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Smart retrofitting of buildings: a bibliometric study

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Smart retrofitting of buildings: a bibliometric study

Sanduni Peiris[1a], Joseph Lai[1] and Mohan M Kumaraswamy[2,3]

[1]Department of Building Environment and Energy Engineering, The Hong Kong Polytechnic University, Kowloon, Hong Kong
[2]Department of Civil Engineering, The University of Hong Kong, Pokfulam, Hong Kong
[3]Department of Building Economics, University of Moratuwa, Moratuwa, Sri Lanka

[a]sanduni.peiris@connect.polyu.hk

Abstract. Smart Building (SB)s have gained significant attention over the past decade. This is mainly because of the performance and efficiency enhancements that smart features can enable a building system to achieve, for example, net-zero energy consumption, operational savings, state-of-the-science user-friendliness, safety and security. Nowadays, many new buildings are being designed with smart features. The 'grand challenge', however, is converting the existing, ordinary buildings into SBs, through a process called "smart retrofitting (SR)". This process, while affecting the existing building components and the end-users, is challenging to the relevant facilities managers. As strengthening the SR knowledge base will enable better-informed, hence more effective decisions, the focus of this research is to undertake a bibliometric analysis of SR research to assess its development in terms of prominent authors, countries and organisations. The bibliometric searches were conducted on the 'Scopus' and 'Web of Science' databases. A total of 107 journal articles were identified and analysed using the "VOSviewer" software. The findings revealed: the co-authorship patterns; the connections among the most influential authors, countries, and organisations; and the weak collaboration among the authors and organisations. This study is the first bibliometric analysis on SR, the results of which not only serve as a useful reference for both researchers and practitioners but also signpost further works to be undertaken for complementing the current results.

Keywords. Bibliometric; buildings; retrofitting; review; smart; VOSviewer.

1. Introduction
The demand for smart cities has grown as a result of increased urbanisation, which is causing a variety of problems including climate change [1]. SBs, as the core hardware of a smart city, play a critical role in smart city performance [2]. An SB is defined by Al Dakheel et al. [3] as "a nearly Zero Energy Building (nZEB) that is able to manage the amount of Renewable Energy Sources (RES) in the building and the Smart Grid (SG), through advanced control systems, Smart Meters (SM), energy storage and demand-side flexibility while reacting to the users' and occupants' needs and is able to diagnose faults in building operations". With the use of the Internet of Things (IoT) to provide intelligent control and reliable connectivity between web-connected hardware, remote controllers, and sensor networks [4], an SB goes beyond the structure and function of an ordinary building [5]. Rather than being programmed by humans to do automatic tasks, an SB can learn to predict future states of the building by observing the surroundings and occupant behaviour, such as the frequency of turning lights on and off [6]. The use

of sensors for real-time monitoring of fresh air in a building, for example, can also transfer signals to the intelligent control system to reduce unnecessary heating and cooling load, thus ensuring good indoor environmental quality [7]. SBs can offer a range of benefits to occupants, including comfort, energy savings, time savings, reduced maintenance costs, safety, health and care, expert systems, and assistive domotics [3].

Existing buildings, if retrofitted appropriately [8] to become SBs, offer a huge potential for achieving the above benefits. This way of retrofitting – a process called “Smart Retrofitting (SR)” – is an excellent approach to modernising and upgrading building performance [9, 10, 3].

Given the several obvious advantages of SBs, it is puzzling why so few building owners have considered retrofitting their buildings to be "smart." For instance, nearly 75% of the European building stock is still energy-inefficient [11] and the commercial building sector in the United States (US) still consumes 30% of all US energy [12]. Previous studies have reported several reasons for this hesitancy which can be categorised under: (1) technical concerns and (2) social concerns.

In terms of technical concerns, SBs are extremely vulnerable to cybersecurity threats posed by IoT-based communication networks with the SG and within the building itself [13, 14]. Adversaries could exploit heterogeneous communication networks, which include devices such as "smart sensors" to launch various types of malicious cyber-attacks that compromise data integrity [15, 16]. Another concern arises from the technical challenge of installing new technologies and optimising the legacy systems to communicate with such new technologies [3]. Mechanical and electrical system vendors contribute to such compatibility concerns in some ways by continuing to manufacture products that communicate via their own distinctive protocols [4]. According to this author, even when systems are based on common network protocols such as BACnet, LONWorks, or both, manufacturers can configure devices to prevent free-flowing data exchange with equipment from other vendors. The most challenging part of SB applications lies in its management. Even if an organization has the financial resources and foresight to adopt SBs, it may be useless if the facility management team lacks IoT experience [17]. In most cases, the absence of the facility management team during the early stages of a project causes several risks throughout the operation and maintenance phase of an SB [18].

The social issues relate mainly to the stakeholders involved in SR, of whom the investors and occupants of a facility play a key role. Although affordability is always an issue when deploying new technologies, Berawi et al. [19] report on how for SBs and hence, SR, these concerns relate not only to the initial cost of the devices and networking, but also to the cost of Software as a Service (SaaS), installation, and training. Therefore, it is difficult to attract investors without an indication of immediate returns, as in such cases. Building contractors are hesitant to participate in SR projects, for fear of complicated job tasks and increasing project risk and costs [20]. Convincing building occupants could be a daunting task amidst the social problems that they have to face in accepting the change to smarter buildings [3]. They are also hesitant to reveal their personal information to IoT devices due to concerns about the party responsible for storing and analysing the data, as well as their purpose for using it [21].

Such concerns and constraints, which could be stronger and stricter in existing buildings, compared with new constructions, complicate the implementation of SR [22]. It is clear that the lack of SR knowledge and comprehension plays a significant role in the aforementioned challenges. Various studies have focused on different aspects of SR [23, 3], but there is still a lack of proper understanding of this concept and its current state [24]. Knowledge in the area of SR has been developed with neither a structure nor a proper direction. To contribute to enhanced understanding, a quantitative study using the bibliometric analysis technique was conducted on SR-related journal articles to identify the prominent authors, countries and organisations in the field. The following sections of this paper first describe the methods and process utilised in the study. The results in terms of the performance of publications and science maps are next presented and discussed. Further works to be undertaken to complement the results of this study are highlighted in the conclusion section.

2. Research Methodology

The question that prompted this research is "What is the present state of SR research?". According to Liu and Xia [25], co-authorship analysis of existing literature is the most suitable approach to resolve this question. In co-authorship analysis, two authors who co-authored a research article together are linked, and the analysis can reveal specific elements of the author network, such as how dispersed or cohesive the network is, or who the best-connected authors are [26]. Since bibliometric analysis is commonly used to determine co-authorship [27], it was selected as this study's research method. By rigorously making sense of vast volumes of unstructured data, a high-quality bibliometric analysis is valuable for interpreting and visualising the cumulative scientific knowledge and evolution of research domains [28], based on which a solid foundation can be cast for expanding a research field in a novel and insightful way.

First, data was collected from publication databases using the search terms. The resultant datasets were refined to meet the study's objectives before being exported. The datasets were then screened for duplicates and errors before a final, clean dataset was obtained. This dataset was imported into a bibliometric analysis and visualisation software. The research process is shown in figure 1, and the findings are discussed thereafter.

Data collection was conducted on two of the most reputable databases of relevant research literature, namely, Web of Science (WoS) [29] and Scopus [30]. The utilisation of both these databases guarantees the required literature coverage and the flexibility in effective searching based on topic (comprising title, keyword and abstract), type of source, timeframe and various other parameters [31, 32]. Furthermore, a large dataset combined from the two databases verifies that the dataset utilised for the research is complete without bias [33]. Authors further state that the search terms used for a database search should be carefully considered because it has a significant impact on the results of the study. Therefore, the keywords used as the search terms were chosen after reviewing an initial batch of relevant research publications.

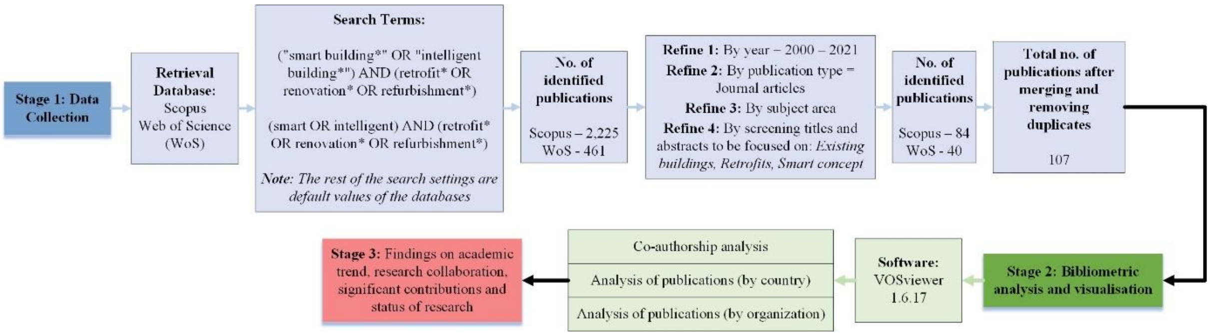

Figure 1. Research process.

The refined datasets were exported to Microsoft (MS) Excel format. Each MS Excel file was edited to remove duplicates and erroneous entries. The edited MS Excel files were merged to obtain a final dataset, which consisted of 107 journal articles. This file was imported to the selected bibliometric analysis and visualisation software. Various pieces of software such as VOSviewer [34], CiteSpace [35] and Gephi [36] are available for use in bibliometric analysis. This study selected VOSviewer, which is notable for its user-friendliness and capabilities of combining clustering and mapping techniques in a single approach. It also supports several databases including WoS and Scopus [34].

Findings resulted from the bibliometric analysis and visualisations are discussed in the following sections.

3. Findings and Discussion

Co-authorship analysis of literature was used to identify academic collaborations, collaborative behaviours, or schools of thought in a research field by observing the authors and their affiliations [37].

Such findings could be valuable for research and policy that seeks to approach the subject with the assistance of specialised groups [38].

3.1. Co-authorship analysis

When analysing the bibliometric data using VOSviewer, certain parameters need to be set in order to analyse the dataset in accordance with the objectives of the study. These parameters include the thresholds for the minimum number of documents and citations of the subjects undergoing analysis. In the case of authors, the threshold limit for the minimum number of documents of an author and the minimum number of citations were set at '2' and '1' respectively. Of the 264 authors, only nine (3.4%) met the threshold, as visualised in figure 2.

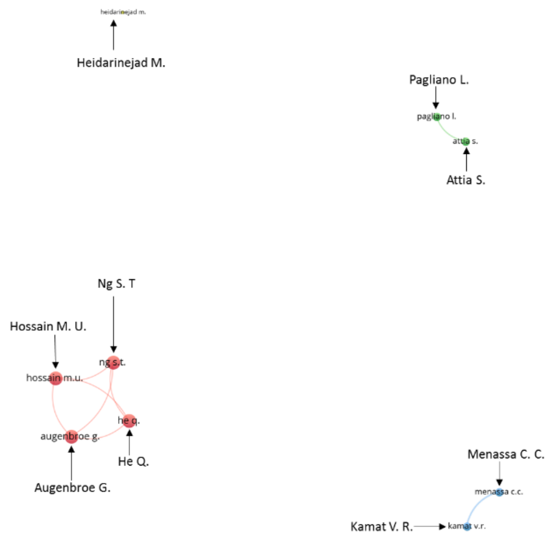

Figure 2. Co-authorship analysis (network visualisation based on links).

In figure 2, the size of a node represents the number of co-authorship links with other authors and the node colours represent the collaboration clusters. Of the four collaboration clusters, the only cluster with more than two authors comprises authors 'S.T. Ng', 'M.U. Hossain', 'G. Augenbroe', and 'Q. He'. These authors have the strongest network with a total link strength of eight out of 14 (57%). Researchers' influence on each other is shown by their distance and connectivity. As the clusters are dispersed and the number of links is small, more collaboration between researchers should be encouraged for addressing any key concerns in SR research.

Table 1, generated using the 'save as' option in VOSviewer, summarises the findings of the analysis, with the authors ranked based on the Average Citations (AC). It shows that even though some authors have a relatively low link strength, their publications have been frequently cited. Possible reasons for this include: (1) those publications contain fruitful findings; and (2) they are relatively old publications which had more time to be cited. For example, 'L. Pagliano' and 'S. Attia' have co-authored a highly cited paper titled "Overview and future challenges of nearly zero energy buildings (nZEB) design in Southern Europe" [39]. This is a useful reference for SR researchers who need to identify key components of the background including threats, opportunities for SR implementation and research gaps.

Table 1. Co-authorship analysis of Authors.

Rank	Authors	Documents	Links	Total Link Strength	Average Citations (AC)	Average Publication Year (APY)
1	Attia S.	2	1	1	83	2017
2	Pagliano L.	2	1	1	75	2018
3	Kamat V.R.	2	1	2	23	2018
4	Menassa C.C.	2	1	2	23	2018
5	Heidarinejad M.	2	0	0	8	2019
6	Augenbroe G.	2	3	2	1	2021
7	He Q.	2	3	2	1	2021
8	Hossain M.U.	2	3	2	1	2021
9	Ng S.T.	2	3	2	1	2021

3.2. Analysis of publications (by country)

The threshold limit for the minimum number of documents of a country and the minimum number of citations were set at ‘2’ and ‘1’ respectively. Of the 54 countries, only 21 (38%) met the threshold. Among these 21 countries, only 16 were connected, as visualised in figure 3 and figure 4.

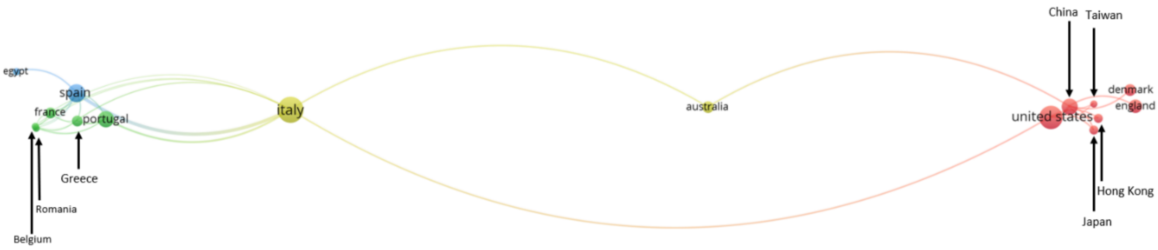

Figure 3. Network visualisation based on documents (by country).

In figure 3, the size of the nodes represents the number of publications. A larger node implies a larger contribution to publications from that country. Four scientific clusters in SR research have been distinguished with four different colours. Italy, Spain, Portugal, France, the United States (US) and China have produced relatively more publications. In terms of co-authorship, the US, China, Taiwan, Hong Kong, and Japan as well as Italy, Spain, Portugal, France, Greece and Romania show intense collaboration. Australia is active in maintaining co-authorship links with other countries in different clusters. Overall, Italy is the most active country in publication and collaboration.

Figure 4. Overlay visualization based on citations and APY scores (by country).

In figure 4, the size and the gradient colour of the nodes represent the number of citations and the APY of countries (as per the legend). Publications by many countries have received high citations, which could be from strong co-authorship links of these countries with countries in other regions. The older APY of Taiwan, the US and France could be another contributor to their high number of citations. The most recent SR publications have been produced by Hong Kong and Egypt, implying that these places are active in this emerging research area.

3.3. Analysis of publications (by organisation)

The threshold limit for the minimum number of documents of an organisation and the minimum number of citations were set at '2' and '1' respectively. Of the 189 organisations, only 14 (7.4%) met the threshold and among these 14 organisations, 13 were connected (figure 5).

Figure 5. Overlay visualization based on citations and APY scores (by organisation).

The node size represents the number of citations, and the line between two nodes demonstrates the academic link between the two organisations connected. Hence, a shorter line indicates a closer relationship. Only seven organisations have collaborated with at least one other. In terms of collaboration, only one cluster shows the existence of strong links, with a total of 14 links among five universities: Georgia Institute of Technology (GIT), Purdue University (PU), The University of Hong Kong (HKU), City University of Hong Kong (CityU), and Nanjing Tech University (NTU). Figure 5 indicates that the organisations are doing well independently in terms of research output, but there is a lack of collaboration links among the research organisations. This suggests a need for researchers from the various institutions to collaborate, which would boost research productivity and quality. In terms of number of publications, there is no significant difference between the organisations.

The gradient colours of the nodes demonstrate the APY of organisations according to the legend. It is clear that the numbers of citations received by the University of The Basque Country (UBC) and Politecnico Di Milano (PDM) are significantly higher than the other organisations. A main reason could be their informative publications in SR. Furthermore, their APY is comparatively less recent, allowing more time for researchers to recognise and reference those publications. Universities such as NTU, GIT, PU, HKU, CityU, and Universitat Politècnica de Catalunya (UPC) have the most recent average publication years, implying that they are the relatively more influential organisations in the latest SR research.

4. Conclusions and Further Research

SR is currently regarded as an ineffective and costly process [20, 3], since various areas of the underlying concept remain underexplored, hence misunderstood. With the aim of improving the SR knowledge base, a bibliometric analysis was undertaken to unveil its current development. The review was conducted covering 107 journal articles published between 2000 and 2021. Using VOSviewer, co-authorship analysis of literature was performed to identify the prominent authors, organisations and countries in the SR research domain.

Notably, authors 'S.T. Ng', 'M.U. Hossain', 'G. Augenbroe', and 'Q. He' were found with the strongest network with the same number of publications, but the author clusters are quite distanced and disconnected. Organisations including GIT, PU, HKU, CityU, and NTU have the strongest collaboration and the most recent publications whereas publications by the UBC and PDM have been cited the most. Italy is the most productive in terms of SR related publications and collaboration with other countries, while Hong Kong and Egypt's recent APY imply that they are emerging leaders in SR research.

On the whole, there were weak collaboration links between authors and organisations in the SR research base. Hence, it is essential that authors and organisations take concerted initiatives to promote cutting-edge research and innovation, given the importance of SR and the value of sharing and synergising knowledge from various domains. This should be preferably supported by research grants from governments or research councils. Conferences and summits with SBs and SR as key focus areas would also encourage researchers to share and exchange research ideas and findings, thus facilitating collaborative research to be made.

While the study's objectives have been met, some limitations remained. First, the keywords used as the search terms were carefully selected from previous studies in the area of the present study, but publications without these keywords might not have been identified from the search process. Second, findings from SR related reports of non-academic organisations (e.g., US Department of Energy, European Commission – Energy) have not been included in this study. Third, drawing conclusions on the research productivity based on 'citations', which significantly depends on the recency of publications, may give rise to disagreement.

Despite the above limitations, the findings of this study do generate many valuable pointers with useful theoretical and practical implications. This is the first bibliometric analysis of SR research, and it uncovers solid and useful patterns for future scholars to consider. Researchers planning to conduct SR research can recognise which authors and organisations are active or leading in this field. This, in turn, serves as a directory for the researchers in the literature search. The results of this study are also beneficial for students who wish to pursue SR studies/research, as they can identify the best universities to enrol in. Industry practitioners can similarly identify which organisations or scholars are at the forefront of SR research and make better-informed decisions on who to consult in tackling SR related problems. Since this study has only identified the prominent authors, organisations and countries, future studies can focus on unveiling the research gaps and trending topics in SR research. To identify the key SR issues that warrant further examination, a qualitative analysis of the literature is also required.

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