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Smart retrofitting for existing buildings: state of the art and future research directions

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Abstract

Transforming ordinary buildings into smart building (SB)s, considered as 'smart retrofitting (SR)', requires retrofit works that involve smart technology applications. Given the limited knowledge about the SR concept, a systematic literature review was conducted using a mixed methods approach. Following the 'Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA)' framework, which is a well-recognized comprehensive reporting guideline for systematic reviews, SR-related literature was first identified from 'Scopus' and 'Web of Science'. A bibliometric analysis of the identified literature revealed that the past research predominantly focused on energy efficiency and occupant comfort while social and legal issues were underexplored. A further, qualitative review of the shortlisted literature unveiled the SR research gaps and six future research areas: (1) smart retrofit performance evaluation, (2) SR applications for building envelope optimization, (3) renewable energy integration through SR applications, (4) SR applications for demand side management, (5) stakeholder engagement in SR, and (6) planning for effective SR implementation. Outcomes synthesized from this study include a framework consolidating the review findings and a mapping exhibiting the nexus of future research directions, which serve to facilitate and catalyze expected efforts for realizing smart buildings.

Keywords

Bibliometric; building; retrofit; review; smart.

1.0 Introduction

Urbanization, which causes a multitude of environmental issues including excessive energy consumption and carbon emissions (Lu & Lai, 2020; Lu & Lai, 2019), leads to the elevating demand for smart cities (Obringer & Nateghi, 2021). As the core hardware of smart cities, smart building (SB)s play a vital role in determining the cities' performance (Bach et al., 2010). SBs are the more advanced successors of intelligent building (IB)s with better longevity, energy efficiency, comfort, and satisfaction (Buckman et al., 2014); they go beyond the form and function of traditional buildings by incorporating intelligent control systems and automation of interconnected components (Dincer, 2018). The internet of things (IoT) facilitates connectivity between systems and devices of an SB, allowing for the efficient use of web-connected hardware, remote controls, and sensor networks. An SB can learn to forecast the future states of the building by analyzing the surroundings and tenant behavior and can make operational decisions on its own rather than requiring regular human intervention to conduct automatic duties (Cook & Das, 2004).

Not only newly developed SBs but also existing buildings can attain smartness if they are retrofitted appropriately (Ho et al., 2021). It is estimated that by 2050, 80% of the buildings that exist today will still be in operation. In this context, it is crucial to properly retrofit existing buildings. The literature discusses a variety of building retrofitting topics, including energy retrofitting, green retrofitting, seismic retrofitting and integrated seismic and energy retrofitting. In order to achieve greater energy and carbon reductions, energy retrofitting primarily refers to the adaptation of energy-saving technologies to existing systems (Pacheco-Torgal et al., 2017). Building energy retrofitting can include a variety of energy efficiency measures, such as improving the envelope by incorporating insulation, energy-efficient windows, airtightness, the use of energy-efficient lighting systems and high-performance heat ventilation and air conditioning (HVAC) systems (Asif, 2022). As stated in the report of United States Green Building Council (2003), green retrofitting is defined as ‘‘...any type of upgrade to an existing building that is wholly or partially occupied to improve energy and environmental performance, reduce water use, improve comfort and quality of space in terms of natural lighting, air quality, and noise, all done in a way that it is financially beneficial to the owner”. Similar to energy retrofitting, there is a substantial amount of literature on green retrofitting (Jagarajan et al., 2017). Seismic retrofitting is typically carried out when a building’s structural integrity has been weakened and it is not possible to demolish and replace the structural elements (ElGawady et al., 2004). A myriad of solutions related to seismic retrofitting have also been proposed in previous studies (Ferraioli et al., 2023). However, relatively little research has been done to investigate the need for integrated seismic and energy retrofitting solutions (Tetteh et al., 2022). The susceptibility of old buildings that were not built in accordance with today’s construction standards could pose safety issues while also reducing the potential effectiveness of energy retrofits (Belleri & Marini, 2016). If a structure fails, for example in the event of an earthquake, investments in energy saving measures may be entirely lost. As a remedy, recent research (Baek et al., 2022; Pohoryles et al., 2022; Pohoryles et al., 2020) recommends the novel approach of integrated seismic and energy retrofitting. This approach aims to achieve energy efficiency and seismic resilience in combination in a particular retrofit intervention.

Among the various retrofit aspects, the one that this paper focuses on is smart retrofitting (SR), which is defined by Al Dakheel et al. (2020) as: “The process to transform the existing building into an SB, that is a net Zero Energy Building (nZEB) with the capability to respond to the changing conditions of climate and grid, communicate with the user and predict failures in its operations, through the use of information and communication technology (ICT), renewable energy sources (RES), and building energy management systems (BEMS)”. While carbon reduction and energy savings are the primary drivers of SR, there is a myriad of other goals to be achieved by making buildings smarter (Wong & Li, 2008) which make SR different from green retrofits, general energy retrofits or seismic retrofitting. They include reduced operating and maintenance costs as well as a more flexible, convenient, and comfortable environment. These lead to more productive and happier occupants thereby increasing the marketability of the building (Huseien & Shah, 2022). SR is considered by many an excellent technique to modernize and improve the performance of buildings (Al Dakheel et al., 2020; Farahani et al., 2019; Luddeni et al., 2018). However, a standard definition of the concept of SR is not yet available. While the definition and the scope of SR could be enhanced by combining it with the processes of other retrofit aspects, in the context of the present paper, SR means retrofitting building services in existing, non-SBs with smart features such as smart sensors, smart controls, smart management, and smart appliances (Aliyu et al., 2017) to achieve the SR goals defined by Al Dakheel et al. (2020). Retrofits to the structure of a building are beyond the scope of this paper.

In spite of their benefits, SR applications encounter certain loopholes. Issues such as cybersecurity risks related to IoT devices (Wendzel, 2016), the necessity to optimize existing systems to interface with new technologies (Al Dakheel et al., 2020), the lack of IoT-related experience within the facility management (FM) team (Pašek & Sojková, 2018) and non-technical issues such as the legal complications surrounding the SR process and the social challenges associated with the change management of building users (Al Dakheel et al., 2020) are among the key sources of conflict in SR. SR is typically thought to be costly (Sun et al., 2018), and many building contractors are unwilling to participate in SR projects due to concerns about undertaking sophisticated work tasks, which would increase project risk and expenses (Yang & Peng, 2001). Essentially, implementation of SR has to face the limitations and obstacles that arise when converting an existing building into an SB, which can be different from those encountered when constructing a new SB. The eventual goal of SR often covers a wide and ambitious scope, which is somewhat different to that of green retrofits or energy retrofits. In addition to promoting environmental sustainability and energy efficiency, SR seeks to improve building performance along various dimensions such as user satisfaction, health, safety, and so on. Additionally, when integrating convenience enhancement initiatives such as space occupancy management, smart parking systems, etc., it is important to consider both the change management needs of the tenants and the FM staff during the SR process.

While previous studies have reviewed the concept of SBs, their development as well as other types of retrofits, no work has been undertaken with a specific focus on reviewing the concept of SR and its complexities. There were studies that review SB literature (GhaffarianHoseini et al., 2012). Some studies briefly covered the challenges in SR (Al Dakheel et al., 2020), while some others focused on introducing new technology for SR (Al Dakheel et al., 2020; Capeluto, 2019; Li et al., 2021; O'Grady et al., 2021; Panopoulos & Papadopoulos, 2017). While some studies have developed assessment systems to evaluate smartness of buildings after or before the retrofits (Engelsgaard et al., 2020), many of the prevailing challenges in SR have not yet been addressed. These existing gaps in SR literature have triggered confusion among practitioners and researchers. To date, a proper comprehension of this topic and its current state is still lacking (Jaspert et al., 2021). Given the dramatic increase in the demand for smartness in existing buildings (Aliero et al., 2021), attention to the complex issues of SR is urgently needed.

In view of the above, it is imperative to understand the past development and the status quo of SR so as to pave proper pathways for the future of SR. To this end, the following research questions (RQs) arise:

- RQ1: Who are the prominent contributors and what are the prominent keywords in SR research?
- RQ2: What are the past and recent research areas in SR research?
- RQ3: What are the potentially useful future research directions in SR research?

To answer the above question, a research study bearing the following objectives was initiated: firstly, to conduct a quantitative study on SR-related journal articles using the bibliometric analysis technique to identify the prominent contributors and keywords in the SR field; secondly, to qualitatively review a rigorously-selected set of journal articles to identify the past and recent research areas in the field; and finally, to identify the gaps in SR research and hence the potentially useful future research directions.

The materials and methods used in this review are discussed in section 2 of this paper. Section 3 includes the results of the bibliometric analysis and section 4 describes the results of the manual qualitative analysis. The findings are discussed in section 5 and the concluding remarks are presented in section 6.

2.0 Materials and methods

Towards the above objectives, a three-stage methodology was developed with reference to the interpretivist epistemological design adopted in past review studies such as Chamberlain et al. (2019) and Adegoriola et al. (2021). Central to this methodology is a systematic literature review, which follows a mixed method approach that combines a bibliometric analysis and a qualitative analysis to synthesize and evaluate the existing literature on the topic under study (Hargen & Thomas, 2010). Qualitative analysis is a powerful tool for facilitating in-depth understanding and finding gaps in literature (McGowan & Sampson, 2005). While subject to personal judgment and biases (He et al., 2017), this shortcoming of the qualitative analysis can be minimized using the mixed methods approach (Heyvaert et al., 2016) as the bibliometric literature analysis is quantitative and objective. Hence a mixed method systematic review produces fruitful yet unbiased results when compared to the 'mono-method systematic review' (Heyvaert et al., 2016).

The three main stages of the methodology are: Stage 1 – data collection; Stage 2 – quantitative analysis using bibliometric analysis and visualization; and Stage 3 – qualitative analysis. The Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) framework, which facilitates transparent and complete reporting of systematic reviews, was applied to select and screen publications in Stage 1 (See Figure 1).

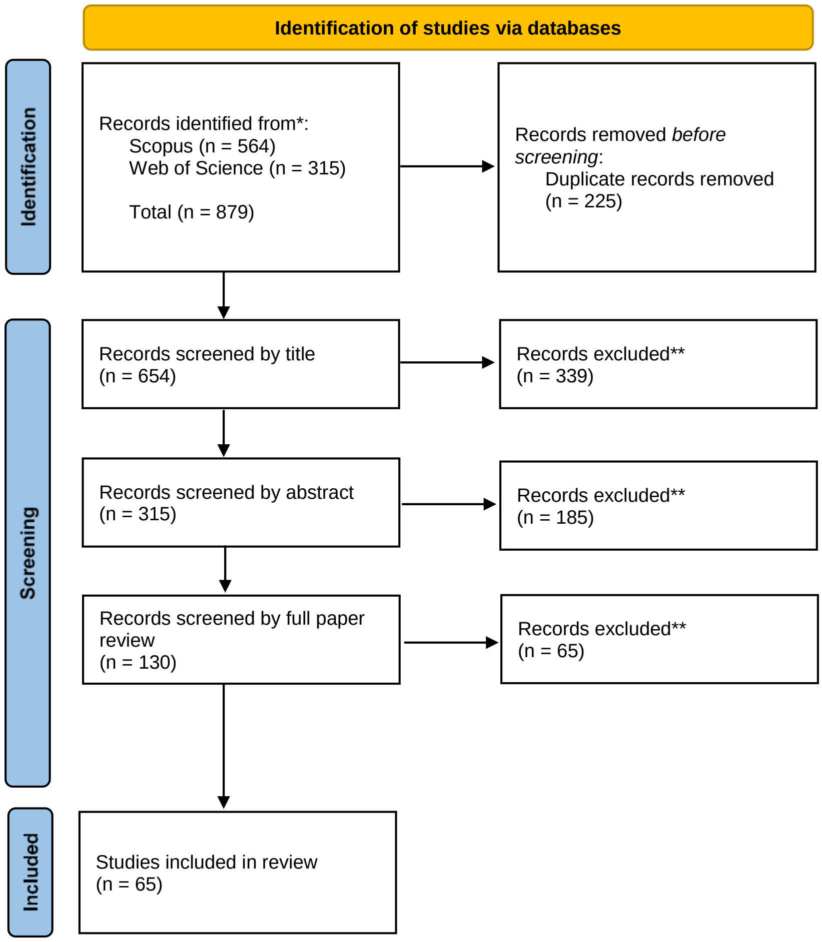

Figure 1: The PRISMA process

At the initial stage of this study, search terms were developed and used to gather data from well-established literature databases, namely, Web of Science (WoS) (Sedighi & Jalalimanesh, 2017) and Scopus (Aghaei Chadegani et al., 2013). A search term, comprising of a set of words that may best capture the relevant literature, was formulated based on the author keywords of previous similar studies (Al Dakheel et al., 2020; Capeluto, 2019; Engelsgaard et al., 2020). The search terms used in this study comprise SR-related keywords combined with Boolean operators: *building* AND (retrofit* OR renovation* OR refurbishment*) AND (smart OR intelligen*).*

The search process was conducted using the 'TITLE-ABS-KEY' field in Scopus and the 'Topic' field in Web of Science. The resultant dataset was then refined to articles published between 2003 and 2022 because the field of study is rapidly evolving and studies from the past 20 years should be sufficient to answer the RQs of this study. All publications except journal articles were excluded in order to limit the dataset to articles that contain an appropriate level of detail and required information (Butler & Visser, 2006). Empirical research articles and review papers were both included in the review because, similar to empirical research, knowledge captured in review papers are important for further development of the field. The dataset was further refined to articles written in English. The search process was completed in December 2022 and a total of 879 records were exported from the databases (see Figure 1).

These records were then exported to an MS Excel Spreadsheet and duplicates were removed. The remaining records were screened by title and abstract review. The following inclusion/exclusion criteria were used in the screening.

Inclusion criteria:

- Papers mainly focused on retrofitting smart technology to existing buildings
- Papers introducing smart innovative technology that can be retrofitted to existing buildings
- Papers discussing the integration of renewable energy (RE) technologies that can communicate with the grid
- Papers on post smart retrofit performance evaluation

Exclusion criteria:

- Papers focusing on smartification of the retrofit process only
- Papers introducing smart technology that can be incorporated only into new buildings
- Papers focusing only on retrofitting the structure of a building

A high-quality bibliometric analysis is useful for explaining and visualizing the growing scientific knowledge and progression of research fields (Donthu et al., 2021). 'VOSviewer', a bibliometric analysis and visualization software (Van Eck and Waltman, 2013), was used in Stage 2 to analyze the dataset of 130 records in order to answer RQ1. Prominent keywords and prominent contributors were thus identified in terms of authors, countries, organizations and journals.

In Stage 3, a qualitative review of selected publications was conducted to find answers for RQ2 and RQ3. The full-texts of the 130 articles were screened by the same inclusion/exclusion criteria, and this resulted in having 65 articles shortlisted. Content analysis was made on these articles; their main contents identified were summarized using a manual coding process and the content of each article was coded into discernible categories.

3.0 Bibliometric Analysis Results

3.1 Number of annual publications and citations

The 130 journal articles, which were identified through the bibliometric search, were analyzed using Microsoft Excel based on the number of annual publications and annual citations. The results in Figure 2 indicate an increasing trend of publications in the period 2005 - 2022. Initially, there was moderate growth in publications between 2005 and 2016 with slight drops in between. Only 19% of the 130 articles were published over that period. From 2016 to 2017, the number of publications showed a significant increase which was maintained until 2019. However, in 2020 the number of publications show an increase of 136% which is the highest among all years. A minor drop can be observed from 2020 to 2022. However, 53% of the 130 publications were published in the period of 2020 to 2022.

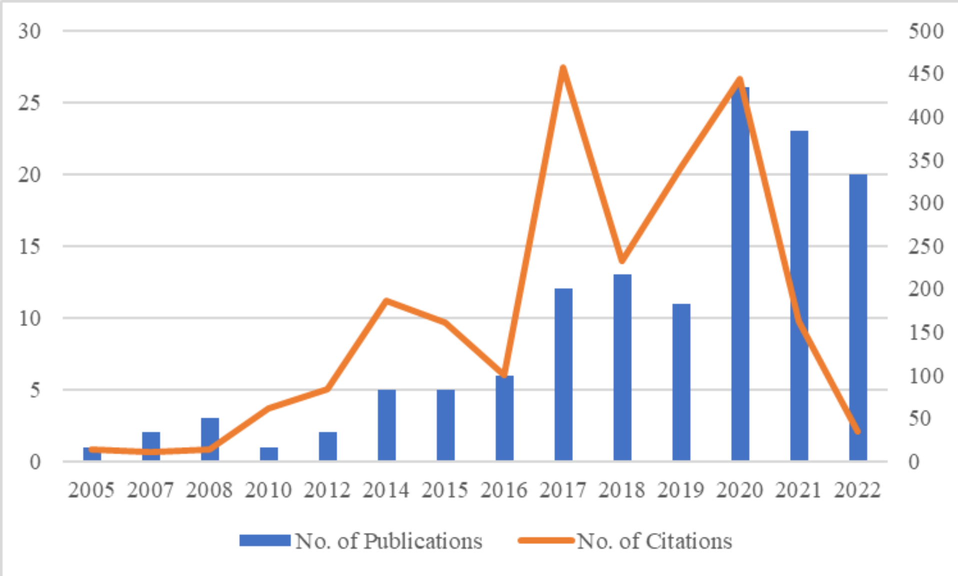

Figure 2: Annual publications and citations

As evidenced by the increasing trend in the annual number of publications, the main reason for the overall rise could be the increased interest of researchers in SR. This could be attributed to the new rules enforced by various governments in the pursuit of nZEB, including the European Union (EU)'s Energy Performance of Buildings Directive (EPBD)'s targets (Al Dakheel et al., 2020). The majority of papers related to SR were published between 2020 and 2022, indicating that research in this area has grown in popularity and that there is more ground to be explored.

Figure 2 further shows that there is no obvious trend in the number of citations received by the journal articles published each year, particularly between the years 2014 and 2020. Over the years, the fluctuating trend has continued, with substantial surges in several cases. However, following 2020, there is a significant and continuing reduction. This could be due to two factors: (1) the significant time it takes for new publications to be cited, and (2) the interest in this topic not reaching maturity yet. This echoes the findings of Al Dakheel et al. (2020) and Jaspert et al. (2021) that deeper research is needed in the field.

3.2 Prominent contributors

When investigating a research field, particularly its current condition and evolution, it is critical to identify and recognize its contributors because such findings can provide insights and inform implications of research collaboration between experts in the related fields. In this study, the VOSviewer software was used to analyze the contributors using different attributes such as item, publications, links, total link strength (TLS), average citations (AC), average publication year (APY), and occurrences. These attributes are defined as follows: (i) item - the objects of interest in a map which may for example be publications, researchers, or terms; (ii) publications - the number of documents published by a source, an author, an organization, or a country/place; (iii) links - a link is a connection or a relation between two items. Between any pair of items, there can be no more than one link; (iv) TLS - the strength of a link may for example indicate the number of publications two researchers have co-authored (when the strength of links owned by an item is totaled, it is the TLS); (v) AC - the average number of citations received by the documents in which a keyword or a term occurs or the average number of citations received by the documents published by a source, an author, an organization, or a country/place; (vi) APY - the average publication year of the documents in which a keyword or a term occurs or the average publication year of the documents published by a source, an author, an organization, or a country/place; and (vii) occurrences - the number of documents in which a keyword occurs.

Five types of contributors were identified based on prominence: (1) authors, (2) countries/places, (3) organizations, (4) journals, and (5) keywords. Analysis of the first three types of contributors (i.e. authors, countries/places, and organizations) was reported in Peiris et al. (2022); findings on significant keywords and journals are reported in the following.

3.2.1 Analysis of keywords

The threshold limit for the co-occurrence of keywords was set at '2'. Twenty-eight (28) keywords that met this condition (after merging duplicates and similar words) are illustrated in Figure 3, where the frequency of occurrences of keywords is represented by the size and density of the nodes. The more a keyword was co-selected among the SR publications, the larger and more solid the node. The difference in distance between two keywords reveals the relative strength and topic similarity. The node color, varying from purple to yellow (see legend), indicates the APY of each keyword.

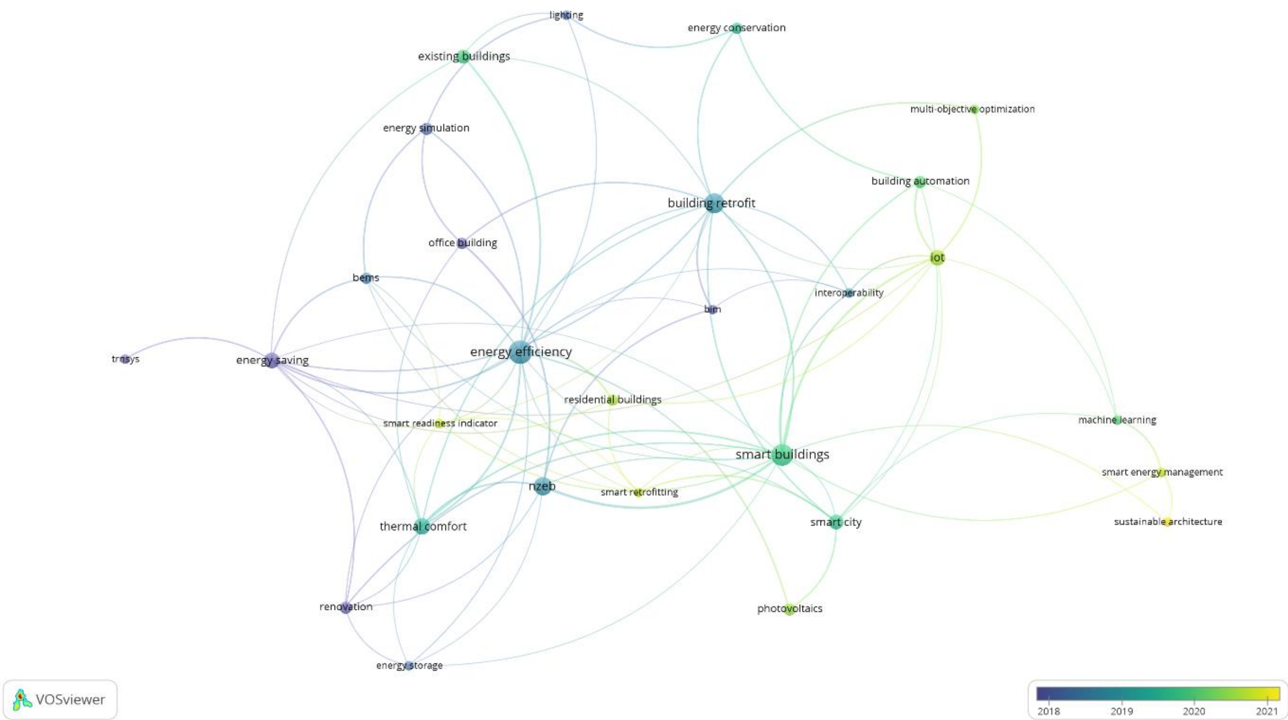

Figure 3: Density visualization based on links between keywords

The keywords are ranked based on the number of occurrences (Table 1). 'Energy efficiency' has the highest number of occurrences and links. There are cases where keywords with high occurrences do not have high citations and vice versa. For instance, 'renovation' has a relatively high average citation of 60 but the occurrence value is low: 5. The high AC could be because studies with these keywords were undertaken in earlier years.

Based on the APY (from the yellow nodes in Figure 3 and Table 1), keywords such as 'internet of things', 'smart energy management', 'smart readiness indicator', 'smart retrofitting', 'sustainable architecture', and 'residential buildings' appeared in most of the recent publications, indicating that they are becoming significant topics in this discipline.

Rank	Keywords	Occurrences	Links	TLS	AC	APY
1	Energy Efficiency	17	16	13	21	2019
2	Smart Buildings	15	16	14	20	2020
3	Building Retrofit	13	13	11	21	2019
4	nZEB	10	7	8	29	2019
5	Thermal Comfort	9	9	7	33	2019
6	Energy Saving	8	11	8	24	2018
7	IoT	8	9	7	21	2021
8	Smart City	7	8	5	7	2020
9	Existing Buildings	6	4	3	25	2020
10	Building Automation	5	5	4	11	2020
11	Energy Simulation	5	4	4	22	2018
12	Photovoltaics (PV)	5	2	2	6	2020
13	Renovation	5	6	4	60	2018
14	BEMS	4	6	4	29	2019
15	Energy Conservation	4	3	3	8	2020
16	Office Building	4	4	4	17	2018
17	Residential Buildings	4	4	3	10	2021
18	Building Information Modelling (BIM)	3	4	3	18	2018
19	Energy Storage	3	5	2	15	2018
20	Interoperability	3	5	3	37	2019
21	Lighting	3	4	3	12	2018

22	Machine Learning	3	4	2	20	2020
23	Multi-Objective Optimization	3	2	2	23	2020
24	Smart Energy Management	3	3	2	7	2021
25	Smart Readiness Indicator (SRI)	3	7	3	30	2021
26	Smart Retrofitting	3	6	3	30	2021
27	Sustainable Architecture	3	2	1	2	2021
28	TRNSYS	3	1	1	22	2018

Table 1: Quantitative measurements of the keyword network

The network of prominent keywords consists of key reasons for SR such as aiming for improvement in SRI score and the drive towards the smart city concept. The network includes some of the most important SB characteristics such as ‘IoT’, ‘BIM’, ‘Machine Learning’, ‘building automation’, and their ‘interoperability’. Apart from the above, energy management being one of the key drivers of SR, the keyword network consists of several building energy related terms: ‘energy efficiency’, ‘photovoltaic’, ‘energy storage’, ‘energy saving’, ‘energy simulation’, ‘energy conservation’, ‘nZEB’, ‘smart energy management’ and ‘BEMS’.

It is evident that the most studied themes in SR research are key drivers of SR including development of an SRI, smart city realization and the use of SR for energy management in buildings. To ensure their effectiveness, the facilitators of SR are also studied.

3.2.2 Analysis of journals

The thresholds for the minimum number of documents and citations of a journal were each set as ‘3’. Out of the 130 journals, only 11 influential journals met this criterion, as visualized in Figure 4. The node size there represents the number of journal publications. The connecting lines were determined by the relationship or closeness of journals in terms of mutual citations. The node color, varying from purple to yellow (see legend), indicates the APY of each journal.

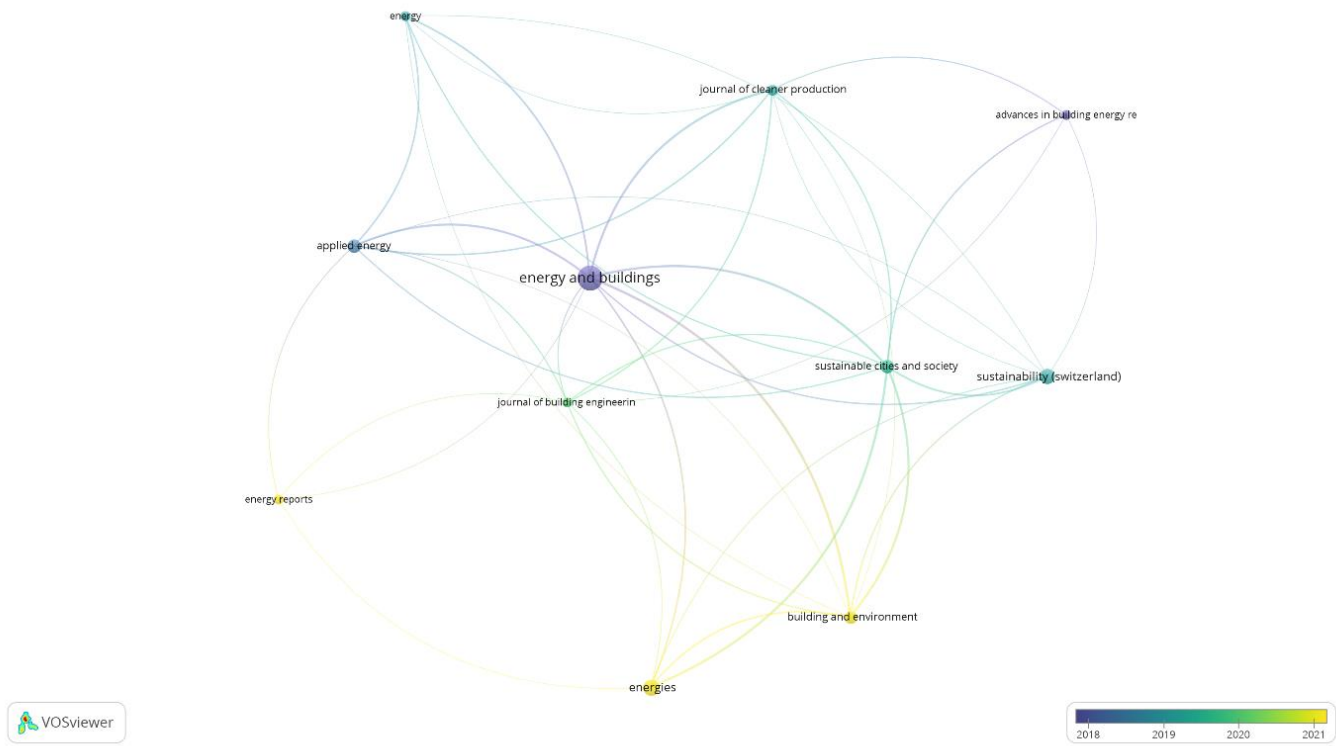

Figure 4: Overlay visualization based on links between journals

In Table 2, the journals are ranked based on number of publications. Together with the findings shown in Figure 4, it can be seen that the journal with the highest number of publications (nearly 30%) is ‘Energy and Buildings’. This journal also showed strong links with all other 10 influential journals.

Rank	Journal Title	Publications	Links	TLS	AC	APY
1	Energy and Buildings	19	9	72	33	2018
2	Energies	8	6	30	6	2021
3	Sustainability (Switzerland)	7	8	23	10	2019
4	Applied Energy	6	8	35	32	2019
5	Sustainable Cities and Society	6	9	66	29	2020
6	Building and Environment	5	8	43	6	2021
7	Journal of Cleaner Production	4	8	33	33	2019
8	Advances in Building Energy Research	3	4	10	10	2016

9	Energy	3	6	21	19	2019
10	Energy Reports	3	4	5	2	2022
11	Journal of Building Engineering	3	8	24	23	2020

Table 2: Quantitative measurements of the journal network

Regardless of their number, the articles published in journals such as 'Energy and Buildings', 'Journal of Cleaner Production' and 'Applied Energy' were cited the most. 'Energy and Buildings' takes the lead probably because of its multidisciplinary scope. It covers a wide range of topics such as energy efficiency, ICT integration in building energy management, all of which being relevant to the topic of this paper. The most cited journals are mostly concerned with efficient energy generation and usage in buildings, as well as the application of modern ICT throughout the building lifespan, to promote ecologically sustainable and socially resilient communities. SBs and SR evolve around these key themes. Because the APY of the journals is 2016 or after (i.e. recent), there is room for more SR research in the years ahead.

4.0 Past and Recent Research Areas of SR

As Figure 1 shows, 65 journal articles were shortlisted as eligible for the in-depth qualitative review, which sought to obtain answers for RQ2 and RQ3. The 65 papers comprise 61 empirical research papers and 4 review papers. The main contents of each journal article were coded and then grouped into four categories: (1) research methodology, (2) research context and findings, (3) future research directions and (4) study conclusions and implications. The codes identified from the articles were then carefully compared, contrasted, and differentiated. Eventually, six research areas representing the key themes/ideas covered in the articles were identified.

4.1 Area 1: Smart retrofit performance evaluation

Retrofit performance measurement is crucial for determining whether the smart retrofit produced the desired benefits. According to Saffari and Beagon (2022), a retrofitting project is only complete when validation and verification of the retrofit is conducted. The authors explained that retrofit performance evaluation can be conducted by post measurement and verification along with post occupancy surveys. Elaborated below are the findings from other SR related performance evaluation studies.

The performance of low energy smart retrofits in Lyon, Munich, and Vienna were monitored as part of the EU 'Smarter Together' project (Hainoun et al., 2022), which used a novel integrated monitoring methodology (IMM) covering three main steps: monitoring infrastructure, data collection, impact assessment, and following a co-creation process involving key stakeholders. Key performance indicators (KPIs) that address energy-efficiency improvement, local RE contribution, and the associated CO_2 emission reduction at the district scale were used to evaluate performance. According to the findings, zones within a building should be studied independently for better results. Furthermore, it was stated that various projects cannot be quantitatively compared without additional effort (for example by carrying out further interviews).

Oh et al. (2020) compared the indoor air temperature profiles of a smart thermostat between the pre and post retrofit periods in a single-family residence. Binned, weather-adjusted quartile analysis was used for the comparison of the zone-by-zone electricity use before and after the smart thermostat installation. The findings demonstrate that wireless occupancy and temperature sensor based smart regulating of the indoor air quality substantially enhances the condition in each zone while delivering significant electricity savings for both the homeowner and the electric utility. Pritoni et al. (2016) evaluates the effectiveness of occupancy responsive learning thermostats for energy conservation in university dormitories. Energy modelling was used to predict savings before the retrofit, and measurements taken after the retrofit were used to determine actual savings. Comparison of the results revealed that the model estimates overestimated the energy savings. The results thus offer insight on enhancing field assessments and improving model presumptions to more accurately estimate the effects of occupancy-responsive thermostats. A similar study was done by De Bock et al. (2021): results of a week-long automatically steered heating experiment in 14 single-user dorm rooms demonstrated significant energy savings and reduction of environmental impact, while there was no noticeable impact on the calculated thermal comfort.

Che et al. (2019) investigated the energy consumption and indoor environment performance of a HVAC system retrofitted to a commercial office building. A sensor-based intelligent building management system (BMS), outdoor air dehumidification, and a two-stage particle filter system were among the retrofitting solutions. Performance was analyzed based on the pre and post retrofit energy data, which revealed that retrofit solutions provided noteworthy energy savings and indoor air quality (IAQ) improvements by around 50%.

Santos et al. (2021) proposes AUSTRET, a tool that can test the automatic step response of a retrofitted building automation control system (BACS), considering its integration and interactions with the building's energy supply systems. Tested on ventilation and room heating systems, AUSTRET detected different dynamic responses and the negative impacts of misleading BACS input parameter configuration, thereby validating its use in retro-commissioning applications in the post retrofit stage (Lai et al., 2023).

Engelsgaard et al. (2020) introduced 'IBACSA', a unique holistic instrument for BACS assessment and smartness evaluation based on a qualitative-based multi-criteria approach. Using the points grading principle, the suggested tool may measure the consequences of the specified control capabilities in the building systems based on five criteria (energy efficiency, maintenance and fault prediction, energy flexibility, comfort, and information to occupants).

The SRI concept has appeared in an increasing number of journal articles since its launch in 2018. Among these articles, Ramezani et al. (2021) conducted a study to investigate the use of SRI in retrofitting actions for Mediterranean structures. The SRI was applied to two case studies and its effects on IAQ and energy performance were examined between the case studies by comparing the measurement and energy simulation outcomes. Canale et al. (2021) devised a method for estimating the SRI for the Italian residential construction stock under three scenarios: (a) base scenario (as-is); (b) "energy scenario" (basic energy retrofit); and (c) "smart energy scenario" (energy retrofit from a smart perspective). The study by Apostolopoulos et al. (2022) examined the retrofitting cost towards smartification for typical residential buildings, using the SRI technique to measure the change in smartness when alternative retrofitting scenarios are performed. Findings show that buildings constructed after the EPBD implementation are relatively cost-friendly with regard to SR than older buildings.

Different other strategies are also utilized to evaluate post-retrofit performance. The Emergy-based methodological approach employed in Kumar et al. (2022) is one such method. Developed by ecologist Howard Odum (Li et al., 2021), Emergy Analysis (EA) is an energy accounting method that “incorporates the energy, economic costs, and environmental work expended in material formation to assess the total energy inputs and outputs in any system based on the net thermodynamic balance”. This research examines the true environmental cost of incorporating IoT-based sensor devices into a building using the notion of ‘Emergy Neutrality’. While results show that IoT-based sensor devices are effective in reducing the environmental footprint of the selected building, the significance of the ‘Emergy Neutrality’ reporting is emphasized for sustainability assessment of smart retrofits.

Accordingly, it is evident that a considerable number of studies have attempted to develop solutions for SR related performance evaluation. Many have focused on HVAC system related SR performance evaluation while BACS performance evaluation methods as well as holistic building smartness evaluation schemes such as IBACSA and SRI were studied. Some key goals of such evaluations are energy savings, IAQ and environmental sustainability monitoring through methods such as EA. The aforementioned technologies and approaches enable the analysis of retrofitting efforts through a clear side-by-side comparison of the performance of retrofitted systems, providing useful information for future retrofitting.

4.2 Area 2: SR applications for building envelope optimization

The building envelope is one of the top considerations in retrofitting because it is the most visible part of the building (Zennaro & Manfron, 2009). This leads to an improvement of environmental and appearance performances. However, most importantly, the building envelop transmits energy with the outside environment (Premier, 2012). While inadequate insulation may increase the need for heating during colder months, excessive heat and uncomfortable glare from sunlight reflecting on a building’s exterior during the summer may be uncomfortable for residents on both a thermal and visual level (Lin et al., 2020). In response, the HVAC and lighting systems may need to be operated inefficiently (Taveres-Cachat et al., 2019). Hence, improving the performance of building envelope by retrofitting it with energy efficient and dynamic adaptive smart technology will optimize the energy performance and internal comfort for occupants.

This study identified a number of papers that introduced various smart technology that can be retrofitted to building envelopes. Capeluto (2019) presented a prefabricated retrofit system based on solar air heating and solar-tracking blinds for building envelopes, allowing it to be adapted to diverse climate zones. This system can be installed on the exterior of the façade and roof and is adaptable to the specific needs of each building, providing constructive advantages in retrofitting by reducing interruption times for occupants. Psomas et al. (2017) proposed an automatic roof window control system to prevent temperature climate overheating in retrofitted buildings. Test data of this system confirmed that manually operated ventilation and shading systems cannot ensure a high-quality indoor environment, while the automated roof window control system significantly reduces the risk of overheating without considerably degrading the indoor air quality. With the use of simulation, James and Bahaj (2005) predicted the applicability of holographic optical elements (HOE) for glare control in office buildings while maintaining daylighting and external views. Basso et al. (2017) presented an innovative facade module that facilitates adaptability and heat exchange of buildings and is composed of two main parts: an adaptable smart modular heat recovery unit (SMHRU) that can preheat ventilation air in winter while precooling it in summer; and a latent thermal heat energy storage system (LTHES) that is based on phase change materials (PCM).

Dynamic electrical-driven glazing to retrofit windows of historical buildings was mentioned in Scorpio et al. (2020). Simulation results for the dynamic glazing were compared to the same obtained for a conventional double Low-E glazing window. Findings show that the dynamic solution is in ahead with respect to energy saving and visual comfort. Shaik et al. (2022) investigated polymer dispersed liquid crystals (PDLCs) films, which are intelligent glazing materials that change between translucent and transparent states in response to an electric stimulation. Experiments were conducted for PDLC film glazing of four different colors (pink, yellow, blue, and white). While all four types showed promising improvements and acceptable daylighting levels, white PDLC showed the highest reduction in cooling loads and hence cost savings and CO_2 emission reduction. Mahmoudian and Sharifikheirabadi (2020) discussed many uses of smart materials for facades such as diverse varieties, architectural needs, and the beneficial impacts of smart materials. One of the most important systems explored in this research was PCM, which can cut energy usage by 20% if the right type is chosen, and, in addition to natural ventilation, minimizes the building's reliance on mechanical equipment. Gallo and Romano (2018) explored the development of a unique adaptive envelope system for incorporating power generation technologies in the façade (such as PV modules) and innovative materials capable of dynamically aligning with the climatic conditions. According to simulation studies, this technology can significantly enhance energy efficiency; yet it needs to be further verified by applications in buildings. Panopoulos and Papadopoulos (2017) evaluated the state of the art in facade building technology, including double skin facades, façade operation automation, PV integrated smart facades, and facades with smart material. Various façade smartification retrofit solutions that have previously been deployed are also explored. According to the review by Panopoulos and Papadopoulos (2017), it was challenging to achieve near "Zero-Energy Building" status solely through retrofitting the facades but they significantly contribute to lowering greenhouse gas emissions. Habibi et al. (2020) presented a MIVES-Delphi evaluation model that can estimate the long-term viability of intelligent façade layers (IFL). According to the study findings, optimum IFLs evaluated in the Spanish school setting should be dynamic, cost-effective, energy efficient, environmentally friendly, and provide secure, healthy, and comfortable inner classroom conditions.

According to the studies mentioned above, optimizing the building envelope has been accomplished by using various dynamic smart façade systems, smart materials and sometimes with integrated solar panels. These technologies were developed with the intention of reducing energy consumption by controlling overheating of spaces, improving visual comfort by controlling glare, and ultimately reducing emissions. Innovative installation techniques that minimize disruption while making the process highly feasible were also considered by the researchers. The introduced systems were validated using different approaches such as measurements and simulation.

4.3 Area 3: Renewable energy integration through SR applications

A majority of the world's energy needs are met by fossil fuels, and because buildings consume an extensive amount of energy, they also play a significant role in the emission of greenhouse gases (GHGs) and carbon emissions (Hayter & Kandt, 2011). For the building sector to reach the sustainable development scenario anticipated by the International Energy Agency, between 2018 and 2040, approximately 13% of worldwide energy consumption and 50% of carbon emissions from buildings must be decreased (Zhongming et al., 2020). In addition to resolving this by putting energy-saving measures in place for the building, using renewable energy sources to balance off the building's remaining energy requirements is another viable approach (Hayter & Kandt, 2011). Given its sustainability (Zhou et al., 2019) and environmental friendliness (Yan et al., 2019), renewable energy is potentially accepted as a leading solution for the building sector to provide green power (Javed et al., 2020).

Todeschi et al. (2020) presented an approach based on geographical information systems (GIS) to estimate the roof areas that may be converted to produce RE. The methodology was used in an Italian case study where a 3D roof model was created. After the model creation, several scenarios were investigated into, and intervention priorities were set while considering the state of the urban landscape. Finally, an insulated green roof was chosen because it had a high potential for energy savings and greenhouse gas reduction, demonstrating that the proposed GIS-based method is a promising tool for evaluating a roof's suitability for RES application. Tsoumanis et al. (2021) described the installation of building-integrated photovoltaics (BIPV) solutions in Évora's Historic Centre. Circular insulating materials, solar roofs and facades, PV canopy, PV skylight, PV thermal panels, thermo-acoustic heat pumps, and hybrid wind/solar generation systems were all part of the project. The demonstrated successful applications of these systems in Evora and their replicability is considered a valuable example for many of the historic cities in Europe in the drive for Fiorentini et al. (2015) proposed a solar-assisted HVAC system in a ducted system that comprises of an air-based photovoltaic-thermal (PVT) collector and a PCM thermal storage unit connected with a reverse cycle heat pump. The heat stored in the PCM can later be used to condition the room or prepare the air entering the air handling unit. Analytical models for the PVT collector and PCM unit were created so that they could be easily integrated into a practical BMS.

Yousif et al. (2020) used system advisor model software to do a full analysis and concluded that battery energy storage systems have the capacity to match RE supply to demand, however this technique is still far from cost-optimal. Given the high costs of direct energy use, storage, and load matching, the research suggested that RE incentives should shift away from feed-in tariffs and instead subsidize direct energy use, storage, and load matching. Furthermore, to ensure a holistic approach to building upgrading, the cost-optimal analysis should estimate the costs of thermal discomfort, energy poverty, and grid mismatch (Yousif et al., 2020).

With respect to RE integration through SR applications, the studies mentioned above have covered different stages in installation such as planning and technology development. For instance, studies have focused RES integration planning using advanced technology such as GIS. In addition, most studies have focused on introducing different grid-integrated RE solutions, particularly PV. RE storage issues and solutions have also been studied in previous research.

4.4 Area 4: SR applications for demand side management

The demand side of an electrical distribution system, referred to as demand side management (DSM) or demand response (DR), is an essential part of a smart grid (Vos, 2009; Zhong et al., 2010). It includes the programs put in place by utilities or initiatives taken by the customer to control energy use at consumption side of the meter (Mohsenian-Rad et al., 2010). Communication systems, sensors, automated metering, intelligent devices, and specialized processors are needed for the full integration of DR (Oh & Thomas, 2008; Siano, 2014). In this regard, smart meters and cutting-edge ICT solutions in buildings are some of the excellent opportunities to save energy, use RES, and encourage consumer participation in the energy market. DR can assist electricity power markets to run more effectively (Oh & Thomas, 2008), which lowers the peak demand (Nguyen, 2010). This benefit both utilities and customers.

Previous studies have explored and introduced different smart technology that can manage the above stated energy demand of buildings. Globally, many islands are considering the use of RES for energy generation. However, the power systems on islands are less reliable and more sensitive to power instability, which could negatively impact the implementation of RES (Croce et al., 2020). This can be mitigated by having an effective power monitoring and control system that supports DR. 'Overgrid', a new decentralized load management architecture for balancing the energy output changes created by the adoption of renewable sources, is one such kind of load controlling (Croce et al., 2020). Without a centralized server, the 'Overgrid' DR architecture calculates aggregated power demand and forms a virtual "community" of SBs. Overgrid simplifies SR by eliminating the need for a centralized controller in favor of a low-cost software controller that integrates local energy data (smart-plug/smart-meter) and external input to implement DR control mechanisms. As a result, there is no need for redundancy because there is no single point of failure. There are no constraints on the type of hardware or wireless connection either: new smart-plug/smart-appliances can be gradually added and connected via WiFi, Bluetooth, ZigBee, or any other wireless technology.

As a result of the development of harmonic producing-loads, harmonic resonance has grown to be a significant barrier to power factor compensation in commercial power systems such as those for office buildings and shopping centers. In response to this, Lin et al. (2012) introduced a power factor correction controller, which can execute power factor adjustment without causing harmonic resonance under changing demand conditions. The controller does not require any additional measurements because it is based on standard low-cost sensing devices. As a result, the suggested controller can be built as a retrofitting device to easily replace conventional power factor correction controllers.

Even though several smart solutions have been introduced for buildings, incompatibility often render them difficult to be retrofitted into existing buildings with legacy systems. As a solution for improving the energy efficiency of space heating systems that are difficult to be replaced, Syed Ali et al. (2021) proposed a model predictive control (MPC) framework-based automatic radiator control system that may be installed to low pressure steam heating systems in existing buildings. The proposed solution demonstrated high feasibility of installation as well as significant energy savings. Bird et al. (2022) discussed another comparable MPC application. In view of the high energy consumption for heating during cold seasons (and heating is sometimes operated continuously in unoccupied areas), Naji et al. (2020) offered an energy management system based on a wireless sensor network (WSN) that is deployed and tested on a university campus. It can control the heaters and efficiently implement the energy policy with the incorporation of ICT. The thermal comfort of the occupants is often overlooked in buildings, due to the pressing need to reduce energy use. To address this, Gonçalves et al. (2020) introduced and implemented a new generation of adaptable intelligent supervisory predictive control (ISPC) systems, which include a building thermal simulation and multi-objective optimization algorithm that interact with traditional machine-level controllers of HVAC systems to define optimized setpoints based on current and forecasted operation conditions. BEMS can identify issues regarding building maintenance and energy-wastage problems that require management attention and, indirectly, help them understand user comfort needs through repeating data patterns. Using this feature of BEMS, Dey et al. (2020) presented a method for detecting defective HVAC terminal unit (TU) and diagnosing them, automatically and remotely, using a big data framework. While energy management features of smart solutions are well known, retrofitting them into existing structures requires expensive and disruptive techniques. Hence, innovative non-invasive technologies have been introduced, which can lower the cost of retrofitting. Gattuso et al. (2016) discussed the use of one such unique non-invasive retrofit technology called the wireless pneumatic thermostat (WPT) that requires less installation time while providing the same degree of functionality.

Retrofitting lighting can result in significant energy savings. For such retrofits to be successful, thorough monitoring and modelling of lighting demand and supply are necessary. Although sensor networks are frequently used for these purposes, setting up such dense networks could be expensive. Basu et al. (2014) introduces a sensor-based intelligent lighting system for future grid-integrated buildings. Based on predictive models of indoor light distribution created by sensing, the technology is intended to ensure participation of lighting loads in the energy market.

Some research investigated DSM through influencing a variety of systems. Kawasaki et al. (2016) presented a smartification project in a building that aimed for a 50% reduction in energy use compared to before the retrofit. The retrofitted systems include a newly developed light emitting diode (LED) light system that can be controlled remotely via a wireless connection, multiple intelligent human detection sensors, a smart distribution board for each floor, variable air volume (VAV) controllers, inverter type air conditioners, and RES such as solar and wind. Beccali et al. (2018) evaluated the impact of some retrofit scenarios dealing with the utilization of RES and BACS to address energy consumption fluctuations on small islands. Among the possibilities under consideration are appropriate sizing of the power storage combined with the PV plant, LED lighting systems connected with building automation technologies. Yang et al. (2022) proposed a mechanism for using energy generated by user interactions to power automation systems such as motion-triggered doors, remote-control window blinds, and contactless toilet lids. The proposed mechanical mechanism was tested in a 48-hour deployment study, and the findings showed that this “people as power” approach is a feasible way to reduce the energy required for automated smart environments.

Accordingly, it is clear that earlier research has suggested smart solutions for DR at the grid level as well as the building level (for example, utilizing smart grid solutions to solve DR issues on small islands, or using smart systems for power factor correction in buildings). Some of the key goals of these studies are to address the incompatibility/installation issues and the high cost factor, which are obstacles to achieving DR through different energy management solutions. The solutions were proposed for different building systems including lighting, windows, access control, BACS, but mostly for HVAC.

4.5 Area 5: Stakeholder engagement in SR

Despite their many advantages, SR projects are among the riskiest, most difficult, and uncertain to execute. The perceptions of the stakeholders and the management surrounding them are among the numerous aspects that influence the success of these projects, but they are one of the least considered by the project owners (Liang et al., 2015). Stakeholders are worried about the modifications to their existing buildings and the claimed advantages from social, environmental, economic, and technical viewpoints (Menassa & Baer, 2014). Additionally, the constantly changing stakeholder perceptions of value maximization lead to competing demands that prevent the adoption of optimal retrofit decisions (Stephan & Menassa, 2015). Therefore, cooperation between building stakeholders is essential to ensuring that SR achieves its goal of increasing the building’s overall value in the post-retrofit stage.

Preston et al. (2020) investigated two separate EU-funded smart city research projects to uncover practical insights for citizen involvement in low-carbon smart cities. According to the findings, a proper approach should include occupants as active agents (actors) in the development process of smartification projects. Occupants can also add value to these projects by participating in the design and innovation processes.

Lee et al. (2012) investigated the end-user impacts of automated electrochromic windows in a retrofitting project. Monitored data of six months were analyzed and the results revealed that, compared to the existing system, the tested system's energy reductions were 91%. The overridden time was also as low as 4% out of the total time of occupancy, showing high acceptance of the systems by end-users. Ahmed et al. (2021) conducted a post-occupancy evaluation of three schools in the UK that underwent HVAC retrofits. The findings suggested that building users wanted more control over the indoor environment, which contradicted the prevailing trend of automated 'intelligent systems'. Mooses et al. (2022) investigated how occupants with varying attitudes towards the environment and technology evaluated a smart retrofit intervention in a smart city project in Estonia. The findings revealed that pro-technology occupants reported strong interest and trust in smart retrofit interventions, whilst ecologically inclined occupants expressed more critical views. Based on semi structured interviews, six categories of meaning that respondents gave to the smart retrofit intervention were identified: (1) environmental consequences, (2) health consequences, (3) technological issues, (4) financial considerations, (5) utility and personal comfort, and (6) symbolic and emotional values. Kim et al. (2017) discovered that early and extensive occupant involvement in lighting retrofit planning, design, and commissioning phases may better facilitate 'levels of occupant satisfaction' and 'tolerance of construction delays' in a lighting retrofit of an administrative building that included wireless lighting controls and photometric sensors.

Alberg Mosgaard et al. (2016) investigated the issues that stakeholders experience in the SR of buildings and how these challenges lead to alterations in stakeholder constellations. According to the findings, a central stakeholder is required to oversee the major stakeholders and resolve potential conflicts of interest.

Vendors should look for a variety of maintenance solutions and work to improve the system handover process by developing supporting documentation and training materials (Kim et al., 2017).

Accordingly, several previous studies have investigated the stakeholder management in SR projects. The areas of investigation include involvement of end-users in the SR project from the design phase, and end-user acceptance of the retrofitting process and the installed smart solutions. Vendor/contractor management during the retrofitting process has also been studied.

4.6 Area 6: Planning for effective SR implementation

As emphasized by most studies, proper planning is crucial for successful SR implementation. With reference to the typical building renovation process shown in Nielsen et al. (2016), the planning phase of an SR project can be depicted as in Figure 5. The first crucial step is to determine the goals and objectives of SR because all subsequent phases are tailored to these strategic and crucial elements. In reality, this tactical planning phase may be considered the process's rational core. Several studies have therefore focused on yielding a more effective planning phase. From the studies reviewed, their findings on barriers and enablers for SR, cost effectiveness planning, technology planning, and process planning in SR, all of which being key concerns in the planning phase, are discussed below.

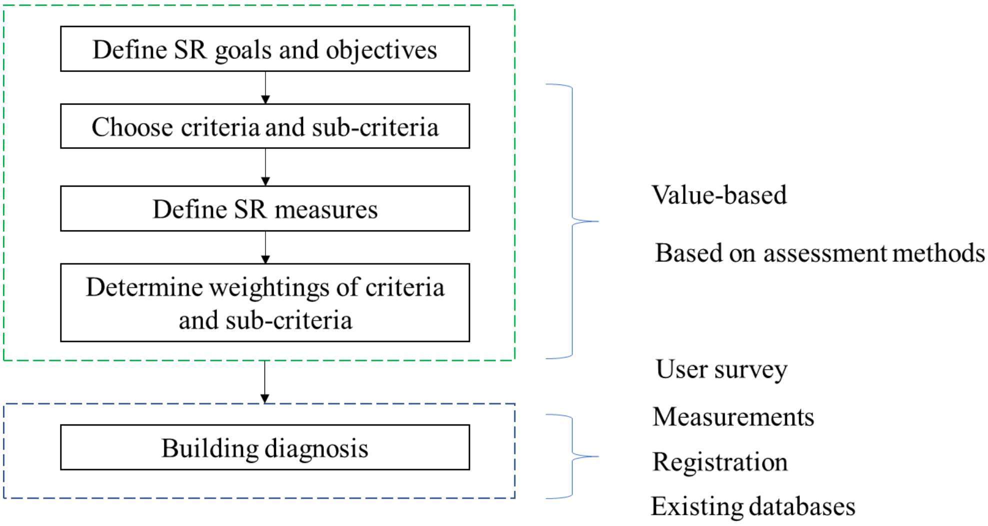

Figure 5: Steps of SR planning

4.6.1 Barriers and enablers for SR

As with other retrofit types, the most common barrier in SR is the lack of communication and integration among stakeholders (Hainoun et al., 2022). Another barrier is the high investment cost, which discourages building owners who support SR (D'Oca et al., 2018; Kokkaliaris & Maria, 2015). The majority of investors and building occupants are also concerned about the personal data and privacy issues associated with the post-SR stage (Kokkaliaris & Maria, 2015). These challenges can be addressed by establishing a good communication foundation and more extensive planning from the start of the SR project (Hainoun et al., 2022).

SR also has certain enablers involved. When it comes to smart meters, the fact that consumers will have access to more information about their electricity consumption is expected to raise their awareness and understanding of the importance of energy efficiency, as well as help encourage them to invest in improving the energy performance of their buildings (Kokkaliaris & Maria, 2015).

A set of review papers covered knowledge on SR enabling technologies and some associated challenges. O'Grady et al. (2021) highlighted the features and benefits of Building Automation System (BAS)—building modelling software, building automation architecture and their benefits, motivations and interactions with occupants (IAQ, daylighting and glare). The review results emphasize the significance of system feedback loops, which can boost occupant acceptance and industry adoption of BAS. Al Dakheel et al. (2020) reviewed the concept of smartness in the built environment, emphasizing the fundamental features, functions, and technology of SBs while also analyzing potential problems for smart retrofit applications. The second section of the article examines the existing KPIs that measure the performance and success of SBs in meeting its goals. However, it was noticed that the energy aspect was predominantly covered in this review with all the KPIs focused on energy efficiency while the social aspect of SR was less considered. Two review papers examined the use of BIM in buildings to achieve smartness. Yang et al. (2021) emphasized the benefits of BIM for reaching various levels of smartness, BIM applications in multiple phases of SBs, and SB functions that can be accomplished with BIM. The review highlights the research trends and gaps for consideration of future researchers: BIM interoperability enhancement; increasing BIM adoption in building operation and retrofitting; and establishing the financial benefits of BIM projects. According to Panteli et al. (2020), the lack of BIM utilization in retrofitting is due to the challenges that still exist in this practice, such as the modelling effort required to convert building data into BIM objects, model information updating, and the handling of uncertain data and objects with existing building models.

4.6.2 Planning for cost effectiveness

By comparing two situations, Schäuble et al. (2020) evaluated the cost-effectiveness of smart thermostats (households with smart thermostats vs. households without smart thermostats). Smart thermostats were found to be cost effective, with both CO_2 concentrations and payback durations falling as relative savings increased.

He et al. (2021) stated that the cooling system, BEMS, and thickness of wall insulation are the most influential retrofitting aspects in Hong Kong for the best net present value (NPV) and energy saving. Felius et al. (2020) investigated the cost-effective retrofitting combinations of building envelope, energy systems, and BACS measures in accordance with EN 15232 automation standard. BACS implementation resulted in up to 24% cost-effective energy reductions. When BACS was paired with the other retrofitting techniques, it was projected that energy savings may be even higher. BACS had a greater impact, especially for compact buildings where there is less room to reduce heat losses via envelope retrofits.

4.6.3 Planning for proper technology

Cho et al. (2021) carried out a study for the EU that emphasized the causal relationship between building attributes, retrofit procedures, and energy performance. The study, for example, discovered that the shape of the roof and the type of façade influenced the energy-saving effectiveness when PV panels were added. The overall findings can be used to choose/plan the best solutions for smart retrofits.

According to Roberta et al. (2018), the first step in building smartification is to equip buildings with sensors, actuation, and data transmission systems: a centralized diagnostics and optimization system that allows energy and economic savings at low cost, based primarily on automation and ICT infrastructure. For remote monitoring and control of SB systems, Reddy and Kumar (2021) suggest a retrofitted IoT-based communication network with hot standby router protocol (HSRP). This suggested network provides a redundant way during link failures, ensuring secure network communication. Chien and Wang (2014) presented a smart partitioning system that may be used for better and more convenient room level integration of smart technologies into existing structures.

Woo and Menassa (2014) introduces the Virtual Retrofit Model (VRM), a cost-effective computational platform that can connect buildings to a smart grid environment in which building energy data can be shared for intelligent decision making. Fernandes et al. (2022) introduced the adaption of the SmartLVGrid metamodel for SR, allowing for gradual technical improvements to obtain new functionalities while retaining old ones to the greatest extent feasible.

To address interoperability concerns in IoT integration, the World Wide Web Consortium (W3C) created a set of protocols known as the Web of Things (WoT). Ibaseta, García, Álvarez, Garzón, Díez, Coca, Pero, et al. (2021) shows how the W3C WoT specifications may be used to effectively integrate heterogeneous IoT-enabled devices in a BEMS. The W3C WoT recommendations provide a mechanism for designing and implementing a network of sensors, actuators, and other devices for SR of buildings.

4.6.4 Planning for proper retrofitting process

Kim et al. (2017) recommended cautious scheduling and monitoring of activities during SR implementation to avoid scheduling slippages and minimize interruptions to living conditions. It is further recommended that any software reporting function that comes with a lighting retrofit should be simple and useful for users to justify the investment, as well as work as a decision support system for assessing the worth of future retrofits.

Wang (2008) stated that retrofitting for smartness is a difficult process that requires a systematic approach that includes vision, assessment, funding, planning, technology considerations, and collaboration with various other parties. Arbizzani et al. (2015) evaluated current governmental and/or private policies aiming at retrofitting towards smartness to determine their energy saving potential in reference to the European Directive 20-20-20 in a study on smart devices for Mediterranean low-income housings. In a second phase, technical solutions and innovative financing mechanisms for increasing energy efficiency were identified, considering the specific characteristics of low-income families as well as the characteristics of Mediterranean countries in terms of identified weather conditions and building types.

Hence, it is important to note that many studies have focused on improving the effectiveness of SR. Different studies, both empirical and review, have highlighted the prevailing barriers to SR and discussed how the enablers could be used to overcome the barriers. Cost effectiveness of SR projects was also investigated by calculating the savings in the post-retrofit stage and comparing them with the predicted payback. Furthermore, suggestions for cost-effectiveness improvement were highlighted and different solutions for SR technology and process planning were also identified.

Table 3 consolidates the findings from the manual qualitative review, with the research area and research subject of the publications summarized. Based on the journal categories assigned to each journal by the Clarivate Journal Citation Reports, fields of publications belonging to each research area are also indicated.

Research Area	Research Subject	Identified Publications	Publication fields
Research Area 1: Smart retrofit performance evaluation	Post SR performance measurement methodologies	Hainoun et al. (2022), Oh et al. (2020), Pritoni et al. (2016), De Bock et al. (2021), Che et al. (2019), Santos et al. (2021)	• Civil Engineering • Computer Science, Hardware and Architecture • Construction and Building Technology • Energy and Fuels • Information Systems • Mechanical Engineering • Thermodynamics
	Application of tools such as SRI, IBACSA	Engelsgaard et al. (2020), Ramezani et al. (2021), Canale et al.	• Civil Engineering • Construction and Building Technology • Energy and Fuels

		(2021), Apostolopoulos et al. (2022)	• Green and Sustainable Science and Technology
	Application of different strategies such as 'Emergy Neutrality'	Kumar et al. (2022)	• Energy and Fuels • Green and Sustainable Science and Technology
Research Area 2: SR applications for building envelope optimization	Smart retrofit applications for heat gain control	Capeluto (2019), Psomas et al. (2017), James and Bahaj (2005), Basso et al. (2017), Diallo et al. (2017)	• Architecture • Chemical Engineering • Civil Engineering • Construction and Building Technology • Energy and Fuels
	Smart window applications for retrofitting	Scorpio et al. (2020), Shaik et al. (2022), Mahmoudian and Sharifikheirabadi (2020), Gallo and Romano (2018), Panopoulos and Papadopoulos (2017)	• Architecture • Civil Engineering • Construction and Building Technology • Environmental Engineering • Environmental Sciences • Green and Sustainable Science and Technology • Multidisciplinary Sciences
	Smart envelope performance assessment methods	Habibi et al. (2020)	• Applied Physics • Energy and Fuels • Green and Sustainable Science and Technology
Research Area 3: Renewable energy integration through SR applications	Estimation of roof area for RES installation	Todeschi et al. (2020)	• Multidisciplinary Chemistry • Multidisciplinary Engineering • Multidisciplinary Materials Science
	Solar-assisted HVAC systems	Tsoumanis et al. (2021), Fiorentini et al. (2015)	• Civil Engineering • Construction and Building Technology • Energy and Fuels • Environmental Studies • Green and Sustainable • Science and Technology
	Battery energy systems for RES applications	Yousif et al. (2020)	• Energy and Fuels
Research Area 4: SR applications for demand side management	Smart load controlling technologies for retrofitting	Croce et al. (2020), Lin et al. (2012)	• Construction and Building Technology • Electrical and Electronic Engineering • Energy and Fuels • Green and Sustainable Science and Technology
	Smart retrofits for improving	Syed Ali et al. (2021), Bird et al. (2022), Naji	• Civil Engineering • Computer Science

	HVAC performance	et al. (2020), Gonçalves et al. (2020), Dey et al. (2020), Gattuso et al. (2016)	• Computer Science • Construction and Building Technology • Energy and Fuels • Information Systems • Theory and Methods
	Smart retrofits for improving lighting performance	Basu et al. (2014)	• Applied Physics • Electrical and Electronic Engineering • Instruments and Instrumentation
	Smart retrofits for improving overall system performance	Kawasaki et al. (2016), Beccali et al. (2018), Yang et al. (2022)	• Electrical and Electronic Engineering • Energy and Fuels • Telecommunications • Thermodynamics
Research Area 5: Stakeholder engagement in SR	Stakeholder involvement in SR projects	Preston et al. (2020), Lee et al. (2012), Kim et al. (2017),	• Civil Engineering • Construction and Building Technology • Energy and Fuels • Industrial Engineering
	Stakeholder perceptions on SR projects	Ahmed et al. (2021), Mooses et al. (2022), Alberg Mosgaard et al. (2016)	• Civil Engineering • Construction and Building Technology • Environmental Engineering • Environmental Sciences • Green and Sustainable Science and Technology • Urban Studies
Research Area 6: Planning for effective SR implementation	Barriers and enablers for SR	Hainoun et al. (2022), D’Oca et al. (2018), Kokkaliaris and Maria (2015), O'Grady et al. (2021), Al Dakheel et al. (2020), Yang et al. (2021), Panteli et al. (2020)	• Civil Engineering • Construction and Building Technology • Energy and Fuels • Environmental Engineering • Environmental Sciences • Green and Sustainable Science and Technology • Green and Sustainable Science and Technology
	Planning for cost effectiveness in SR	Schäuble et al. (2020), He et al. (2021), Felius et al. (2020)	• Chemical Engineering • Civil Engineering • Construction and Building Technology • Energy and Fuels • Green and Sustainable Science and Technology

	Planning for proper smart technology	Cho et al. (2021), Roberta et al. (2018), Reddy and Kumar (2021), Chien and Wang (2014), Woo and Menassa (2014), Fernandes et al. (2022), Ibaseta, García, Álvarez, Garzón, Díez, Coca, Pero, et al. (2021)	• Architecture • Civil Engineering • Construction and Building Technology • Energy and Fuels • Green and Sustainable Science and Technology
	Planning for proper retrofitting process	Kim et al. (2017), Wang (2008), Arbizzani et al. (2015)	• Architecture • Civil Engineering • Industrial Engineering

Table 3: Summary of findings from the qualitative review

5.0 Research gaps and future research directions

The codes explained at the beginning of Section 4 were further examined in Stage 3 to answer RQ3. This was done by analyzing the documented codes under the ‘future research directions’ category to identify the research gaps and potentially useful future research directions. A framework integrating the past and recent research areas and the potentially useful future research directions was also developed, with the key research areas elaborated as shown in Figure 6.

Figure 6: Framework of the existing research areas and future research directions

5.1 Area 1: Smart retrofit performance evaluation

According to Kumar et al. (2022), Emergy Neutrality computations are susceptible to non-specific unit emergy values (UEV), data uncertainty, missing values, multiple UEV values for the same process, and a lack of standardized databases. Furthermore, data loss and lack of interoperability between various modelling tools such as BIM, building energy modelling (BEM), and EA are significant limitations for computing Emergy neutrality. As a result, these modelling tools must be integrated into a meta-model for seamless semantic integration of building sustainability assessment approaches while using reliable and current databases.

Some of the achieved KPIs on post retrofit performance can only be explained in relation to specific user behavior, e.g., rebound effects, higher room temperature, tilted windows (Hainoun et al., 2022). In this direction future research on KPI measurement should include a qualitative analysis of occupancy behavior to assess its impact on the monitored data as well on the resulting project impact.

Current performance measurement tools such as IBACSA do not consider the impact on the investment cost and the related returns (Engelsgaard et al., 2020). Hence, future studies can consider integrating provisions to measure economic performance of retrofits to such tools. These additions could ultimately improve the retrofit decision-making of building owners, managers and consultants.

Past studies have not considered SRI improvement as a retrofit objective (Ramezani et al., 2021). However, an SRI-based multi-objective selection approach could aid the selection of the possible smart retrofit actions based on their effectiveness on SRI. A potential future research direction is therefore to develop a SR decision making model by incorporating SRI improvement.

Studies have also highlighted certain limitations in the SRI calculation methodology. They include the inability of the SRI to capture different climate conditions (Al Dakheel et al., 2020), building construction date, systems type (autonomous or centralized) and the building users' activities (Apostolopoulos et al., 2022) and the lack of clarity in calculating the overall functionality level and the impact of personal judgement (Ramezani et al., 2021). Future studies could therefore consider further development of the current SRI methodology.

5.2 Area 2: SR applications for building envelope optimization

Studies highlight that despite the many technological advances, there is a lack of policies encouraging smart envelope retrofits (Capeluto, 2019). Further, the current regulations fail to identify all the possible occupant discomfort issues (Psomas et al., 2017) that need to be addressed through smart envelop retrofits. Hence, an important future research direction is to promote the establishment/improvement of policies and regulations in this regard.

Apart from the introduction of different technology for building envelope smartification, the impact of user behavior on the performance of these technologies is yet to be established (Psomas et al., 2017). This could be a potential research direction in the future.

Despite the introduction of smart glazing systems, its cost-effectiveness compared to external shades have not been studied before (Krarti, 2022). Hence, this can be explored in future studies for both residential and commercial buildings.

5.3 Area 3: Renewable energy integration through SR applications

It was observed in this review that all RE related studies mostly considered the onsite integration of solar energy. Hence, future studies can explore the feasibility of integrating other RES such as wind, geothermal and biogas.

While the technology aspects of onsite RE integration have been widely studied, the research areas such as the management aspect including the proper communication between the building systems/demand can be studied further to propose better strategies.

The current cost-optimal analyses related to onsite RE does not quantify the costs of thermal discomfort, energy poverty and grid mismatch (Yousif et al., 2020), to ensure a holistic approach to retrofitting of buildings. Hence, future research should focus on applying the multi-criteria approach covering the above aspects to consider a more comprehensive macroeconomic analysis.

5.4 Area 4: SR applications for demand side management

The smart applications for DSM can constantly be improved to obtain the perfect balance between performance and energy savings (Syed Ali et al., 2021). Hence, future studies can be focused on further improving these applications with the integration of complex techniques of machine learning etc.

These smart applications which are highly dependent on occupant and building data but still susceptible to security threats (Ibaseta, García, Álvarez, Garzón, Díez, Coca, Del Pero, et al., 2021). Future work can therefore be focused on establishing and improving security mechanisms for these smart applications.

The novel technologies and applications introduced should be properly investigated in future work for different building and occupant populations with different capabilities, frequency of uses in different environments and applications, and beyond (Yang et al., 2022). This investigation will further improve understanding on the performance gaps and the necessary improvements required.

5.5 Area 5: Stakeholder engagement in SR

Different previous work on stakeholder engagement in SR projects have been carried out in an isolated manner. Meanwhile, combining and comparing results of stakeholder engagement and management in large organizations could be helpful to small and medium scale organizations to streamline their approaches (Alberg Mosgaard et al., 2016; Preston et al., 2020). Hence, future work could be focused on addressing this gap.

Further studies are needed on a more extensive application of the introduced smart technology with measured environmental data and subjective response data to better understand user acceptance and satisfaction with these technologies (Lee et al., 2012).

It was also apparent that occupants were only marginally involved in the design stage of the contract and perhaps greater involvement could have allayed the concerns raised during the post occupancy stage (Ahmed et al., 2021). Further work is required to explore this phenomenon in greater detail by conducting cost-benefit analysis between greater investment and higher occupant satisfaction. Such work could establish the threshold at which further financial investment produces minimal increases in occupant satisfaction.

5.6 Area 6: Planning for effective SR implementation

Smart retrofit applications need to prove their benefits in terms of investment costs by achieving desirable smartness and/or energy efficiency levels with attractive payback times (Apostolopoulos et al., 2022; Yang et al., 2021). Therefore, further research in this field should define the cost-effectiveness of the various smart technologies in buildings retrofitting, according to the building typology or the year of construction.

Empirical data on relative savings through SR applications is scarce while it has a strong impact on mitigation costs and payback times (Schäuble et al., 2020). In this direction, statistically relevant databases of empirical data are needed not only to document realized savings but also to investigate determinants of savings through these smart applications.

As there were no studies considering the indirect benefits of SR for decision-making models (He et al., 2021), future studies could focus on establishing such a holistic SR decision making model incorporated with both direct and indirect benefits of SR.

Although a fully automated environment would maximise energy savings, this approach would be received negatively by certain end users. Occupants feel dissatisfied when decision making for functions is automated and thus removed from their control (O'Grady et al., 2021). While full automation of buildings may be considered normal in the future, a link between technology and acceptance must be developed. With qualitative and quantitative feedback loops present in BAS, the iterative operational engagement process needs to be further developed. The added benefits from smart decision-making logic with integrated feedback loops will be a great asset to SR, its users, and hence, society.

6.0 Discussion

This systematic literature review aimed to examine existing knowledge in SR research in order to answer three research questions: (RQ1) Who are the prominent authors, and what are the prominent organizations, countries, journals, and keywords in SR research? (RQ2) What are the past and recent focus areas in SR research? (RQ3) What are the potentially useful future research directions in SR research.

One key finding of this review is that the past and recent research areas fall into six groups. Research area 6, 'Planning for effective SR implementation' is relatively more prominent, with 20 out of the 65 journal articles falling into this group. Following the identification of the past and recent research areas, potentially useful future research directions of research areas were also identified. Figure 7 depicts a mapping of the nexus of different potentially useful future research directions. For illustrative purpose, it also indicates some examples of interrelationships between various domains of the six research areas that have been identified above. The interrelationships were determined by manual content analysis of the potential research insights highlighted in the identified literature. Such interrelationships are delineated as follows. Single-sided arrows portray the interrelationships with unilateral links with one another, while the bilateral links are portrayed by the double-sided arrows.

Introducing SRI as an SR objective and improving SRI calculation methodology will be helpful to develop holistic SR decision making models in Research Area 6. Qualitative analysis of occupant behavior in Research Area 1 is important to compare and contrast occupant engagement and response data in Research Area 5. Cost effectiveness of various smart technologies identified in Research Area 6 and investigating the analysis between greater investment and higher occupant satisfaction in Research Area 5 is important for incorporating economic performance aspects to different tools in Research Area 1. Occupant impacts on smart envelope performance identified in Research Area 2 is useful to conduct qualitative analysis of occupant behavior in Research Area 1.

Comparison of cost effectiveness of smart glazing systems in Research Area 2 is helpful for cost effectiveness analysis of various smart technologies in Research Area 6. Occupant impacts on smart envelope performance identified in Research Area 2 is useful for comparing different stakeholder levels and collecting occupant response data in Research Area 5. Furthermore, investigating the applied technologies with measured environmental data and subjective response data under Research Area 5 could provide rich occupant centric insights for promoting the establishment/improvement of policies and regulations in Research Area 2. Developing a link between smart technology and user acceptance in Research Area 6 is helpful for identifying occupant impacts on smart envelope performance in Research Area 2.

Findings of Research Areas 3 and 4 are important for cost effectiveness analysis and understanding benefits for SR decision making model development in Research Area 6. Application of SR technology for various building populations in Research Area 4 could aid the comparison of different stakeholder engagements and satisfaction levels in Research Area 5.

Investigating the applied technologies with measured environmental data and subjective response data under Research Area 5 could enhance the insights for further improvement of SR technology in Research Area 4 and for developing a link between smart technology and user acceptance under Research Area 6, based on the observed impact of user behavior and their acceptance of technology. Development of a holistic SR decision making model with the incorporation of direct and indirect benefits in Research Area 6 could be an aid for conducting cost-benefit analysis between greater investment and higher occupant satisfaction in Research Area 5.

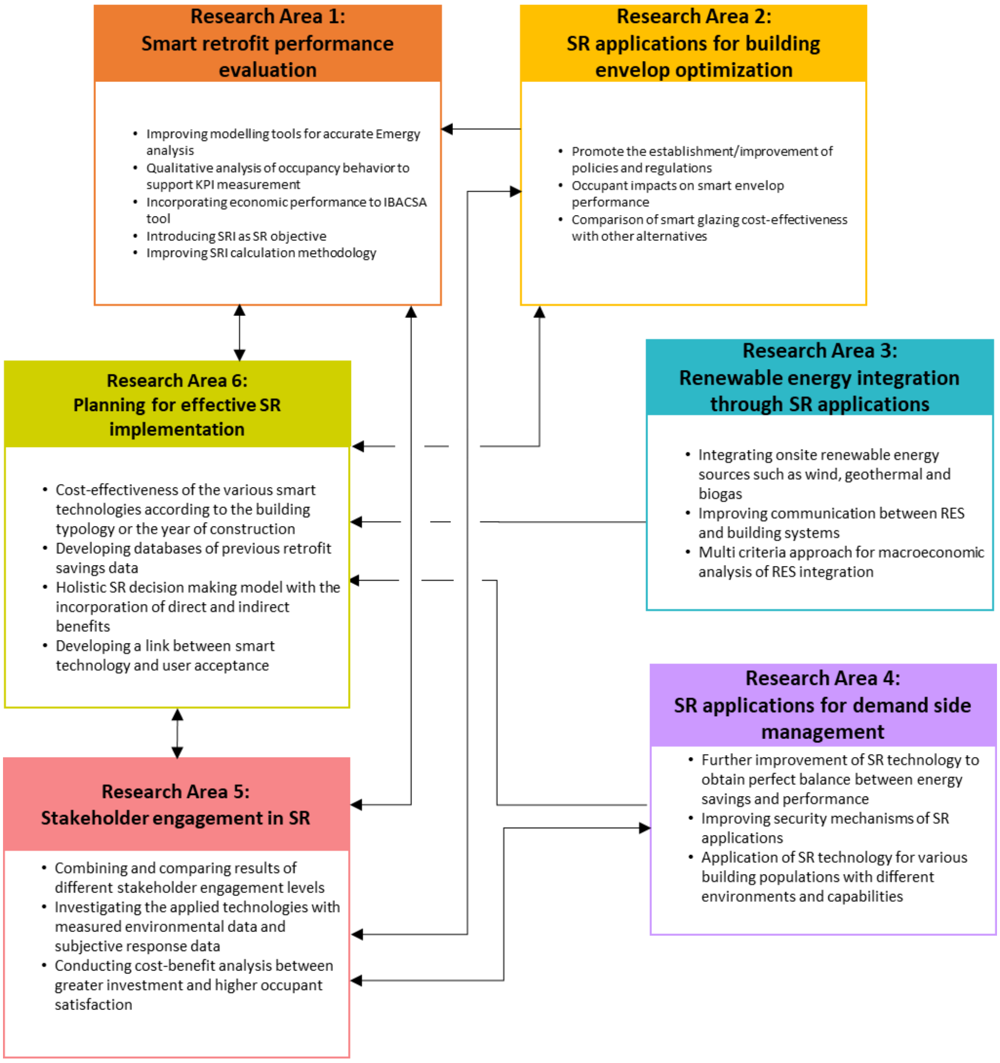

Figure 7: Nexus between future research directions

It is interesting to observe that while some research areas only have unilateral links with one another, some have bilateral and multiple interrelationships, showing a high potential for collaboration and shared contribution. In particular, Research Area 6 exhibits the largest number of interrelationships with the other research areas, implying that it is the most influential, complicated and challenging area for future research.

Overall, it is worth noting that the potentially useful future research directions identified above are consistent with the findings of the bibliometric analysis, viz. keywords including ‘energy,’ ‘smart grid,’ and ‘IoT’ have been featured in recent papers, indicating that they are becoming significant topics in this discipline. The diverse nature of the research areas in this field and the significant gaps in these areas indicate that SR research has yet to be developed in proper directions. One likely cause for this is the lack of a standard definition for SR, based on which authors can properly formulate their research studies in this field. Another factor could be that neither researchers nor practitioners have paid heed to the difference between ordinary retrofits and smart retrofits. A further cause could be the difficulty in executing and managing SR for existing buildings where user demands are ever-changing. Despite these hurdles, the future research directions drawn from the above systematic literature review should help promote SR research studies for contributing to SBs and the sustainability of the built environment.

7.0 Conclusions

Aimed at improving the SR knowledge base, this is the first systematic literature review that combines a bibliometric analysis and an in-depth qualitative review. The bibliometric analysis, which revealed the relationships between prominent contributors and keywords in SR research, provides answers to RQ1. In answering RQ2 and RQ3, the qualitative review uncovered the past and recent developments of SR research, research gaps and future research directions. This study’s findings are pertinent to non-SBs that are to be retrofitted into SBs and also existing SBs that require upgrades to improve or replace their facilities.

The analysis of the selected 130 journal articles published between 2003 and 2022 revealed a rapid annual growth in SR-related publications, indicating a high level of research interest in recent years. The bibliometric analysis identified the prominent contributors and keywords in the SR research domain. From the prominent journals and keywords, it is evident that the SR knowledge base is still largely focused on the energy efficiency improvement and occupant comfort aspects. However, many more facets of smartness in buildings were also identified as important, including: improved response to users’ needs, user convenience, and improved cyber security and privacy. Therefore, further research is needed to emphasize the importance of such social and legal aspects of SR. It is recommended that leading journals and conference organizers highlight these aspects as underexplored areas, which would encourage scholars to focus on these, and then generate, share and exchange related research findings.

The qualitative review of the 65 shortlisted journal articles further identified the key pieces of SR literature and categorized them into six research areas: (1) smart retrofit performance evaluation, (2) SR applications for building envelope optimization, (3) RE integration through SR applications, (4) SR applications for DSM, (5) stakeholder engagement in SR, and (6) planning for effective SR implementation. Since there has never been such a classification of existing SR research, this key finding offers a fresh, well-organized platform with pointers for future development of SR research.

The framework consolidating the major findings and deficiencies in these research areas, which signposts potentially useful future research directions for plugging the current gaps in SR research, is a significant outcome of this study. The need for technical as well as managerial insights for improved RES integration, improving calculation methodologies of smartness evaluation systems, strengthening the cyber-security of SR applications, establishing legal and policy requirements for SR applications, and improving the soft side of SR including better stakeholder management and rigorous decision-making are among the suggested future research directions. The nexus of the various future research directions, as mapped and illustrated with examples of interrelationships between the key elements in the six research areas, is newly synthesized knowledge for directing SR-related research and catalyzing research collaborations in the future.

From a research perspective, the key insights drawn from this study include the imperatives to: i) allow researchers to unveil the significant gaps in SR research, hence highlighting the urgent need for pragmatic SR solutions; ii) pave the way to enhance SR performance evaluation tools with advanced modelling and calculation capabilities, holistically covering relevant aspects including economic and occupant behavior, Emergy analysis, and SRI; iii) encourage the development of methodologies and tools for SR decision-making with a 360^0 coverage of relevant aspects; and iv) highlight the need for developing databases with savings related data from previous SR projects and cost effectiveness data of different SB technologies.

From a practical perspective, this study yielded new evidence to make strong cases for: i) emphasizing and disseminating the current difficulties encountered in SR implementation, inspiring practitioners and policymakers to develop solutions in cooperation with researchers; ii) unveiling relevant prominent resources, including active journals and impactful studies, which can be referred to in tackling SR-related issues; iii) providing a full picture of the state-of-the-art SR approaches available for building envelop optimization, RES integration, DSM, and post-retrofit performance evaluation; and iv) highlighting effective strategies for technology and process planning in SR as well as for successful stakeholder engagement in SR projects.

While the intended research outcomes have been attained, the study is not without limitations. First, the bibliometric analysis method adopted in this study may be considered as straightforward when compared with advanced techniques such as centrality measurement of networks, clustering (e.g. exploratory factor analysis, hierarchical clustering, k-means clustering) using other visualization software such as ‘Bibliometrix R’ (Donthu et al., 2021; Raza & Hameed, 2021). Second, the review has not covered publications on integrated seismic retrofitting and energy retrofitting (Pohoryles et al., 2022). While issues in this aspect may have influence on SR, the focus of the above review is on SR. Third, while the search terms were carefully chosen from prior research in this field, publications without these keywords might not have been found through the literature search process. Fourth, non-academic SR-related reports of public organizations were not included in this study. Fifth, the literature reviewed was confined to the publications contained in the two databases, viz. Scopus and Web of Science. Further review work is planned after addressing these limitations, after which the expanded review results are expected to extend those reported above, with further in-depth insights too.

8.0 CRediT authorship contribution statement

Sanduni Peiris: Conceptualization, methodology, investigation, validation, formal analysis, writing original draft, visualization, project administration, and fund acquisition. **Joseph H.K. Lai:** Conceptualization, supervision, writing (review and editing), project administration, and fund acquisition. **Mohan M. Kumaraswamy:** Writing (review and editing) and supervision. **Huiying (Cynthia) Hou:** Writing (review and editing) and supervision.

9.0 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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