building" AND "Energy Efficiency";
ii) "BIM" AND "Building" AND "Energy Efficiency" OR "Energy Performance";
iii) "BIM" AND "Building" AND "Green".

Considering the type of publications, all types of documents in the research were included, to guarantee a wide diversity of information sources.

From these databases, and with the determined search terms, 1271 publications were gathered and stored in the library manager software EndNote. Additionally, 285 publications were added to the library, these being gathered from the reference lists of publications considered of major relevance to the subject of this paper.

2.2. Phase two: Exclusion criteria

Regarding exclusion criteria, these were applied in three stages. Firstly, the duplicates were removed. This stage excluded 215 references from the library created. After that, through the reading of titles and abstracts, 781 records were excluded from the database. The third and final stage consisted of a full and detailed reading of the remaining papers and excluded 341 references. The final number of publications used in the following sections of this paper was 219, corresponding to references [2–16,18–221].

2.3. Phase three: scientometric analysis

Several categories of quantifiable bibliometric data, such as the evolution of publications per year, evolution of citations per year, etc., were analysed with statistics-based methods. The metric data was exported from EndNote to Microsoft Excel to process the data and produce graphs, which help to interpret this type of data.

Additionally, co-occurrence and co-authorship analysis were carried out, these types of analysis being the most associated with the concept of scientometric analysis [28,62,127,210]. The metric data was exported from EndNote to VOSViewer, a software capable of creating bibliometric networks [222], which allow these types of analysis to be performed.

2.4. Phase four: Systematic literature review

In this phase, the main topics of information were identified and grouped into key categories of information. In total, 14 main topics were identified, and five main categories were created, allowing for a structured presentation of information.

The systematic literature review consisted of the establishment of the state of the art for each of the 14 main topics. Thus, for the papers related to each topic, their research gaps, findings, conclusions, and current shortcomings were identified. Possible solutions to overcome the actual gaps and shortcomings were proposed.

3. Scientometric analysis

In this section, a scientometrics analysis is made. Several bibliometric properties of all the gathered papers were analysed, with the goal of exposing the current state and evolution of knowledge surrounding the topics of BIM and energy efficiency in buildings.

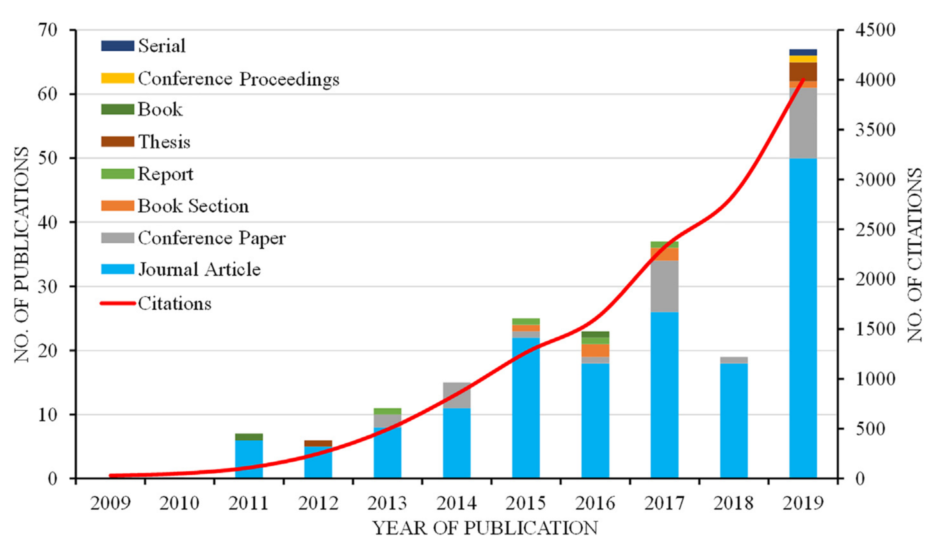

Fig. 2. Evolution of the number of publications and citations.

3.1. Number of publications and citations

The evolution of the number and type of publications was evaluated over the period between the years 2009 and 2019. The evolution of publications per year and the respective types are shown in Fig. 2.

There is an upward trend in research associated with the use of BIM to improve building energy efficiency. Starting in 2011, a non-linear evolution of publications was identified, with occasional exceptions in 2016 and 2018. The maximum number of publications was identified in 2019, with 67 publications. It can therefore be said that the subjects under analysis in the current paper are of current and high interest in the scientific community.

Between the years 2009 and 2019, most publications (169 of 214) were journal articles. This may indicate that a great portion of the gathered information is reliable, increasing the quality of the analysis done in this paper. Similarly, a clear rise in the number of citations is visible between 2009 and 2019.

With the exception of book sections, all the other types of publications had their maximum number of occurrences in the year 2019, the last analysed, which corroborates the previous hypothesis that research on the use of BIM to improve building energy efficiency is of current high interest.

3.2. Publication source

Regarding the source of publications, only the two highest types of publications were considered, these being journal articles and conference papers. A total of 50 scientific journals and 27 conferences were identified. Considering the high number of journals, Fig. 3 includes only the journals with two or more articles published and the total of articles presented in conferences.

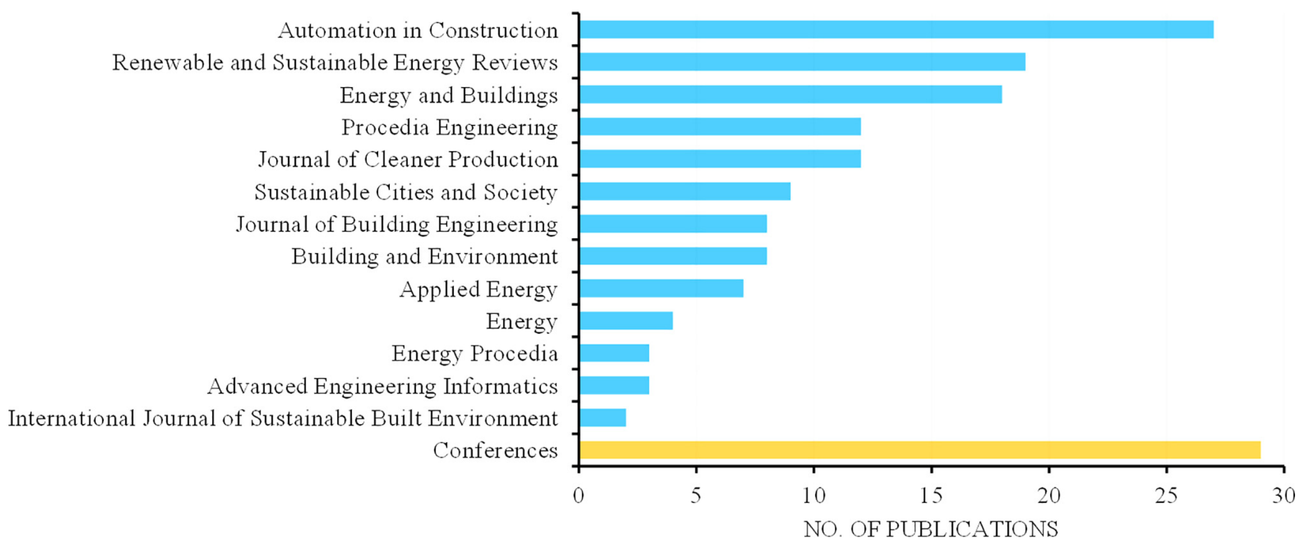

Fig. 3. Publication sources.

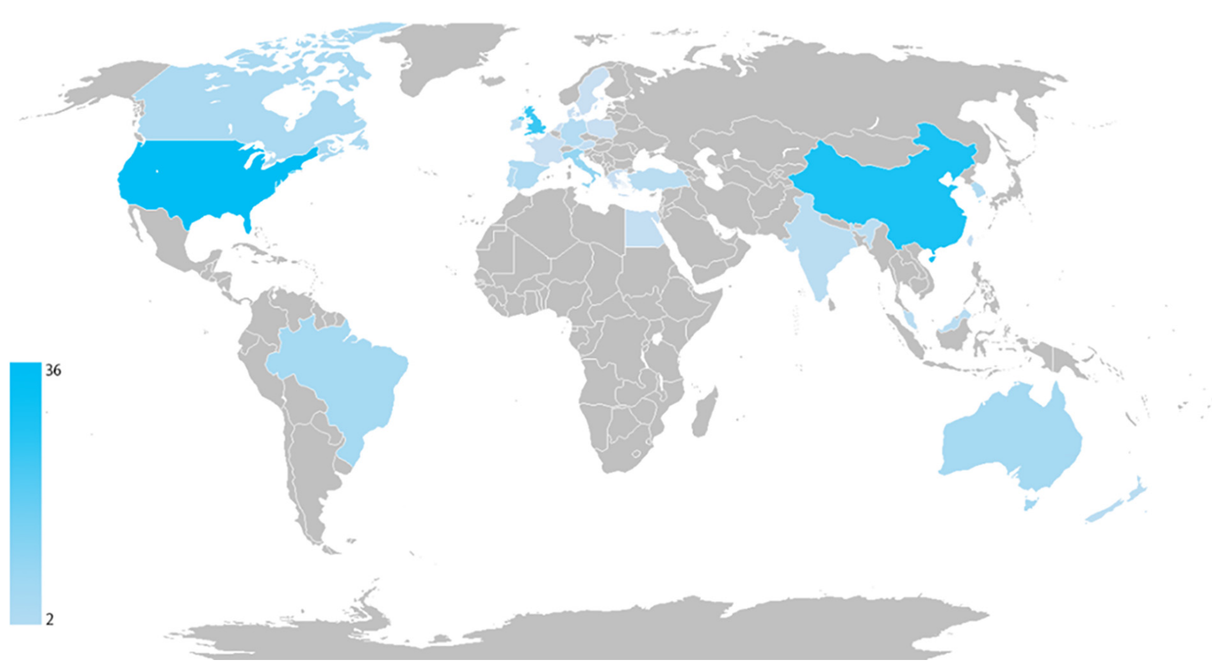

Fig. 4. Distribution of publications by country.

It was observed that the three journals with the most publications were Automation in Construction with 27 publications, followed by Renewable and Sustainable Energy Reviews with 19 publications, and Energy and Buildings with 18 publications. These journals are all edited by Elsevier and can be considered as references regarding the use of BIM and/or energy efficiency in buildings. On the conferences side, a total of 29 publications were identified. Of these, 18 were held between 2017 and 2019, which indicates a growing interest in the topic.

3.3. Origin of publications

For this analysis, it was decided to assign to each publication the country represented by the institution of its first author. A total of 37 countries with publications were identified. Of these, 26 had two or more publications, as shown in Fig. 4. The research leaders in terms of number of publications are the United States of America, China, and the United Kingdom, which demonstrates the interest of developed countries in reducing their environmental impacts.

It can therefore be stated that the higher technological development of each country can contribute to a greater amount of research on these fields, which are technology reliant. This is corroborated by the lack of research in less developed countries.

3.4. Most cited publications

The absolute number of citations for each publication was also analysed. The five most cited publications are presented in Table 1 and includes both general publications about BIM, as well as specific publications about energy efficiency.

3.5. Keywords co-occurrence

For this analysis, a normalisation of ambiguous keywords was necessary. After this process, a total of 565 different keywords were identified and used as input in VOSViewer, creating a keyword co-occurrence network. The created network, shown in Fig. 5, visually represents the number of occurrences of a keyword

Table 1
Top 5 cited publications.

Order	Citations	Title	Authors	Institution
1	1809	Building Information Modeling (BIM): Trends, Benefits, Risks, and Challenges for the AEC Industry [34]	S. Azhar	Auburn University [USA]
2	1163	Building Information Modeling (BIM) for existing buildings — Literature review and future needs [10]	R. Volk J. Stengel F. Schultmann	Karlsruhe Institute of Technology [Germany]
3	1064	A review on the prediction of building energy consumption [221]	H. Zhao F. Magoulès	Ecole Centrale Paris [France]
4	602	How to Measure the Benefits of BIM [38]	K. Barlish K. Sullivan	Arizona State University [USA]
5	582	Energy Performance of LEED® for New Construction Buildings [16]	C. Turner M. Frankel	New Buildings Institute [USA]

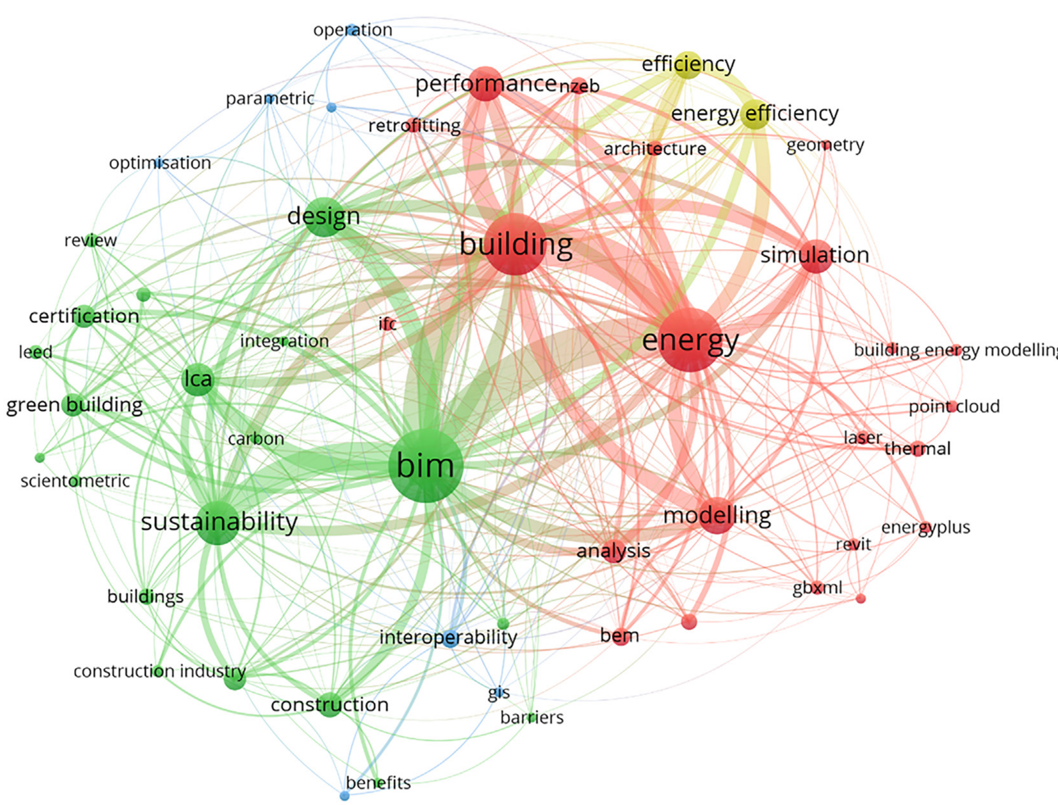

Fig. 5. Keyword co-occurrence network.

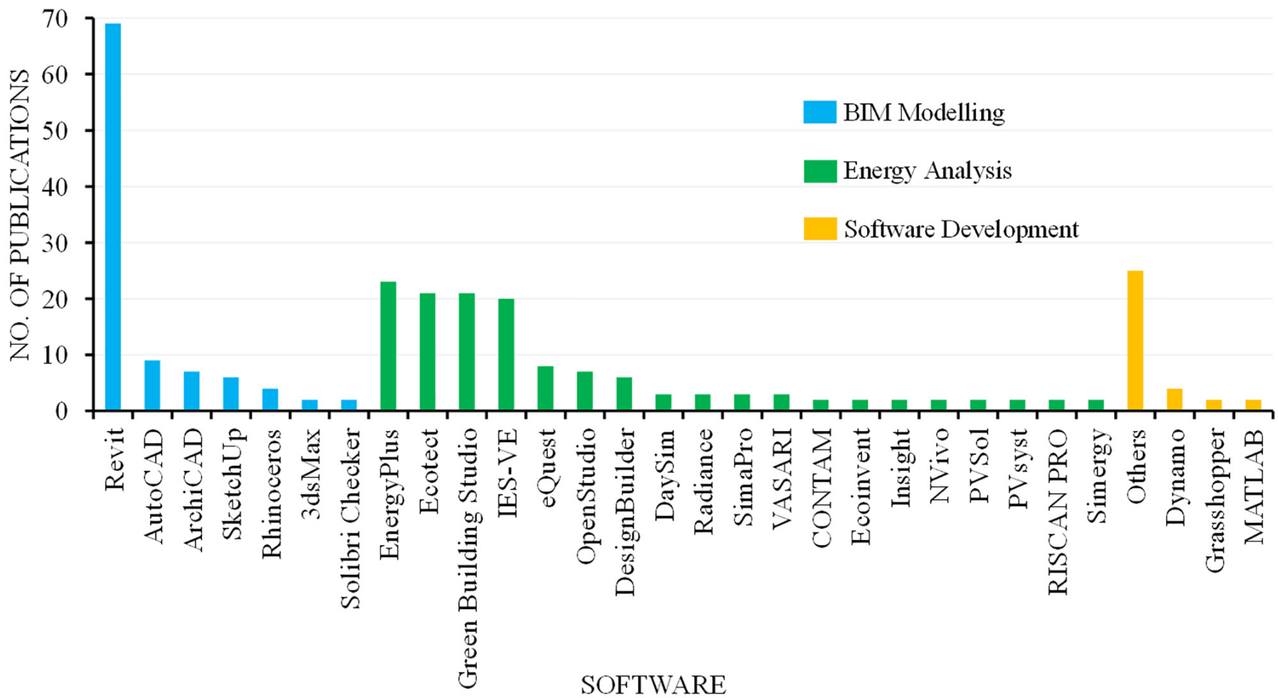

Fig. 6. Software used by authors/researchers.

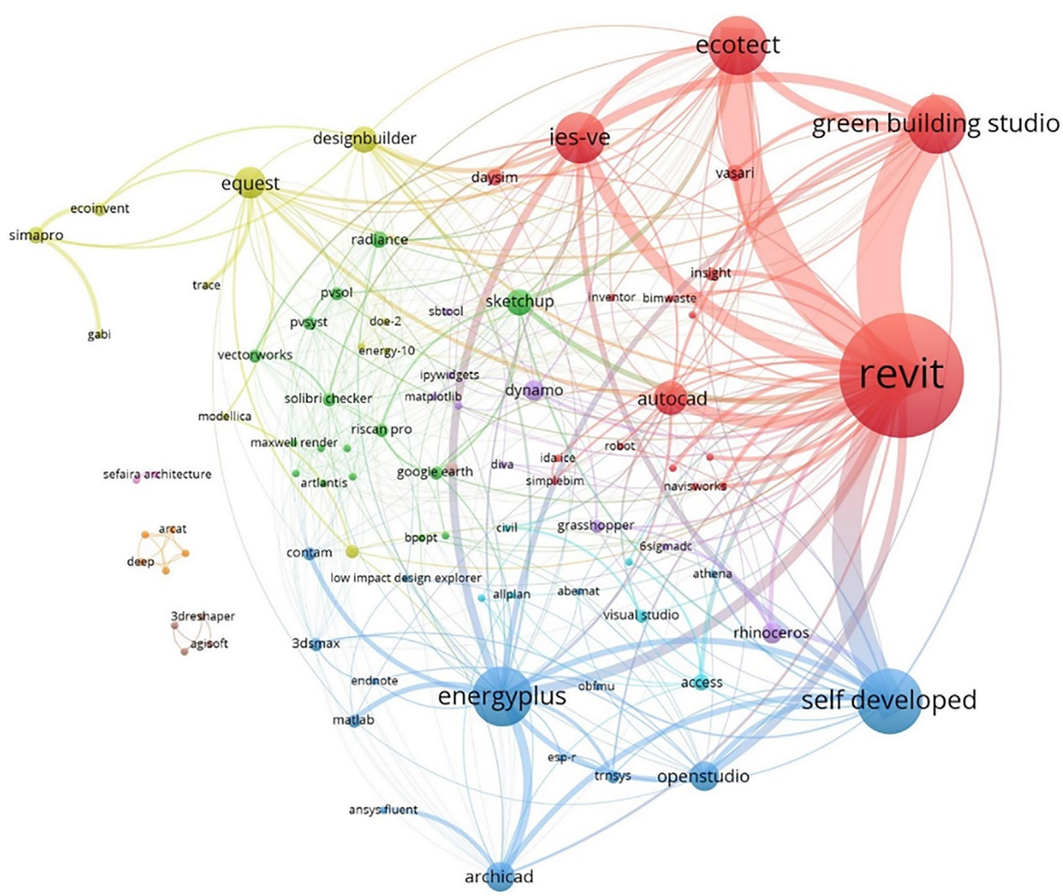

Fig. 7. Software co-occurrence network.

by the node size, and the degree of co-occurrence between keywords by the link thickness.

As expected, "BIM", "Energy" and "Building" are the biggest nodes of the created network. In the keyword co-occurrence network, keywords such as "Sustainability", "LCA", "Design", and "Construction" display strong links with "BIM", which may indicate that efficiency could be improved by analysing the effect that BIM can have regarding the subjects that these keywords represent.

Regarding the "Building" keyword, it displays strong links with keywords such as "Performance", "Retrofitting", "NZEB" and "Architecture". These keywords may therefore represent processes capable of improving a building's energy efficiency.

Thus, these secondary keywords represent relevant fields of study, representing some of the main topics of information identified and analysed in Section 4.3.

3.6. Software

A total of 94 different software tools were identified. Fig. 6 illustrates the 30 most used software tools in the library, organized by their application fields: BIM modelling, energy analysis and software development.

Regarding the BIM modelling software, Autodesk® Revit, was the most used. Therefore, it can be considered as a reference in BIM modelling. This group includes software for building modelling, visual aspect of the models, and model errors checking.

For energy analysis, EnergyPlus is the most used in this field, followed by EcoTect, Green Building Studio, and IES-VE. Regarding the remaining tools in this application field, most of them are used in the energy evaluation of the building, while others are used to simulate lighting, LCA analysis, CFD analysis and air quality analysis.

Lastly, regarding the software development, new tools were identified, referring to several programming languages presented mainly in Dynamo, Grasshopper and MATLAB. The first two are visual languages which are usually incorporated into BIM modelling tools.

3.7. Software co-occurrence

A software co-occurrence network was created, regarding only the tools identified in the publications. In this network, shown in Fig. 7, the node size represents the degree of utilisation of a certain tool, and the link thickness represents the number of times that both tools were mentioned. The created network thus gives some perspective on the current level of interoperability between modelling tools and energy analysis tools.

It is clearly seen that the high use of Autodesk® Revit makes it a central piece of the network. This tool presents several connections with energy analysis tools, including the four most used energy analysis tools and created or self-developed tools, previously identified.

ArchiCAD, on the other hand, presents a connection with only one energy analysis tool, EnergyPlus. As this tool is one of the most popular amongst architects, this may represent a limitation, regarding the design and conception of energy efficient buildings.

Regarding the created, or self-developed, tools, these present a strong connection with Revit, which may indicate that they are based on this tool or created as a plugin capable of enhancing Revit's capabilities, regarding energy analysis.

4. Systematic literature review

In this section, a systematic literature review is done based on the publications within the created library. While reading of these publications, key topics were identified. After that, these key topics were grouped in the main information categories. These categories, topics, and associated publications are presented in Table 2.

4.1. BIM technologies

This category brings together topics associated with BIM technologies or technologies that relate to BIM, and that can shape energy efficiency increase in buildings. The main topics identified in this category relate directly to BIM capabilities and compatibility, emergent technologies integration within BIM and external data combination with BIM tools.

4.1.1. Interoperability

Interoperability, in the specific case of BIM and energy analysis tools, is seen as low [92], tool-dependent [70] and as a challenge to an industry-wide BIM adoption [5,30,85,189]. Some works, from Gao et al. [73], Kim et al. [113] and Lu et al. [126] identify the process of data extraction as one of the challenges hindering high interoperability levels, while others, as per Ceranic et al. [46], Kamel et al. [110] and Tang et al. [190], mention discrepancies in

Table 2
Categories and topics identified.

Category	Topic	Publications
BIM technologies	Interoperability	[3,5,18,28,30–32,39,46,55,60,67,70,72,78,85,91,92,103,106,110,113,126,133,140,152,156,160,167,176,188–190,198,211]
	Laser scanner and thermographic camera data merging	[42,54,74,75,79,89,90,118,119,166,199–201]
	Urban scale analysis (BIM/GIS)	[40,47,56,87,98,149,171,180,184,207]
	Building monitoring	[33,42,59,83,96,131,148,192,197,214,220]
BIM model-based tool development	Software development	[21,22,48,50,77,109,123,129,130,134,135,146,154,155,216]
	Output visualization platforms	[13,14,19,58,149,193]
Sustainable buildings	Materials and solutions comparison and optimization	[2,6–8,34,37,38,53,61,63,69,82,86,94,95,121,124,128,138,147,153,166,173,179,181,182,209,212,213,215,219]
	Energy needs estimation	[36,52,73,76,81,99,104,105,111,117,128,137,161,168,175,182,194,202,217,218,221]
	Nearly Zero-Energy Building (NZEB)	[23,44,52,100,112,116,127,141,187]
	Life-cycle analysis (LCA)	[24–27,41,45,64,66,68,71,84,101,102,114,122,142–144,150,151,158,162,163,172,177,178,185,186,196,205,207,208]
Hygrothermal design	Energy certification	[4,15,16,29,35,51,65,97,115,125,132,139,159,164,165,204,206]
	Thermal comfort	[9,11,12,48,57,93,141,203,210]
	Building renovation	[9,10,43,80,109,120,169,170,174,186]
Training	Training quality	[20,49,62,88,136,145,157]

data file structures of software as another obstruction to the evolution of interoperability. Another obstacle is due to loss of data in the data exchange process between tools, as per Gao et al. [72] and Ghaffarianhoseini et al. [78].

An increase in interoperability levels is necessary [55], accelerating BIM based energy analysis with more reliable outputs [39,91,106,152,167,211]. The automation of BIM models conversion to BEM models [18,140,198] and use of concepts such as openBIM and SimModel could lead to better energy analysis results [28,60,67]. On the other hand, the standardisation of file structures could present itself as the most common solution for interoperability issues [133,156,211]. Actually, Industry Foundation Classes (IFC) stands out as the most used standard regarding BIM data [3,31], and through their model view definitions, such as MVD Energy Analysis View, IFC4 could streamline the process of energy analysis using a BIM model, increasing interoperability levels [28,103,223].

4.1.2. Laser scanner and thermographic camera data merging

Thermographic cameras can be used to create thermal images, whose information (surface temperatures) can be merged with the geometric point clouds (laser scanner) [54], resulting in a file with both geometric and thermal information, usually a gbXML file [118,200,201]. This enables the creation and calibration of models with enough information to analyse their energy performance [89,119], including the assessment of the thermal resistance of materials in their current states [90]. New tools, such as Leica-Geosystems' BLK 360, could potentially increase the speed and precision of the process of creating as-is BIM-thermal models. Moreover, this process creates large files that can have their size reduced by increasing the spacing between points [74,75,200].

4.1.3. Urban scale analysis (BIM/GIS)

The energy performance of a building is directly influenced by the dynamics and interdependencies between the built environment [98,149], air convection, surface radiation and, when it exists, public thermal and energy infrastructure and its own interdependencies. In this regard, SIG 3D tools, like CityGML could help create large-scale models [87]. However, they lack the BIM level of detail. Also, new BIM objects that represent all aspects of urban-scale analyses should be made available in open BIM format. The integration of SIG in the BIM environment could revolutionise the energy analysis of buildings [56,171].

4.1.4. Building monitoring

Real-time building monitoring could contribute to keeping it in its peak efficiency during its lifecycle [83]. Through the creation of a Digital Twin model, maintenance plans can be created and stored in the model. Currently, this type of data can be stored in BIM models [148,192] but, as seen by Zhang. [220], it requires manual data inputs and is only for historic record purposes, given that BIM tools do not have real-time sensor information integration capabilities [33]. Sensor information could also ease diagnostics tasks [42]. However, it is necessary to enable the integration of sensor information and real-time sync with BIM models [59]. Sensor data integration could be the next step in the development of BIM tools, through BIM 7D, or the development of a BIM 11D, dedicated to building monitoring. Another relevant area to this topic, as shown by Dibowski et al. [224,225] and Ferrari et al. [226], regards automated fault detection on buildings and its systems by making manual, time-consuming engineering tasks solvable by a computer, allowing the building to run at its peak efficiency more easily.

4.2. BIM model-based tool development

The wide range of BIM capabilities allow users and developers to explore and create new purposes within BIM models. As such, this category explores the role of BIM in the development of new tools, or new methods of analysis, with focus on enhancing energy efficiency in buildings.

4.2.1. Software development

BIM models are capable of storing vast amounts of information and can therefore be used as databases for external tools with automatic access to the information [48,109]. On the other hand, the direct implementation of visual programming turns BIM tools into easily programmable tools [146], that simulate the most efficient combination of materials and solutions [21,129], taking advantage of the parametric nature of BIM models [50,154,155], the simplification of model conversion [123,216], the energy evaluation of buildings [130] and optimisation of systems [77], including sewage, as per Marzouk and Othman [135]. Also, through Monte Carlo simulation and genetic algorithms [134], it is also possible to economically analyse BIM models with higher accuracy. Some independently developed tools are making their way into mainstream BIM tools.

4.2.2. Output visualization platforms

BIM models and tools could also be used to show results. Sankey diagrams can be used to illustrate energy use flow through a building, but these are based on models created with simplifications [19], that is, with lower accuracy. Alternatively, as Niu et al. [149] and Truong et al. [193] have shown, results can be represented with different colours directly on the BIM, improving the reading and clarity of the results, improving user behaviour [13,193] and promoting the construction of more efficient buildings [14,58]. Therefore, BIM tools developers should concentrate their efforts on making it easier to import data from energy analysis tools and on developing new styles of representation.

4.3. Sustainable buildings

This topic exposes the role of BIM models and BIM tools in the creation of more efficient buildings, through the concept of sustainable buildings methodologies, paradigms, design solutions and energy consumption estimation.

4.3.1. Materials and solutions comparison and optimisation

BIM models possess high levels of versatility [34], allowing design teams [37,212,219] to change building features in a fast and simple manner [38,124,128,138,179], optimising designs and solutions [63,82,209]. BIM tools can help analyse the effect on energy performance of the size and shape of glass panels in solar radiation gains [8,153,173], different insulation materials [153,181], the use of recycled materials [53,215] and different wall solutions [7]. Regarding this topic, BIM tools are mainly used to help analyse the effects of the building envelope [69,86,94] and building orientation [2,6,182] on energy performance. Given the current complexity of building envelopes and their effect on heat losses [2,147], it is necessary to improve the modelling of thermal bridges in the BIM environment [95].

4.3.2. Energy needs estimation

Energy needs are influenced by the building geometry, equipment and user behaviour [218,221]. So far, as a "proof of concept" [76], BIM models can store all of this information, apart from user behaviour, which lacks research [81,99,104] but, as shown by Baldi et al. [227], occupant-building interaction can be automated and help improve overall building performance, opening the door to

BIM integration. Moreover, BIM can act as a basis for energy analysis software to estimate a building's energy needs [36,175,194,202]. Regarding equipment, especially related with renewable energy, BIM tools are not yet capable of modelling all of the existing solutions on this front [105,111]. Seeing the interest in developing a cost estimation tool with 3D features [168], real-time energy consumption should be available in future BIM tools [73], with higher levels of interoperability between these and energy analysis tools [128] and country-specific energy standards [137], achieving more accurate results.

4.3.3. Nearly Zero-Energy Buildings (NZEB)

Nearly Zero-Energy Buildings (NZEB) are characterised as highly efficient buildings, with low heat transfer coefficients and highly efficient equipment. As detailed in Sections 4.3.1 and 4.3.2, BIM tools can help designers to achieve more sustainable buildings [23], even in the early design stages [116,127], by accelerating the estimation of energy needs, allowing them to choose the solutions that bring the needs down to almost zero [52,141,187].

4.3.4. Life-cycle analysis (LCA)

Life-cycle analysis (LCA) applied to buildings involves, among others, a thorough inventory of the energy used during construction, use and demolition [24], given that all stages of a building's life represent environmental impacts [178], with the potential of reducing said impacts [26]. BIM tools can be used for LCA analysis, as per Cavalliere et al. [45] and Fernández et al. [71], on a database capacity [101], storing some physical material properties, according to Edwars et al. [66] and Gao et al. [72]. However, as per Kim [114] and Peng [158], the information that BIM can currently store may not be enough for complete and reliable LCA analysis. In spite of these limitations, BIM-LCA integration can currently be accomplished on three levels [185]: first, material quantification for environmental impact assessment [185,205], second, environmental data integration in BIM materials [64,185,208] and third, data extraction and transfer between tools [185]. Currently, most of the BIM-LCA integration used by researchers is done through ATHENA, joined by Revit [150]. Of all the stages of use of a building, there is however a lack of knowledge regarding end-of-life impacts [25,162,207] and its integration in BIM environment. The LCA-BIM integration could also improve certification processes on the environmental side of buildings [27,84,122], reduce analysis elapsed times [41,151,177] and improve LCA analysis reliability [102,186].

4.4. Hygrothermal design

This category gathers information about using BIM and energy tools to improve the hygrothermal design of buildings. Exploring the integration in BIM of concepts such as energy certification, thermal comfort and renovation processes will allow owners, developers and users to increase the levels of energy efficiency actively and passively.

4.4.1. Energy certification

Energy certification assigns a rating to buildings according to their efficiency, which is influenced by many aspects that BIM is capable of storing [35], and, as such, shows great potential for integration, as per Doan et al. [65]. Using BIM to perform energy certification of buildings could potentially accelerate the process and reduce associated costs, as per Li et al. [4], Ansah et al. [29] and Rezgui et al. [164]. However, for now, researchers are only able to perform specific tasks within BIM regarding specific energy certification systems, such as. Jalaei et al. [15] proceeded to calculate, through BIM, the minimum points needed to obtain certification in the LEED system, while Liu et al. [125] achieved 31 out of 78 Green Mark certification items through BIM. Chen et al. [51] tried to join geolocation services to the LEED certification system in BIM environment, in order to streamline the process and Wong et al. [206] identified 26 BEAM-Plus credits could be attained directly through BIM. The main limitation to this integration concerns the existence of several energy certification systems [132], with each one being specific to a certain country or area [97]. In future developments, the use of thousands of BIM models and big data techniques [16,159] could improve the certification processes currently in use or help create standardised systems.

4.4.2. Thermal comfort

Thermal comfort relies on six parameters [57], with four of them (i.e., solar radiation, temperature, humidity, and air velocity) being completely objective and independent from personal perception. BIM tools can already estimate the levels of solar radiation [48]. For interior air temperature and humidity, their estimation can be performed in an energy simulation tool, after importing the BIM model [11]. Interior air velocity, which can be simulated using CFD tools, once again after BIM model export, [12,141,203]. These types of analysis and simulations have been increasingly used [9], with the goal of optimising thermal comfort [93]. However, data transfer and interoperability between tools must be higher or, alternatively, BIM tools should be developed with native thermal comfort analysis capabilities.

4.4.3. Building renovation

Improving the energy efficiency levels in existing buildings is a complex process, given that almost all of its physical properties are fixed [43]. BIM tools have increasingly been used to evaluate existing buildings' energy performance [170], with the benefits, through simulation, of allowing the comparison of the current performance with the performance after the proposed renovation [9] and identifying the best renovation solutions [80]. Scherer [174] establishes two stages for the creation of an as-built BIM model: data acquisition [10,169] and data analysis [109,120,186]. However, and in order to create more reliable models, the process of data acquisition, specifically, thermal and physical properties, must be developed, with possible solutions as presented in Section 4.1.2.

4.5. Training

This category represents the current state and limitations of training future professionals in the use of BIM to enhance energy efficiency in buildings.

4.5.1. Training quality

The evolution of knowledge represents a challenge for educational institutions, and curricula must include the most recent knowledge [88]. Regarding the scientific fields of BIM and energy efficiency, and despite the inclusion of modelling in current curricula, HVAC systems design is not taught (except for mechanical engineers), resulting in a low implementation level of BIM for energy calculations. However, the implementation of energy analysis through BIM will allow future designers to solve existing issues more easily [20]. In this regard, the European project BIMcert sought to find solutions to some training limitations [136]. Collaboration between educational institutions can mitigate this issue [62], promoting a standardisation of methodologies [49,145]. Additionally, BIM knowledge acquired in the classroom could lead to solutions to all the current barriers associated with BIM tools and energy efficiency analysis.

5. Conclusions

With the rapid increase of the global population, we will need to build 13,000 new buildings per day by 2050 [228], which represents a capital projects investment of approximately $3.3 trillion annually [229]. This growth represents significant potential environmental impacts. However, higher energy efficiency can help reduce the negative environmental impacts frequently associated with the AECO sector. BIM coupled with BEM can play an important role on this front, allowing designers to achieve more efficient solutions, helping owners maintain their buildings at their peak efficiency level for longer, and constructors to achieve more efficient building processes, forging a way to a more sustainable future. This paper provides an overview of the current state of BIM adoption regarding the enhancement of energy efficiency in buildings. From this work, the following conclusions can be drawn:

i) Regarding the scientometric analysis:
- There is a high interest among the scientific community in the topic covered in this paper, given the exponential growth in the number of publications and citations verified, the fact that there are 50 journals with publications on this topic, and the number of conferences identified, the majority very recent.
- The main keywords identified were "Building", "Sustainability" and "Design". These keywords reveal that research into BIM and energy efficiency may influence the sustainability levels in buildings, through designers' choices.
- "Revit" is the most used BIM modelling software. Regarding energy analysis, there are several tools in use, with the most used being "EnergyPlus", "Ecotect", "Green Building Studio" and "IES – Virtual Environment". "Revit" presents strong interoperability connections with several energy analysis tools. On the other hand, ArchiCAD, which is most used by architects, does not, which may make the design of energy efficient buildings difficult.

ii) Regarding the systematic literature review:
- Currently, interoperability is described by Hanafi et al. [92] as being low. Farzaneh et al. [70] characterizes this property as being software dependent. As such, interoperability is hindered by loss of information in the data transfer processes, mainly because of different file structures. On this front, researchers, like Carvalho et al. [3] and Arayici et al. [31] make use of Industry Foundation Classes to overcome current interoperability challenges. Through IFC4 specification, MVD Energy Analysis View may represent a solution to the issues of compatibility between tools. Regarding this topic, a future survey paper, regarding only the interactions between BIM and energy analysis tools would be beneficial to understand the true extent of current interoperability levels.
- Currently, as is BIM models can have geometric data merged with thermographic data, by using thermographic cameras with laser scanners, as seen by Chi et al. [54]. Ham et al. [89] states that this data association is essential to enhance calibration process of as-is BIM and BEM models. However, as seen by Lagüela et al. [118], thermal bridges and other defects cannot currently be included in the gbXML schema used in this process. As such, new tools, capable of surveying geometric and thermographic data simultaneously could be the solution to the current issues.
- Energy efficiency in buildings is highly influenced by its surroundings [98,149]. As such, BIM-GIS integration, possibly through CityGML, as suggested by Gröger et al. [87] will allow calculations to include energy interdependencies between buildings in the urban environment and the impact of urban infrastructures on a building's energy efficiency, revolutionizing current energy efficiency calculation methods [53,171].
- Regarding building monitoring, the Digital Twin concept is the frontrunner technology. This process could, for instance, ease fault diagnostics processes in buildings, as stated by Bruno, et al. [42]. However, as seen by Aste et al. [33], BIM tools are not yet ready for the process (storing live data from sensors and visualising the results). A new BIM dimension (BIM 11D – Monitoring) could result from this research trend.
- Promoted by the ease of use of visual programming tools, there has been a great deal of software development to tackle current software limitations on building energy modelling and analysis.
- BIM tools have been used as visualisation platforms, with researcher using different methods to represent results. Some, such as Niu et al. [149] and Truong et al. [193] represent energy analysis results directly on models as colour gradients, while Abdelaim et al. [19] resorted to Sankey diagrams to display such results. However, new representation capabilities should be implemented in future BIM tools, as well as better data conversion and visualization mechanisms [149].
- BIM tools and models have allowed designers to achieve the most efficient solutions and choose the most efficient materials when designing or renovating a building. Aspects such as building orientation, window sizes, and wall materials, can be changed iteratively on the models, until the most efficient solution is achieved. Currently, some researchers focus their work on the impact of the building envelope in the building's energy performance, such as Evins [69], Granadeiro et al. [86] and Hensen et al. [94], while others, namely Pacheco et al. [2], Abanda et al. [6] and Singh et al. [182] focus their research on the impact of building orientation on energy performance. However, given the complexity of current buildings' envelopes, BIM tools need to improve their thermal bridges modelling capabilities [95].
- In the past, the energy needs of bigger buildings were estimated using specific software. Nowadays, with BIM, this can be easily done for all kinds of buildings, helping designers while still in the design phase. However, as stated by Gao et al. [73], there is a need for a BIM capability in which real-time energy consumption can be calculated. Additionally, country specific energy standards should be implemented [137] in such a tool, allowing its use internationally.
- According to Cavalliere et al. [45] and Fernãndez et al. [71], BIM technology represents a good support for LCA analysis. However, there is still the necessity to research further the impact of the end-of-life phase of buildings [25,162,207] and its integration on BIM models, as well as the need to include LCA-relevant parameters in BIM databases.
- BIM could and should be used as the basis for future energy certification of buildings. However, first it is necessary to internationally standardise the energy certification schemes. As such, in future developments, the use of thousands of BIM models and big data techniques [16,159] could improve the certification processes and help the certification systems standardization processes.
- The use of BIM to analyse thermal comfort levels has been increasingly used [9], with the goal of optimising them [93]. However, there is still a lack of interoperability between tools, hindering this process. As such, the inclusion of plugins or native thermal capabilities into BIM tools would improve these estimations.

- BIM training has been on the rise lately. However, energy efficiency analysis through BIM should be included in future curricula, preferably in a standard way worldwide.

Currently, BIM is already capable of influencing the energy efficiency levels in buildings, whether at the design, operational or end of life stage, or even during renovation operations. However, we are only halfway through the process of maximising the abilities of BIM, with many possible future developments showing the potential for improving the energy efficiency levels in buildings, by resorting to BIM models. One of the major challenges we still need to overcome is data exchange between design tools and energy simulation software. Aside from interoperability issues between BIM and BEM, there are also challenges surrounding the value BEM brings to owners and designers. Traditionally, owners and developers wanted designs to be completed quickly and at a low cost. As a result, architects felt pressured to focus their designs on functionality and cost, as opposed to energy consumption and sustainability. Hence, we need more research on the economic benefits of implementing building energy modelling, so as to convince owners that BEM can potentially help increase their financial bottom line. In addition, BIM software needs to develop solutions to streamline the integration of BIM and BEM. With the increasing research activity in this area, we will be able to continue to generate data to make a strong case for the integration of BIM and BEM and its use starting in early design decision, which is when designers' can more significantly impact a building's potential towards sustainable and financially viable solutions.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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