Developments in the Built Environment 18 (2024) 100393

Contents lists available at ScienceDirect

Developments in the Built Environment

journal homepage: www.sciencedirect.com/journal/developments-in-the-built-environment

Energy-efficient façade design of residential buildings: A critical review

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ARTICLE INFO

Keywords:
Façade for residential buildings
Energy-efficient façade design
Design research
Domain knowledge
Research guide

ABSTRACT

Appropriate design of residential façades can save the buildings' energy consumption on indoor comforts significantly. Research on *energy-efficient façade design of residential buildings (EFDRB)* has attracted increasing academic interest during the past decade. Although a variety of studies have been conducted diversely, no review has organised the relevant knowledge structurally, leaving the domain research dispersed. This research conducts a literature review of the current EFDRB study based on 62 highly relevant publications from 2011 to -2021 in the field. A descriptive analysis, thematic analysis, and thematic discussion are conducted to reveal the research status quo, outline, contents, and features of the field comprehensively. Correspondingly, an ontological discussion with an explicative domain knowledge map is proposed, followed by insights into future directions. The findings will assist researchers in understanding the field, determining appropriate methods and design strategies, and positioning their work effectively.

1. Introduction

The residential sector consumes more than 25% of the global energy and the residential buildings are considered the fourth largest source of carbon dioxide emissions globally, which significantly affect the environment (Nejat et al., 2015). Households consume considerable energy for a variety of life services such as heating, cooling, cooking, entertainment, and transport (Australian Government Department of Climate Change, 2022). In European Union (EU), households represented 28% of the final energy consumption (Final energy consumption by sector, EU, 2020) (European Commission, 2020). In 2020–21, households in Australia consumed 11.7% of Australia's total energy use (Australian Energy Update, 2020) (Australian Government Department of Climate Change, 2022).

Envelopes, especially façades of residential buildings, can substantially impact the buildings' energy performance (Kheiri, 2018; Thalfeldt et al., 2013). According to Aksamija (2015), the façades of most buildings can affect the building's energy demand and the indoor comfort above all other systems. For instance, the properties and configurations of façade elements such as wall or glazing material conduction, solar transmittance, effective aperture, or window-to-wall ratio, can impact the adoption of natural resources (e.g., sun-light, solar heat, and wind) thereby affecting the energy load on household heating, cooling, ventilation, or artificial lighting (Kheiri, 2018). The World Business Council for Sustainable Development (WBCSD) has advocated the building industry to improve buildings' energy efficiency through a series of measures such as policy designation, consumer informed choice, technology and design innovation (Aflaki et al., 2015). The "design", among which, plays a crucial role, as investigations reveal that proper design and application of residential façades (such as "double skin green façade") can save up to 76% of electricity consumption for specific demands (e.g., heating, cooling, ventilation, or lighting) in certain regions (Wong and Baldwin, 2016). Thus, careful and appropriate design of residential façades at the design stage can considerably reduce the energy use of residential buildings in later stages (Aksamija, 2015; Aksamija, 2016), potentially contributing to global energy conservation and environment protection.

The studies of designing energy-efficient façades for residential buildings have been extensively explored in recent years. Many scholars have done detailed research from various fields involving design, engineering, mathematics, computer science, material science, environment, or economy, etc. The studies have mainly covered façade elements or systems (Li et al., 2021; Tong et al., 2021; Hassan, 2020; Yimprayoon et al., 2017; Xue et al., 2016; Siddiq, 2014; Ainurzaman Jamaludin et al.,

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https://doi.org/10.1016/j.dibe.2024.100393
Received 18 May 2023; Received in revised form 27 November 2023; Accepted 1 March 2024

2013; Vijay Kumar et al., 2020), design methods or tools (Watfa et al., 2021; Miller et al., 2014; Chen et al., 2020; Nicholson et al., 2019; Ochoa and Capeluto, 2015), and design strategies (Reyes-Barajas et al., 2021; Altan et al., 2015; Wang et al., 2021; Acosta et al., 2016; Strebkov and Filippchenkova, 2020; Hachem-Vermette, 2018; Hachem et al., 2014; Foroughi et al., 2021) to improve the design accuracy and efficiency in achieving high energy performance. Furthermore, a few investigations have emerged concerning the cost issue (Kalinović et al., 2021) or economic feasibility (Santamaría et al., 2016a; Santamaría et al., 2016b; Drişcu, 2014; Haggag et al., 2017; Maciel and Carvalho, 2019; Shen et al., 2016; Zhang et al., 2015) of applying specific energy-efficient façades on residential buildings.

A few points can be inferred: (1) The research on energy-efficient façade design of residential buildings (EFDRB) has high necessity, importance, and potentiality; (2) The current studies are mainly in-depth at the micro level (e.g., detailed explorations of façade parameters or configurations, etc.), but lack of macro perspective; (3) The research covers diverse fields and thus appears to be fragmented, dispersed, and systematic indistinction. This presents a state of contradiction between the importance and systematicity of the EFDRB research, which limits holistic cognition and prospection. Therefore, relevant knowledge needs to be organised and analysed structurally to form an integral research picture. To this end, this paper conducts an analytical literature review, specifically looking at the following questions:

- What topics have been studied in the current research on EFDRB?
- What objectives do these topics try to achieve?
- What research methods have been adopted in these studies?
- What kinds of design strategies have been employed in the reviewed design research?

Firstly, we explain the current research context of energy-efficient façade design with specificity in residential buildings. Then, the review methodology employed in this paper is expounded, followed by the descriptive and thematic analysis respectively to obtain the profile of the current EFDRB study statistically. Subsequently, we further explain and discuss the contents and features of each theme comprehensively and critically to get a complete understanding of the field. Accordingly, an ontological deliberation is proposed with an explicative domain knowledge map through which the research components and inner relationships are expressed and connected systematically. Lastly, insights into future research directions are suggested, followed by a conclusion. This study aims to obtain a integral picture of the current EFDRB research, by which researchers or practitioners in this field can have a holistic understanding to position their research and determine directions, methods, or design strategies appropriately.

2. Research context of energy-efficient façade design

2.1. Energy-efficient buildings

The concept and research on "energy-efficient facades" are closely related and were introduced after the concept and research on "energy-efficient buildings" (Ionescu et al., 2015). Thus, understanding the evolution of studies on energy-efficient buildings is contextually important.

Ionescu et al. (2015) elaborated the development of energy-efficient buildings chronologically:

The modern concept of energy-efficient buildings is deemed to have begun in 1930s, marked by the "House of Tomorrow" (by George F. Keck) and "MIT Solar House 1" (by Hoyt C. Hottel) (Jones and Bouamane, 2012). The two buildings initiated a trend in energy-efficient building design that relied on scientific calculation methodologies, as well as design and construction strategies. Thermal design and solar collectors were the focus at the time. Since then, the improvement of thermal insulation became a fundamental requirement (Marszal et al., 2011). By the 1970s, the energy storage system enjoyed development and the computer estimations of building's energy load started to be validated and applied. The interest in energy efficiency was surged by the oil crisis in 1973, resulting in the emergence of "sustainable buildings" concept integrating the principles of "Self-sufficient House", "Autonomous House", and "Green House" (Chen et al., 2009). Technical measures, high performance and recycled materials had been increasingly adopted. In the 1970s, the modish term "Zero-Energy House" came out. In the 80s, the "intelligent building" was created with the development of technologies. Later, the "Passive House" concept was proposed in the late 80s and the standard of "Passive House" was developed in the 90s (Schnieders et al., 2015). Nowadays, computer technologies and design software have dominated energy-efficient building designs.

In 2002, Meier et al. (2002), summarized the properties of an energy-efficient building:

- Possess effective equipment and materials suitable for the site and circumstances.
- Provide facilities and services suitable for the expected usage.
- Be managed in a way that minimizes energy consumption compared to similar buildings.

2.2. Energy-efficient façade design

Modern research and design of energy-efficient building façade has been developed since the aforementioned oil crisis in early 1970s (Ionescu et al., 2015). The early research dates to 1979 which was published by the US government (Wilson, 1979; Mazria, 1979). The studies developed the thermal storage wall design manual and investigated the passive systems (including location, shape, orientation, materials, windows, thermal mass, and movable insulation) making use of solar energy and heat theory. In terms of the practical design, airtightness, insulation, multi-layer windows, and passive solutions to improve thermal energy efficiency were the main means at the time (Ionescu et al., 2015). Since then, study of energy-efficient façade has grown rapidly.

With advancement of technologies, study and design of energy-efficient façade has become increasingly diverse nowadays. For instance, the "adaptive façade systems" use sensors, solar panels, and intelligent devices to auto-control façade systems in response to surrounding environment to optimisze energy performance (Ahmed et al., 2016). Another example is the "Building integrated photovoltaics (BIPV) facade systems" which integrate solar cells into building façade to generate energy for the building use thereby reducing dependence on external energy supplies (Yang and Zou, 2016). Apart from improving the thermal energy efficiency, modern research of energy-efficient façade systems also focus on reducing building's energy consumption on artificial lighting and mechanical ventilation (Gorantla et al., 2016). Thus, the studies on energy-efficient façade design have become a key aspect of sustainable building design and urban development (Halawa et al., 2018).

Today, the "energy-efficient" building façades are also known as "energy-saving", "sustainable", or "high-performance" façades (Aksamija, 2015; Aksamija, 2016; Aksamija, 2013; Afonso, 2020). As Aksamija (2013) claims, the energy-efficient façades *"can be defined as exterior enclosures that use the least possible amount of energy to maintain a comfortable interior environment, which promotes the health and productivity of the building's occupants"*. The properties of an energy-efficient façade include (Aksamija, 2015; Aksamija, 2016):

1) Improving daylighting;
2) Facilitating natural ventilation;
3) Increasing thermal mass;
4) Blocking unwanted solar heat;
5) Preventing air or moisture from infiltrating;

6) Reducing heat transfer through insulation.

These properties are highly context-specific and can be impacted by various factors, such as climate and environment, building types and functions, morphology and orientation, façade types, occupancy behaviours, and equipment load (Aksamija, 2015; Lee et al., 2002). As such, to formulate and maintain a universal and immutable design standard for energy-efficient façade is unfeasible. However, the basic design methods and principles for energy-efficient façade can be generally summarized as (Aksamija, 2015; Aksamija, 2016; Aksamija, 2013):

- Optimisze building massing and orientation to adapt to sun position;
- Utilize shading techniques to reduce cooling loads and enhance thermal comfort;
- Promote natural ventilation to improve air quality and decrease cooling demands;
- Incorporate energy conservation measures such as improved insulation and daylighting to reduce the need for artificial lighting and mechanical heating and cooling.

Nevertheless, the detail requirements and emphases of energy-efficient façade design can vary significantly depending on different types of buildings (e.g., residential, commercial, or public buildings) (Pérez-Lombard et al., 2008). For example, façades of commercial buildings (such as office buildings where curtain walls are largely adopted (McFarquhar, 2012)) are relatively globalized and homogeneous due to the popular "international style" aesthetic (Al-Azzawi and Al-Majidi, 2021), while façades of residential buildings (especially houses) are more localised and climate orientated. Therefore, the differentiation of design requirement and applicability result in the increasing segmentation of studies on energy-efficient façade design. This paper will concentrate on the research of *energy-efficient façade design for residential buildings* (EFDRB) specifically.

The EFDRB research studies the design possibilities or economic feasibilities of exterior faces of residential buildings to use the least external energy to satisfy household indoor comforts. As mentioned in the Introduction section, current studies on EFDRB mainly focus on micro level from various aspects. For instance, detailed issues are explored in depth, such as specific façade element parameters or configurations, design methods or strategies under specific climatic conditions, and economic issues. However, a macroscopic overview of domain knowledge is lacking. Moreover, although the majority studies demonstrate household energy savings by proper EFDRB means, some research argues that a better insulation may cause increasing energy demand for cooling which has negative implications in case of energy poverty (Pyrgou et al., 2017). Thus, the current research on EFDRB is in-depth in detail but seems dispersed, inconsistent, and lack of systematic sorting, which will be addressed in this paper.

3. Methodology

This review paper uses the content analysis-based literature review method (Seuring and Gold, 2012) to obtain a profound understanding and prospect of the EFDRB research domain. Scopus is employed as the database for literature searching because it is deemed to be the "largest abstract and citation database" (Welzenbach) and offers the most extensive overview of global scientific data ('Content). The words "energy efficient" and "residential façade design" are the primary key words for search. Indeed, many façade technologies studied on non-residential buildings (e.g., office buildings or commercial buildings) could also be applied on residential buildings (especially large-scale residential projects). However, the requirements of the same façade technologies may differentiate when applying on different types of buildings. Therefore, those studies are exclusive from this review to ensure the precise boundary and clear contents of this study and avoid confusion. This is the reason of including "residential" in the searching keywords particularly. Since "energy saving" is often used to describe the concept of energy efficiency, the words "energy saving" are added too as supplementary keywords. As a result, the searching keywords are finally determined as: energy efficient OR saving AND residential façade design.

The last decade (2011–2021) is set as the search time frame to see the latest progress in this research area. The source types are set as "Journal" and "Conference Proceeding" to guarantee timeliness and quality.

Therefore, the criteria of the preliminary search are as followings (also shown as Fig. 1):

- Database: Scopus.
- Search: article title, abstract, keywords.
- Search keywords: energy efficient OR saving AND residential façade design.
- Time frame: 2011 to 2021.
- Source type: Journal and Conference Proceeding.
- Publication language: English.

Initially, 87 documents were found according to the above criteria. After excluding the documents of non-related subject areas (e.g., Physics and Astronomy, Medicine, Business, Management and Accounting, and Chemical Engineering), 78 documents were filtered as highly relevant. Through careful reading of the abstracts, 62 publications out of the 78 were finally selected for further review and analysis due to the rest 14 being unrelated (e.g., not about residential or façade design, etc.) or duplicated.

Based on the dataset, we elaborate on the analysis section (including descriptive analysis and thematic analysis) and discussion section (including thematic discussion and ontological discussion) in the following sections. After that, the insights of future research directions are suggested accordingly.

Firstly, the *descriptive analysis* studies the distribution of subject areas, journals of publication, annual development, and geographical distribution of authors with a specific investigation of the largest regional group quantitatively.

Secondly, the *thematic analysis* examines theme-related information statistically to present the current research state and profile. The theme-related data is extracted from the selected publications concerning the above research questions, specifically looking into the information regarding the principal purposes, research objectives, adopted methodologies, and types of design strategies applied.

Thirdly, based on the result of the thematic analysis, the *thematic discussion* discusses the contents, development, advantages, disadvantages, and trends in detail to understand the domain knowledge completely and critically. The discussions are organised into four major topics (in line with the research questions), covering research topics, research objectives, research methods, and design strategies.

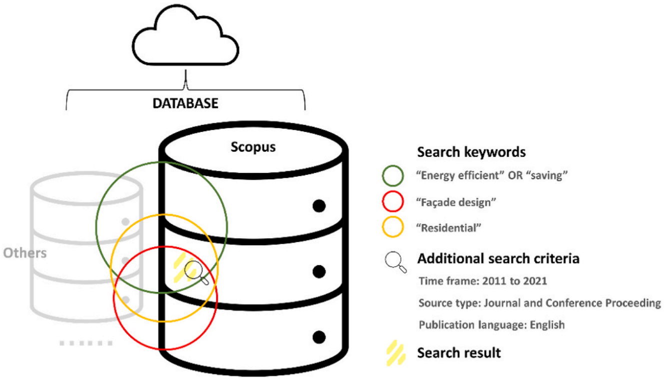


Fig. 1. Graphic abstract of the search scope.

Fourthly, inspired by the thematic discussion, the *ontological discussion* proposes a domain deliberation of the EFDRB study, by developing an explicative domain knowledge map to illustrate the research profile, development, inner connection, and prospection structurally and succinctly.

Lastly, we suggest the research potentials on the section of *insights into future directions*, by considering the strengths emerging from the discussions.

4. Analysis

4.1. Descriptive analysis

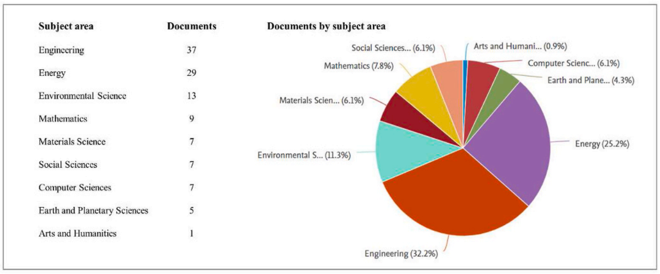
The descriptive analysis studies the distribution of subject areas, journals of publication, annual development, and geographical distribution of papers.

Fig. 2 indicates the distribution of subject areas of the selected 62 publications. The “Engineering” area occupies the largest proportion (32.2%), followed by the fields of “Energy” (25.2%), “Environmental Science” (11.3%), “Mathematics” (7.8%), “Materials Sciences”, “Social Sciences”, and “Computer Sciences” (6.1% respectively), “Earth and Planetary Sciences” (4.3%), and the least “Arts and Humanities” (0.9%). The findings reveal the extensive but fragmented academic attention of the EFDRB research in the past decade.

Table 1 summarises the top publication sources in terms of amount and year (2011–2021). The journal “Energy and Buildings” and “Energies” are the most popular publication sources in the last decade, followed by “Buildings”, “Applied Energy”, “Sustainability (Switzerland)”, and “Iop Conference Series Materials Science and Engineering”, etc.

Fig. 3 presents the overall and rapid growth of publications in the past 10 years (although a slight fluctuation), which demonstrates an increasing academic interest. The soar from 2012 to 2015 may be stimulated by a regional supportive research project called the “Multi-functional Energy Efficient Façade System for Building Retrofitting” held by Spain between 2012 andto 2016 covering Europe (‘Multifunctional Energy Efficient Façade System). Also, in EU, policies for energy savings have raised an emphasis on building stock since 2002 (Loussos et al., 2015; Ascione et al., 2022). The statistical models and data of building stock have influenced energy targets for existing residential retrofits and new residential constructions (Loussos et al., 2015; Capeluto and Ochoa, 2014), which have facilitated the EFDRB research in EU. This can be demonstrated by Fig. 4 to a certain degree, which shows that research in Europe accounts for the largest proportion. The fluctuation may be caused by the completion of the supportive project and the follow-ups of the previous studies. We can infer that the policy and funding support plays a vital role in the development and prosperity of research.

To summarise briefly, the descriptive analysis demonstrates a growing, extensive, but dispersed academic interest in the EFDRB study, looking from the multi-disciplines, diverse journals, wide geographic distribution, and increasing publication numbers. It implies that the research on EFDRB is developing rapidly, however, suffering from the confusion of disciplinary boundaries (Sabini et al., 2019). We will address this in the following sections.



Subject area	Documents
Engineering	37
Energy	29
Environmental Science	13
Mathematics	9
Materials Science	7
Social Sciences	7
Computer Sciences	7
Earth and Planetary Sciences	5
Arts and Humanities	1

Fig. 2. Distribution of subject areas of the selected 62 publications.

4.2. Thematic analysis

The thematic analysis aims to present and conclude the status and profile of the EFDRB study by examining the theme-related information statistically. The theme-related data is extracted from the selected publications concerning the above research questions, specifically looking at the information regarding the principal purposes, research objectives, adopted methodologies, and types of design strategies applied.

The analysis of the principal purposes of the selected publications reveals that the current major research topic is the *Investigation of residential façade components* (occupying 79%) as shown in Table 2. Another research topic, the *Demonstration of design methods and tools* (accounting for 21%), receives less attention. Thus, we can infer that the current research mostly stays at the micro and fundamental level, especially the detailed exploration of parameters or configurations. However, it lacks synthesis or practicality to guide actual façade designs. We will explain and discuss this in detail in the following thematic discussion section.

Another thematic analysis regards the research objectives. We found that the common research objective of all the 62 publications is to satisfy some indoor comforts (i.e., thermal comfort, visual comfort, and air quality) energy-efficiently by optimising the façade design. Generally, using energy for thermal comfort means to provide domestic heating or (and) cooling depending on local climates, while for visual comfort and air quality refer to generating indoor artificial lighting and conducting mechanical ventilation respectively. As claimed in many studies, considerable energy would be consumed for indoor comforts if the residential façades are not well designed as façades are the most important components separating the indoor and outdoor environments (Aksamija, 2015; Aksamija, 2016). The analysis of type distributions on satisfying indoor comforts (Fig. 5) indicates that to achieve thermal comfort with less energy consumption is the absolute research emphasis of the current EFDRB study.

The total percentage of Fig. 5 exceeds one hundred implying that some papers involve meeting multiple indoor comforts. Moreover, other objectives (e.g., reducing construction cost (Kalinović et al., 2021) or economic feasibility studies (Ochoa and Capeluto, 2015; Reyes-Barajas et al., 2021; Santamaría et al., 2016a; Santamaría et al., 2016b; Drișcu, 2014; Haggag et al., 2017; Maciel and Carvalho, 2019; Shen et al., 2016; Zhang et al., 2015, etc.) are also found in the 62 publications, however, less proportion is occupied. Based on the objective volume, in this study, we classify the 62 publications into two categories: single-objective study and multi-objective study. Specifically, if a publication only aims to achieve one certain type of indoor comforts energy-efficiently, then it is categorised as a single-objective study. On the other hand, if a paper tries to satisfy multiple indoor comforts or to achieve other objectives at the same time, it is considered a multi-objective study. As shown in Fig. 6, multi-objective studies only account for 35%, while single-objective studies make up 65%, which presents the current academic preference. It indicates that the research objective of the current EFDRB research is relatively homogeneous, mostly limiting to single-objective studies of reducing indoor thermal energy consumption. However, multi-objective studies often required in the actual energy-efficient façade design are deficient. The detailed findings will be elaborated and explained in the following thematic discussion section.

The third thematic analysis is the adopted methodologies. Overall, the quantitative research approach dominates the current EFDRB study (adopted in 59 publications out of 62). Specifically, all the 59 publications employ design-related quantitative research methods, whereas 10 papers also use other quantitative methods for economic issue studies. It shows that the quantitative relationship between façade parameters and energy performance data is a general concern. Regarding the design-related quantitative methods, we summarise five major types based on

Table 1

A summary of the top publication sources in terms of amount and year (2011–2021).

Source Title	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	Sum
Energy And Buildings						3			1		1	5
Energies		1					1				3	5
Buildings					2				1	1		4
Applied Energy				1		1				1		3
Sustainability (Switzerland)							1		2			3
Iop Conference Series Materials Science and Engineering									1	2		3
Energy Efficiency					1		1					2
Energy Procedia					1	1						2
E3s Web of Conferences								1		1		2
International Multidisciplinary Scientific Geoconference Surveying Geology and Mining Ecology Management Sgem				1			1					2
Sum	0	1	0	2	4	5	4	1	5	5	4	31

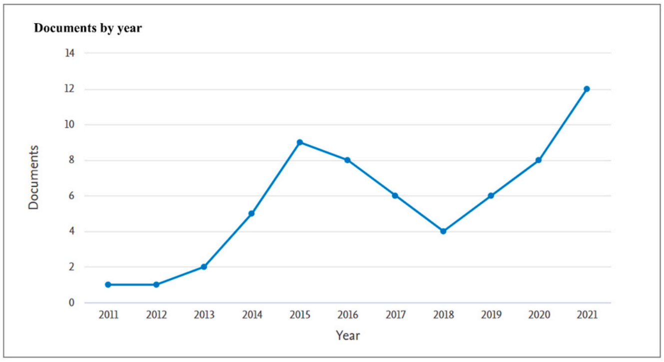


Fig. 3. Annual development of the selected 62 publications.

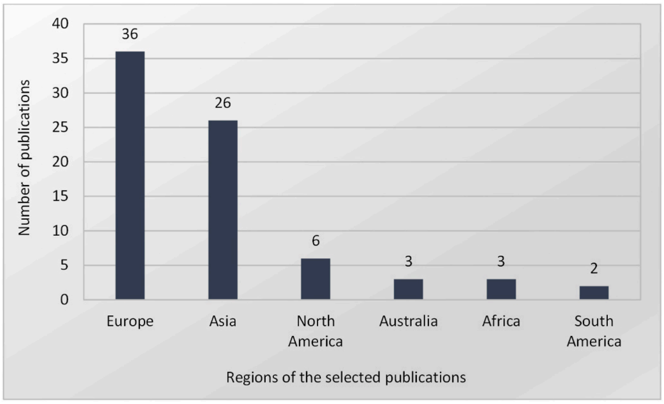


Fig. 4. Geographical distribution of the selected publications.

the means of data collection (Albertson), i.e., simulation-based method, derivative-based method, experiment-based method, observation-based method, and combined method. The distribution analysis of the five major types (Fig. 7) indicates that the simulation-based method occupies the vast majority (71%), which demonstrates a high reliance on simulation techniques and a high pursuit of data precision. However, the deficiency of methodological diversity can limit the flexibility, adaptability, and breadth of studies. Elaborations will be found in the following thematic discussion.

The fourth thematic analysis evaluates the design strategies applied in the selected 62 publications (Fig. 8). Three major strategies are classified: passive design strategies, active design strategies, and the combined strategies of both (these strategies are elaborated on the following Discussion section). As shown in Fig. 8, the passive design strategies lead the present research (occupying 78%) illustrating that the "very low energy demand and consumption" is the priority when conducting an energy-efficient façade design (Rodriguez-Ubinas et al., 2014; Aksoy and Inalli, 2006). This also indicates an academic preference for maximising the use of natural conditions in energy-efficient façade design studies, which is beneficial for the detailed exploration of various passive design means. However, strategic diversity may be affected, which may restrict the pursuit of higher energy-saving goals. A detailed discussion will be carried out in the following section.

The profile of current EFDRB study is reflected in the thematic analysis. The *investigation of residential façade components* is the majority research topic currently, with achieving thermal comfort energy-efficiently as the priority research objective. The simulation-based quantitative research methods and passive design strategies are adopted and applied mostly in the current investigations. Analysis indicates that the current studies are generally in-depth and detailed but relatively homogeneous and lack practicality in the actual design guidance. Studies that have great potentiality but are currently less proportioned statistically are yet discussed, which will obstruct the holistic understanding and prospection. The next section will provide further explanations and discussions in terms of the thematic features and ontological deliberation to gain a more comprehensive and critical view of the EFDRB research.

5. Discussion

5.1. *Thematic discussion*

The thematic discussion section aims to obtain a more complete understanding of EFDRB research field by concerning both the less proportioned studies and the majority. Detailed contents and features of each theme are explained and discussed comprehensively and critically. To be in line with the four themes analysed above, the thematic discussion will be unfolded into four subsections:

- Research topics: fundamental or innovative
- Research objectives: explore bounders or seek trade-offs
- Research methods: design-related or cost-related
- Design strategies: energy reduction or generation

5.1.1. *Research topics: fundamental or innovative*

The discussion of research topics about the EFDRB study reveals two important features, fundamental and innovative, which correspond to the two major research topics respectively. The topic of *Investigation of residential façade components* mainly revolves around the fundamental compositions of façade elements or systems, while another topic, *Demonstration of design methods and tools*, provides innovative design methods and tools.

5.1.1.1. Fundamental - investigation of residential façade components. According to Table 2, the current major research topic is the *Investigation*

Table 2
Analysis of the research topics and principal purposes of the 62 publications.

Research topic	Characteristic	Sum	Principal purposes	
1. Investigation of residential façade components	Detailed and in-depth study of the specific façade parameters, however, lack of synthesis or practicality to guide actual façade designs.	49 (79%)	To investigate façade elements	Window to wall ratio (WWR) (Li et al., 2021; Tong et al., 2021; Hassan, 2020; Yimprayoon et al., 2017; Xue et al., 2016; Siddiq, 2014; Ainurzaman Jamaludin et al., 2013; Vijay Kumar et al., 2020), Window insulation (Tong et al., 2021; Altan et al., 2015), Window materials (Altan et al., 2015; Wang et al., 2021; Acosta et al., 2016; Santamaría et al., 2016a), Window shape (Hassan, 2020, Acosta et al., 2016; Khalil et al., 2018), External wall materials (Hassan, 2020; Afonso, 2020, Khalil et al., 2018; Rais et al., 2021; Fernandez-Antolin et al., 2019; Wilkinson et al., 2017; Perlova et al., 2015; Mlakar and Štrancar, 2013), External wall insulation (Tong et al., 2021; Altan et al., 2015, Santamaría et al., 2016a; Drişcu, 2014; Khalil et al., 2018; Kubečková and Vrbová, 2021; Pavlov et al., 2018), External wall type (Kalinović et al., 2021; Khalil et al., 2018; Perlova et al., 2015), External wall thickness (Reyes-Barajas et al., 2021; Kalinović et al., 2021), Shading (Tong et al., 2021; Xue et al., 2016; Santamaría et al., 2016a; Haggag et al., 2017; Khalil et al., 2018; Liu et al., 2019; Sari and Chiou, 2019; Singh et al., 2015), External wall material positions (Reyes-Barajas et al., 2021), Building or window orientations (Watfa et al., 2021; Acosta et al., 2016), Façade geometries or morphology (Hachem-Vermette, 2018; Santamaría et al., 2016a; Pacheco-Torres et al., 2015).
			To investigate façade systems	Double skin façade (DSF) (Drişcu, 2014, Khalil et al., 2018, Ramadhan et al., 2021), Timber-glass upgrade module (Š et al., 2016; Kravanja et al., 2019; Š et al., 2017), Ventilated façades (Maciel and Carvalho, 2019; Mercader-Moyano et al., 2021), Trombe wall (Ramadan, 2020; Bogdanovic et al., 2018), Prefabricated façade panel (Guerrero Delgado et al., 2020; Mika, 2017) BIPV system on façade (Hachem-Vermette, 2018; Hachem et al., 2014), Adaptable façade using movable Photo Voltaic (PV) (Foroughi et al., 2021), Polar photovoltaic-thermal modules (PVT modules) (Strebkov and Filippchenkova, 2020), Biomimetic building façades (Webb, 2021), Adaptive kinetic shading system (Ahmed et al., 2016), Multifunctional energy efficient façade system (the "Meefs" system) (Paiho et al., 2019), Solar thermal façade (STF) (Shen et al., 2016), A novel loop-heat-pipe based solar thermal façade (LHP-STF) (Zhang et al., 2015), Textile reinforced concrete (TRC) precast Façade sandwich panel (Colombo et al., 2015).
2. Demonstration of design methods and tools	Constructive, innovative, and practical in assisting the actual façade designs but need to base on sufficient parameters data and correct parametric relationships.	13 (21%)	To develop or demonstrate design method or tools	A design and analysis method combining BIM and BEM (Watfa et al., 2021; Miller et al., 2014), A numerical-based optimizsation model based on BIM to optimise window design (Chen et al., 2020), A BIM method to optimise the shape coefficient (Han et al., 2016), An iterative design method combining architectural, engineering, and building science approaches to reach net-zero (Nicholson et al., 2019), A computer model to assess the economic profitability of energy rehabilitation operations (Santamarí et al., 2016b), A "four steps" design method[a] to decrease the operational and embodied energy use in façade retrofitting (Loussos et al., 2015), An "expert system"[b] for the early stages of façade retrofit design to diagnose the best alternatives (Ochoa and Capeluto, 2015), A simulation-based method to identify preferred energy and comfort design strategies for apartment façade retrofitting (Capeluto and Ochoa, 2014), An experimental method using "test cells" to evaluate energy performance and thermal comfort (León-Rodríguez et al.,

(*continued on next page*)

Table 2 (*continued*)

Research topic	Characteristic	Sum	Principal purposes
			2017), A façade refurbishment toolbox (FRT) approach (Konstantinou, 2015), A DFuzzy-DAHP decision-making model (Liu et al., 2012), A sensitivity analysis approach (Sesana et al., 2011).

[a] The "four steps" design method refers to a method for the façade refurbishment strategy design introduced in Loussos et al.'s work (Loussos et al., 2015), including: the material comparison, the strategy comparison per façade part, the strategy comparison for a whole apartment, and the final refurbishment design.

[b] The "expert system" for the early stages of façade retrofit design refers to a design methodology developed by Ochoa and Capeluto (2015) which can form a base for a design expert program. The system uses the methodology steps including the Input, Selection, and Output to diagnose the best design alternatives.

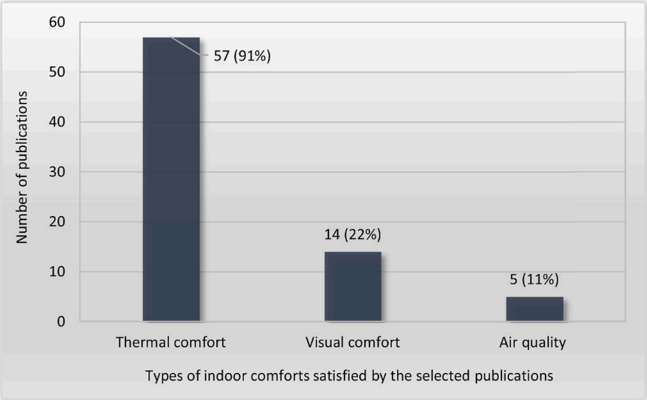


Fig. 5. Type distributions on satisfying indoor comforts based on the 62 publications.

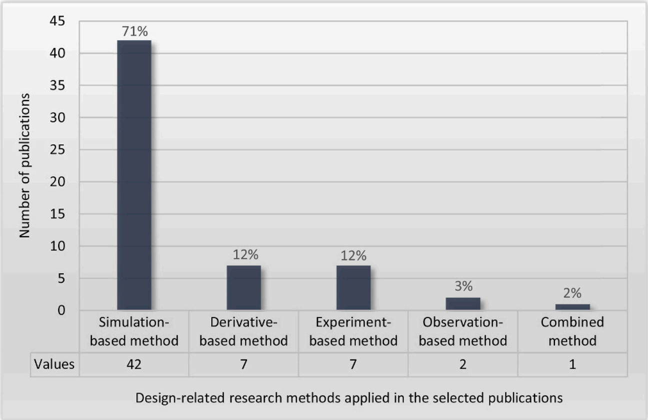


Fig. 7. Documentary distribution of the four major specific methods related to design research.

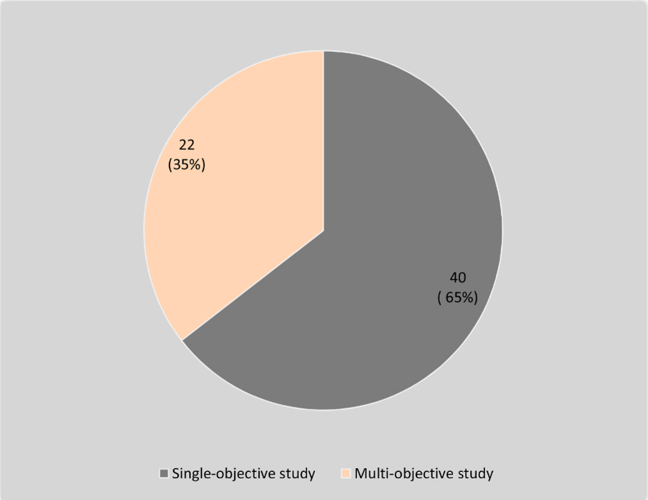


Fig. 6. Distribution of the objective categories based on objective volume.

Fig. 8. The current application status of design strategies in EFDRB study.

of residential façade components, containing 49 publications out of the 62 (accounting for 79%). In the 49 publications, studies on façade elements are found slightly more than façade systems at present. Research on façade elements mainly involve the very fundamental façade components, such as external window elements (e.g., window to wall ratio, window insulation, window materials, window shape), external wall elements (e.g., wall materials, wall insulation, wall type, wall thickness), shading elements, as well as positions, orientations, and geometries etc … Investigations on façade systems mainly look into the systems under specific climate conditions. For instance, studies of the double skin façade (DSF) in tropical areas, timber-glass upgrade model in temperate oceanic climate zones, ventilated façades in Mediterranean (or almost) climate, trombe wall, prefabricated façade panel, BIPV system on façade, and other photovoltaic applications in different climate zones, etc.

The studies of this topic aim to explore the optimal design parameters or configurations of the fundamental façade elements or systems of residential buildings to reduce energy consumption. The research findings are detailed and in-depth, and can vary depending on different indices of natural conditions (e.g., climate zones, solar or wind parameters, etc.) which are pre-set in the studies. It implies that the diversity of natural conditions provides fertile soil for fundamental studies, but imposes constraints at the same time. Thus, it makes the fundamental research necessary and in-depth, but in the meanwhile, lacks synthesis or practicality for general guidance to some extent.

5.1.1.2. Innovative - demonstration of design methods and tools. Studies of the topic: *demonstration of design methods and tools*, account for less (13 out of 62, occupying 21%) as shown in Table 2, maybe because of the higher research complexity and the reliance on the first topic's research findings. Specifically, the integration and utilisation of diverse technologies increase the research complexity, and the requirement of sufficient parameter data and correct parametric relationships raise the reliance on fundamental studies. For instance, different building-related computer technologies such as the building information model (BIM) and the building energy model (BEM) are adopted or integrated into some studies to form methodologies (Watfa et al., 2021; Miller et al., 2014). Some research develops an innovative design method by using the data and formula extracted from fundamental studies as well as a BIM platform to optimise the external window design for energy-efficiency (Chen et al., 2020). More examples can be found in Table 2.

This research topic aims to present innovative thinking by developing design methods, tools, or systems to improve the efficiency of energy-efficient façade designs. It is more constructive and innovative in terms of design methods, and practical in assisting the actual façade designs. However, it needs the strong support of adequate data and advanced technologies, which probably make this research topic proportionally less at present. We infer that this innovative study topic expects to prosper with the advancement of technologies as well as the growing data generated by fundamental studies. We suggest it as an important research direction in the future.

5.1.2. *Research objectives: explore bounders or seek trade-offs*

The discussion of research objectives finds that there are two major targets that the current studies try to achieve: to explore parameter boundaries by single-objective studies or to seek parameter trade-offs by multi-objective studies. As shown in Fig. 6, the single-objective studies involve 40 publications (occupying 65%), more than the multi-objective studies including 22 papers (accounting for 35%), indicating the current academic preference. In the following paragraphs, we discuss the findings in detail.

5.1.2.1. Explore parameter bounders - single-objective study. The single-objective study aims to achieve a certain type of indoor comfort with less energy consumption through proper façade designs. The parameter bounders (i.e., extremums of parameters or configurations) of specific façade components under a certain energy-efficient constraint (i.e., to achieve one indoor comfort with less energy consumption) are investigated in these studies. As analysed before, the current single-objective studies mostly focus on reducing indoor thermal energy consumption, i.e., exploring the extremums of façade components in minimising energy consumption on indoor thermal comfort. For instance, 252 options of shading panels were simulated based on a Hong Kong public housing to obtain the optimal panel parameter for reducing energy consumption on domestic cooling in hot summer (Liu et al., 2019). Optimal configurations of the BIPV system on façades of multi-story residential buildings in Canada were tested to balance the energy consumption for household heating and cooling (Hachem et al., 2014). In addition to the investigations of reducing indoor thermal energy consumption, a small number of studies concerns lowering lighting or ventilation energy consumption. For example, the optimal parameters of external windows were examined under different European weather conditions to lower energy use for indoor artificial lighting (Acosta et al., 2016). More examples can be found in Table 2.

The examples indicate that single-objective studies have relatively simple research requirements (only need to consider a single energy-efficient constraint) and abundant research needs (provided by the diverse natural conditions). These factors may lead to the current academic dominance of single-objective studies. In addition, the fewer research constraints are conducive to the in-depth explorations of parameter bounders, which are beneficial to the studies of design possibilities regarding specific façade elements or systems. However, less consideration of complex constraints may prevent the practicality. Therefore, we believe that the findings of single-objective studies can be used as control indicators in design standards or provisions, but are less suitable for design practices that always consider multiple and complex constraints.

5.1.2.2. Seek parameter trade-offs - multi-objective study. The multi-objective study tries to satisfy multiple indoor comforts energy-efficiently or other purposes simultaneously by investigating façade elements, systems, or design methods. Various parameters of façade components are traded off in these studies under different constraints (e.g., to meet multiple indoor comforts energy-efficiently or cost-beneficially) to seek the optimal parametric balance.

Fig. 9 indicates the current objective distributions of multi-objective studies. It shows that to achieve multiple indoor comforts simultaneously with less energy consumption has drawn the most academic attention, involving 9 publications of the 22. For example, (Chen et al., 2020; Altan et al., 2015; Foroughi et al., 2021; Singh et al., 2015; Pacheco-Torres et al., 2015; Kravanja et al., 2019; Han et al., 2016) focused on achieving thermal comfort and visual comfort, while (Watfa et al., 2021; Rais et al., 2021) concentrated on satisfying all the three indoor comforts simultaneously.

Another 9 papers concern achieving multiple indoor comforts energy-efficiently while studying economic feasibility. In these studies, parameters of specific façade systems are investigated by balanced means to demonstrate the energy benefit as well as the long-term economic benefit (Ochoa and Capeluto, 2015; Reyes-Barajas et al., 2021; Santamaría et al., 2016a, Santamaría et al., 2016b; Drișcu, 2014; Haggag et al., 2017; Maciel and Carvalho, 2019; Shen et al., 2016; Zhang et al., 2015). The research findings reveal that although the initial investments of specific façade systems are high, the long-range economic benefit and investment return are significant. This type of multi-objective study can assist the rational design of energy-efficient façade systems, in the meanwhile, facilitate market promotion and wide acceptance. Other studies account for less, however, they hint at a trend to explore a wider range of the field.

Intricate constraints in multi-objective studies increase the research complexity and difficulty, which may cause the current less occupied of studies. However, unlike single-objective studies, the parameter values in multi-objective studies are not necessarily the extremums, instead, they are trade-offs obtained through a balanced or joint manner (Reyes-Barajas et al., 2021) under various constraints, which are much more practical. Therefore, we believe that the multi-objective study will increase in practice and is an important future direction.

5.1.3. *Research methods: design-related or cost-related*

The discussion of research methods intends to obtain a more detailed understanding of the quantitative research methods in existing studies to propose insights for improving diversity. As analysed above, the quantitative research approach dominates the current EFDRB studies (covering 59 publications out of 62, occupying 95%). Thus, the following discussion will only focus on the quantitative research methods. Two major aspects form this discussion: design-related quantitative research methods and cost-related quantitative research methods. Among them, the design-related methods are discussed primarily as they are adopted in all 59 publications. The discussion of cost-related research methods will be an overview only rather than expounding because they only involve 10 publications.

5.1.3.1. Design-related quantitative research methods. Quantitative research methods are primarily adopted in design-related studies, as the quantitative relationships between façade parameters and energy performance data need to be investigated. The research methods will vary depending on the different ways of acquiring data. In this paper, five

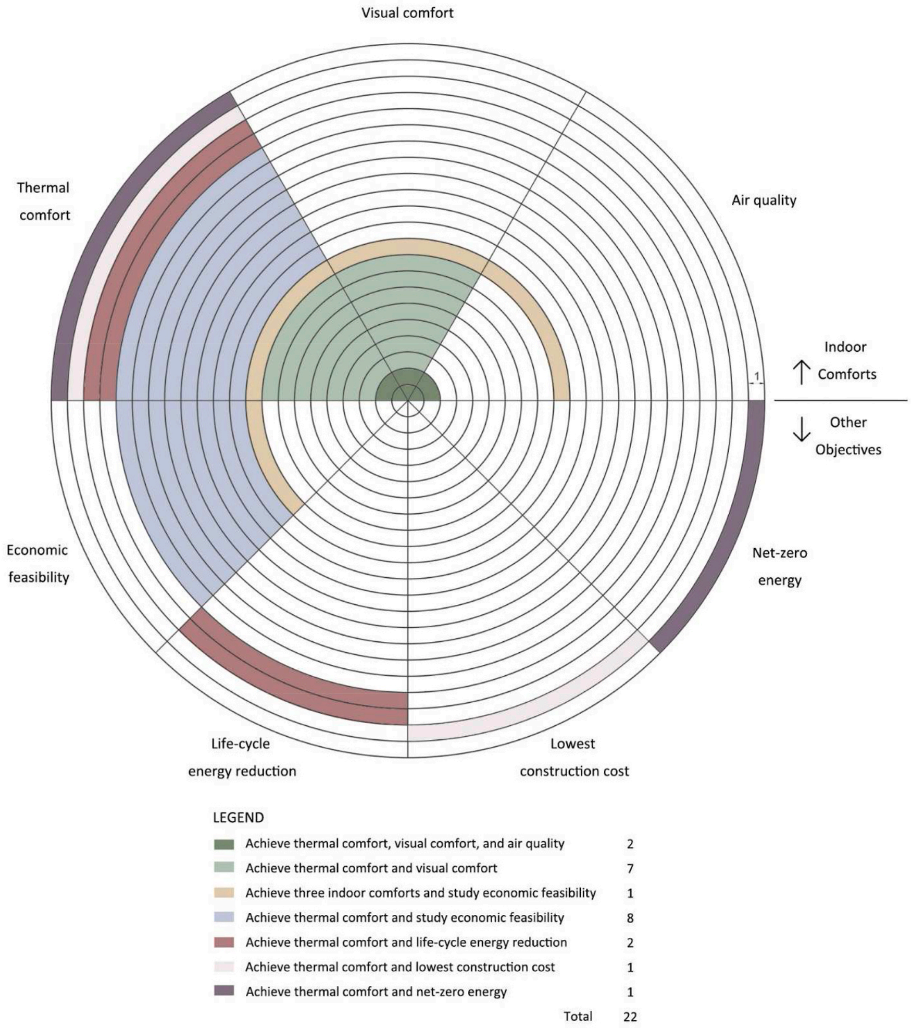


Fig. 9. Objective distribution map of multi-objective studies.

major quantitative research methods are classified and discussed based on the means of data acquiring (Albertson), i.e., simulation-based method, derivative-based method, experiment-based method, observation-based method, and combined method. As analysed above, the simulation-based method is adopted mostly in the current studies (as shown in Fig. 7), which indicates a high reliance on simulation techniques. There are pros and cons to all five methods. The following will discuss and compare their characteristics in detail to assist scholars or practitioners in this field to determine methods reasonably and flexibly, which can also facilitate method diversity.

5.1.3.1.1. Simulation-based method. The simulation-based method classified in this paper means that the quantitative data of energy consumption is generated by simulation in computer models under the variations of imitating the real-world environment and operations (Albertson).

As indicated in Fig. 7, the simulation-based research method is currently the most adopted, involving 42 publications of the 59, accounting for the highest percentage, 71%. It is also deemed to be the state-of-the-art method in the research domain of energy-efficient buildings (Nguyen et al., 2014). According to Nguyen et al. (2014), a simulation-based method for energy-efficiency research is the use of dynamic computer simulation programs to analyse energy behaviours in achieving energy-efficient objectives, by altering input variables to see the variations in energy performance. Consequently, the input variables (i.e., façade parameters or configurations) that contribute to less energy consumption would form the suggestions for energy-efficient façade design.

Among the 42 publications, the simulation program EnergyPlus of DesignBuilder is mostly applied (involving 21 studies, making up the largest proportion, 50%), followed by eQuest and IES-VE (Table 3). The other programs are used individually by the rest of the articles as needed. Notably, these simulation programs are often used in combination with 3D modelling software (e.g., BIM, Blender, Rhino, and SketchUp (Xue et al., 2016; Watfa et al., 2021; Miller et al., 2014; Maciel and Carvalho, 2019; Rais et al., 2021; Singh et al., 2015; Mercader-Moyano et al., 2021; Bogdanovic et al., 2018)), among which the BIM software is the most common (Shou et al., 2015; DesignBuilder Software Ltd).

The advantage of the simulation-based method is: it can obtain a large amount of dynamic and virtual energy consumption data (close to the real) and various visualised energy performance analysis automatically in a relatively short period (Nguyen et al., 2014). Thus, the energy-efficiency of façade designs (regardless of overall façade design or partial adjustments) can be verified timely. As such, considerable time and cost can be saved compared with the studies based on real constructing, which can facilitate in-depth exploration of parameters. However, the disadvantages are sophisticated training requirements, high skill and expertise demands, time-consuming operation, and ill-adapted nature, etc. (Chen et al., 2020; Nguyen et al., 2014; Attia et al., 2013; Tian et al., 2018). Therefore, it is too difficult for simulation

Table 3
The employed computer simulation programs and the number of corresponding papers.

Simulation programs	Number of corresponding papers
EnergyPlus (in DesignBuilder) (Li et al., 2021; Tong et al., 2021; Vijay Kumar et al., 2020; Miller et al., 2014; Reyes-Barajas et al., 2021; Altan et al., 2015; Hachem-Vermette, 2018; Foroughi et al., 2021; Santamaría et al., 2016a; Santamarí et al., 2016b; Afonso, 2020; Capeluto and Ochoa, 2014; Khalil et al., 2018; Fernandez-Antolin et al., 2019; Liu et al., 2019; Sari and Chiou, 2019; Pacheco-Torres et al., 2015; Ramadan, 2020; Bogdanovic et al., 2018; Konstantinou, 2015)	21
eQuest (Yimprayoon et al., 2017; Nicholson et al., 2019)	2
IES-VE (Shen et al., 2016; Zhang et al., 2015)	2
Combination of Daysim and EnergyPlus (Xue et al., 2016)	1
DaySim (Acosta et al., 2016)	1
AECOsim (Watfa et al., 2021)	1
TRNSYS (Webb, 2021)	1
VI-suite (Rais et al., 2021)	1
HAP 4.9 (Hassan, 2020)	1
WUFI 6.1 (Paiho et al., 2019)	1
LIDER/CALENER Unified Tool (HULC) (Mercader-Moyano et al., 2021)	1
CFD (Computational Fluid Dynamics) (Guerrero Delgado et al., 2020)	1
Green Building Studio (GBS) (Maciel and Carvalho, 2019)	1
TECTITE Express software (León-Rodríguez et al., 2017)	1
Simulation in BIM (SMC, SUN2014, OVen2014, DALI2014) (Han et al., 2016)	1
DIVA for daylight analysis (Singh et al., 2015)	1
Thermal Analysis Simulation (TAS) (Siddiq, 2014)	1
IDA Indoor Climate and Energy (IDA ICE) and CENED PLUS (Sesana et al., 2011)	1
ENORM v1.11 (a Dutch software) (Loussos et al., 2015)	1
Teplo (a Czech software) (Kubečková and Vrbová, 2021)	1
Total	42

studies with large-scale buildings and researchers with little knowledge and skills in simulation programs (Chen et al., 2020; Nguyen et al., 2014).

5.1.3.1.2. *Derivative-based method.* The derivative-based method categorised in this study means that the quantitative data is mainly obtained by different data sources through certain types of transformation, such as an arithmetic formula or numerical calculation software (Albertson). Different from the simulation-based method, the derivative-based method can reflect the energy performance of certain façade designs based on the pre-set rules and computing results, rather than relying on the simulation of energy consumption. 7 papers of the 59 (occupying 12%) have used the derivative-based method, making this method the second largest adoption (Fig. 7).

The derivative-based method refers to a kind of numerical study (Špegelj et al., 2016), by which the numerical relationships between façade parameters and energy demand for indoor comforts are investigated. The relationships can be presented as arithmetic formulas or computed by the numerical analysis software. The purpose is to obtain the optimal parameters of façade elements or systems to achieve the minimum energy demand for indoor comforts. For example, Chen et al. (2020) developed a numerical-based method using a series of arithmetic formulas and a set of rules to study the optimization of façade window design. In that study, much raw data, factors, values, or constraints were obtained from the Australian National Construction Code (NCC) (Chen et al., 2020; Australian Building Codes Board (ABCB), 2019). Moreover, some other studies (Š et al., 2016; Kravanja et al., 2019; Špegelj et al., 2017) use a numerical analysis software PHPP to investigate the development and optimization of timber-glass upgrade modules, where the calculation method and data were based on EN ISO 13790: 2008 (Špegelj et al., 2017;:2008(en), Energy performance of buildings; 2008 (en), Energy performance of buildings).

The major advantage of the derivative-based method is the time and cost saving for raw data collection. Since there are many reliable data resources available (e.g., national, or regional design, construction, or energy code, etc.) (Chen et al., 2020; Australian Building Codes Board (ABCB), 2019; :2008(en), Energy performance of buildings; 2008(en), Energy performance of buildings), researchers are not necessarily to spend as much time as operating simulation programs to obtain the quantitative energy data. Hence, the application of this method is scalable and flexible in terms of the studied building sizes (either large-scale or small size, or even detailed elements). However, the disadvantage is the requirement of mathematical skills, as the complexity of numerical relationships will increase with more façade elements involved. If numerical analysis software is needed to lower the reliance on maths skills, then the software knowledge becomes another requirement, which is also unfriendly for those who have few relevant skills.

5.1.3.1.3. *Experiment-based method.* The experiment-based method is also used in 7 publications (Fig. 7). Research data in the experiment-based method is mainly obtained by conducting field or laboratory experiments (Aziz, 2017; Pisello et al., 2014). This research method primarily aims to collect real data on the energy performance of new building materials, systems, designs, or construction methods, etc. to demonstrate their energy efficiency. For example, Wang et al. (2021) conducted laboratory experiments to investigate the energy performance of mineralized supramolecular hydrogel to demonstrate the application potential in thermo-responsive smart windows. Ahmed et al. (2016) carried out field experiments to test the thermal performance of a residential building with an adaptive kinetic shading system installed thereby proving the system's energy-efficiency.

The most favourable advantage of the experiment-based research method is the data authenticity, which can provide powerful evidence of the real energy-efficiency of the proposals. Thus, this research method is suitable to validate the energy-efficiency of innovative façade materials, designs, systems, or construction methods applied in specific regions or under specific climate conditions. However, the many limitations of this research method restrict the broader application, including time, cost, man-power consuming, fields or laboratories requirements, relatively small data size, and limitation of locality, etc. Therefore, the experiment-based method may not be suitable for the energy-efficiency study of the overall façade or large-scale buildings' façade design.

5.1.3.1.4. *Observation-based method.* The observation-based method means that the research data is collected through the observation of research objects by either human observations, surveys or devices (Albertson). In this research field, the observation-based method mainly aims to observe and capture the energy performance data of the existing designs, constructions, systems, etc. to prove their energy-efficiency. This research method has been employed by only 2 papers out of the 59 (Fig. 7), including (Ainurzaman Jamaludin et al., 2013; Drișcu, 2014).

The same as the experiment-based method, the biggest superiority of the observation-based method is data authenticity. In addition, because of the main concerns on the existing objects, the cost of time, money, and manpower for designing or conducting experiments can be saved. Thus, the observation-based research method is suitable for the energy-efficiency study of existing façade designs, systems, construction methods, etc. However, due to the limitation of focusing on the existing, this research method may not be suitable for the studies of new or innovative façade materials or designs. Additionally, this method is time-consuming for observation and small in data size, which may prevent the applicability of studies on large-scale building façade design.

5.1.3.1.5. *Combined method.* The combined method in this paper means that the quantitative data for one study is obtained by more than one method mentioned above. There is only one publication from the 59 that used the combined method (Fig. 7), in which the parametric data were mainly collected by the simulation-based, observation-based, and derivative-based method to form the database for developing an expert system software (Ochoa and Capeluto, 2015).

The combined method is much more complicated than the other methods because multiple data collection means need to be integrated, which results in more time, cost, and manpower consumption. That might be the reason why this method has been rarely used. However, the combined method can integrate diverse data for more complex, sophisticated, and systematic research, making this method suitable for EFDRB studies on large-scale buildings as well as expert systems or software development.

5.1.3.1.6. Comparison. Accordingly, we propose a table (Table 4) to present the advantages, disadvantages, applicability, and inapplicability of the above methods to facilitate comparison and selection by researchers. The simulation-based method is currently the most accepted method and suitable for many types of energy-efficient façade design research thanks to the various advantages, especially the automatic and dynamic obtaining of numerous close-to-real virtual energy consumption data. However, due to the skill threshold, time-consuming operation, and ill-adapted nature, the simulation-based method may not be a good option for studies of large-scale building façade design and researchers with few skills in simulation programs. Thus, more methods have been developed and employed by researchers.

Each of the other methods has its characteristics and suitability respectively. For example, the experiment-based method is suitable for the energy-efficient research of innovative or new façade materials, designs, systems, or construction methods, while the observation-based method fits for the studies of existing materials, etc. If expert systems or software need to be developed, then the combination method could be an appropriate recommendation. It is worth noting that the derivative-based method can be quite flexible and scalable and fit for diverse types of design research, as it is mainly based on existing data sources rather than extensive simulations, experiments, or observations. As such, we believe that the derivative-based methods expect to be used increasingly with a growing number of reliable databases being established and available.

5.1.3.2. Cost-related quantitative research methods. The discussion of the cost-related research methods provides an overview of the current application. There are 10 publications out of the 59 that have used specific quantitative methods to conduct economic or cost studies. 9 papers among them have used different dedicated business models based on various indicators such as the Net Present Value (NPV), Rate of Return (IRR), Dynamic Payback Period (DPP), or Initial Cost Index (ICI) etc. to evaluate the investment feasibility of the specific energy-efficient façade elements or systems (Ochoa and Capeluto, 2015; Reyes-Barajas et al., 2021; Santamaría et al., 2016a, Santamaría et al., 2016b; Drişcu, 2014; Haggag et al., 2017; Maciel and Carvalho, 2019; Shen et al., 2016; Zhang et al., 2015). The purposes are to demonstrate the long-term economic benefit of the specific façades in terms of reducing energy billing despite the initial investment is high. The other 1 publication has employed genetic algorithms and material costs to optimise the construction cost of building the proposed energy-efficient ventilated façade (Kalinović et al., 2021). Thus, scholars and practitioners in this field are suggested to select appropriate cost-related methods in their studies taking the above as a reference.

5.1.4. Design strategies: energy reduction or generation

In design research, the design strategy is an unignorable topic because it is a necessary way to realise designs. This discussion is to critically understand the types, characteristics, and applications of design strategies in existing studies, to propose more energy-efficient strategic suggestions.

5.1.4.1. Passive design or active design: energy reduction or generation. The popular classifications of design strategies for energy-efficient

Table 4
Comparison among the major types of specific quantitative methods for design-related research.

Specific research methods	Advantages	Disadvantages	Applicable for energy-efficient research of	Inapplicable for energy-efficient research of
Simulation-based method	· Automatically and dynamically obtain a large amount of virtual energy consumption data (close to the real) · Quickly analyse various energy performance · Intuitive visualisation analysis · Cost and manpower saving	· Sophisticated training requirement · High skill and expertise demand · Time-consuming program operation · Ill-adapted nature	· Overall façade design · Partial façade design · Façade elements design · Façade systems design	· Large-scale building's façade design · Researchers with little skills and knowledge in simulation programs
Derivative-based method	· Time and cost saving in raw data collection · Many reliable data resources are available · Large applicable scalability	· Mathematical skills requirement Or · Numerical analysis software skills requirement	· Overall façade design · Partial façade design · Façade elements design · Façade systems design · Large- or small-scale building's façade design	· Researchers with little maths skills Or · Researchers with little numerical analysis software skills
Experiment-based method	· Data authenticity · Provide powerful evidence of proposals' real energy-efficiency	· Time, cost, and manpower consuming · Fields or laboratories requirements · Relatively small data size · Limitation of locality	· Innovative and detailed façade materials, designs, systems, construction methods, etc.	· Overall façade design · Large-scale building's façade design
Observation-based method	· Data authenticity · Cost and manpower savings due to no experiments	· Limitations of focusing on existing façade designs, systems, etc. · Time-consuming on data collection · Relatively small data size	· Existing façade designs, systems, construction methods, etc.	· Innovative or new façade designs, systems, construction methods, etc. · Large-scale buildings' façade design · Overall façade design
Combine method	· Diverse types of data collection · Provide sophisticated database	· Complicated data collection means · Time, cost, and manpower consuming	· Large-scale buildings' façade design · Overall façade design · Façade	· Small-scale buildings' façade design · Partial façade design · Studies

(*continued on next page*)

Table 4 (*continued*)

Specific research methods	Advantages	Disadvantages	Applicable for energy-efficient research of	Inapplicable for energy-efficient research of
			design expert system or software development	with tight time frame

building design are passive design strategies and active design strategies. According to many studies (Rodriguez-Ubinas et al., 2014; Spacey, 2016; Sustainable), passive design strategies make use of natural resources such as sunlight, wind, gravity etc. to achieve indoor comforts without the need to purchase or use energy. Active design strategies use purchased energy or on-site generated energy to run equipment or systems (e.g., air-conditioning, heat pumps, etc.) to keep indoor comforts. Table 5 indicates the definitions, common examples, as well as pros and cons of these two design strategies (Rodriguez-Ubinas et al., 2014; Spacey, 2016; Sustainable; Ochoa and Capeluto, 2008). Thus, from the perspective of energy saving, the passive design strategies and certain active design strategies (e.g., energy-efficient equipment) are to reduce energy consumption. Some other active design strategies such as solar panels or BIPV are to generate on-site energy to offset partial, or ideally, the entire energy use, to ultimately reach the energy-saving effect.

5.1.4.2. Current application and prospection of design strategies. As shown in Fig. 8, the passive design strategies are used in 48 papers out of 62, making up the largest proportion, 78%. The active design strategies are employed in 7 papers (11%), while the other 7 publications (also 11%) apply the combination strategies. Research requirements that only employ passive design strategies are relatively simple, as they do not involve complex electrical utilities, which may be the reason for their widespread adoption. As analysed above, the current domination of passive strategies illustrates the "very low energy demand and consumption" being the priority when conducting an energy-efficient façade design (Rodriguez-Ubinas et al., 2014; Aksoy and Inalli, 2006). This also indicates an academic preference for maximising the use of natural conditions in energy-efficient façade design studies, which is beneficial for the detailed exploration of various passive design means.

Table 5
Definitions, examples, and pros and cons of passive design strategies and active design strategies.

	Passive design strategies	Active design strategies
Definition	Use natural resources such as sunlight, wind, gravity etc. to achieve indoor comforts without the necessary to purchase or use energy.	Use purchased energy or on-site generated energy (e.g., generated by solar panels, wind turbines, etc.) to run equipment or systems to keep indoor comforts.
Examples	Envelope (e.g., external wall, external window, roof, etc.) Orientation Geometric Hybrid solutions Shading solutions Rain garden Recycle materials Natural cross-ventilation, etc.	Solar panel BIPV Wind turbines District heating Deep water cooling Air-conditioning Lighting Heat recovery ventilation (HRV) Drain water heat recovery (DWHR), etc.
Advantages	Free of operational energy and cost Easy maintenance Environment friendly	On-site energy generation (solar panel) High improvement of indoor comforts Precise control of indoor environment
Disadvantages	Limited improvement of indoor comforts Inaccurate indoor environment control No on-site energy generation	High equipment cost High operational energy and cost High maintenance requirement Complex installation Environmental impact

However, it is impossible to achieve lower or even net zero energy consumption (Rodriguez-Ubinas et al., 2014) with only passive designs if equipment (e.g., Air-conditioning systems for heating or cooling) were still needed for indoor comforts. As indicated in Table 5, the solo application of passive design strategies will have limited improvement of indoor comforts and inaccurate control of indoor climate. Thus, the homogeneous adoption of passive strategies may restrict the pursuit of higher indoor comforts and higher energy-saving goals. In this case, proper active designs can be important supplementary strategies because the integration of solar facilities can generate on-site energy thereby offsetting energy use. Correspondingly, the research complexity will increase significantly, which may explain why active strategies or combination strategies are less applied at present. Nonetheless, we believe that increasing active design strategies will be employed in conjunction with passive designs with the advancement of active technologies (e.g., solar panels or BIPV etc.) to achieve the net zero energy target (Rodriguez-Ubinas et al., 2014).

5.2. *Ontological discussion*

In the ontological discussion, we propose a domain knowledge map (Fig. 10) of the current EFDRB study according to the analysis and discussion above to organise and present the relevant knowledge structurally. This deliberation aims to clarify the current outline and system of the field from a macro perspective, succinctly summarise the research contents, characteristics, internal connections, and development levels, and finally puts forward the prospect. Accordingly, researchers and professionals in this field can identify research focus, position their research, and determine proper research methods and design strategies in their studies.

As shown in Fig. 10, the knowledge map consists of five major components, including the Research Aim, Design Strategies, Research Topics, Research objectives, and Research methods. Contents marked with darker grey are currently the research majorities based on the above statistical analysis, indicating the current academic preference and focus.

Specifically, the essential aim of the EFDRB study is to assist the design of residential façades accurately and efficiently to energy-efficiently achieve various indoor comforts and other objectives. To support the research, multiple design strategies, especially various passive designs have been investigated and applied. To realise the essential aim, two major topics have been conducted, which are the fundamental and innovative research topics. The fundamental research topic looks into the *Investigation or optimization of residential façade elements or systems*, which is the major topic currently. The innovative research topic focuses on the *Development or demonstration of design methods and tools*, which has great potential. To fulfil these topics, single-objective and multi-objective studies have been carried out, of which the single-objective study is currently dominating the research. The main feature of a single-objective study is to explore parameter bounders to achieve a certain type of indoor comfort with less energy consumption by proper façade designs. Among them, investigations to meet thermal comfort energy-efficiently have received the most academic attention. To support the objectives, quantitative research methods, especially the simulation-based method has been primarily used to accomplish the design-related research, while various dedicated business models are mainly employed for cost-related research.

The lighter greys in the map have a lower percentage of the research so far, but that does not mean they are less important. Instead, some of them have great potential and are considered future directions. As the growing and maturing of the current research majorities, it will provide and strengthen the research basis for other studies marked in a lighter

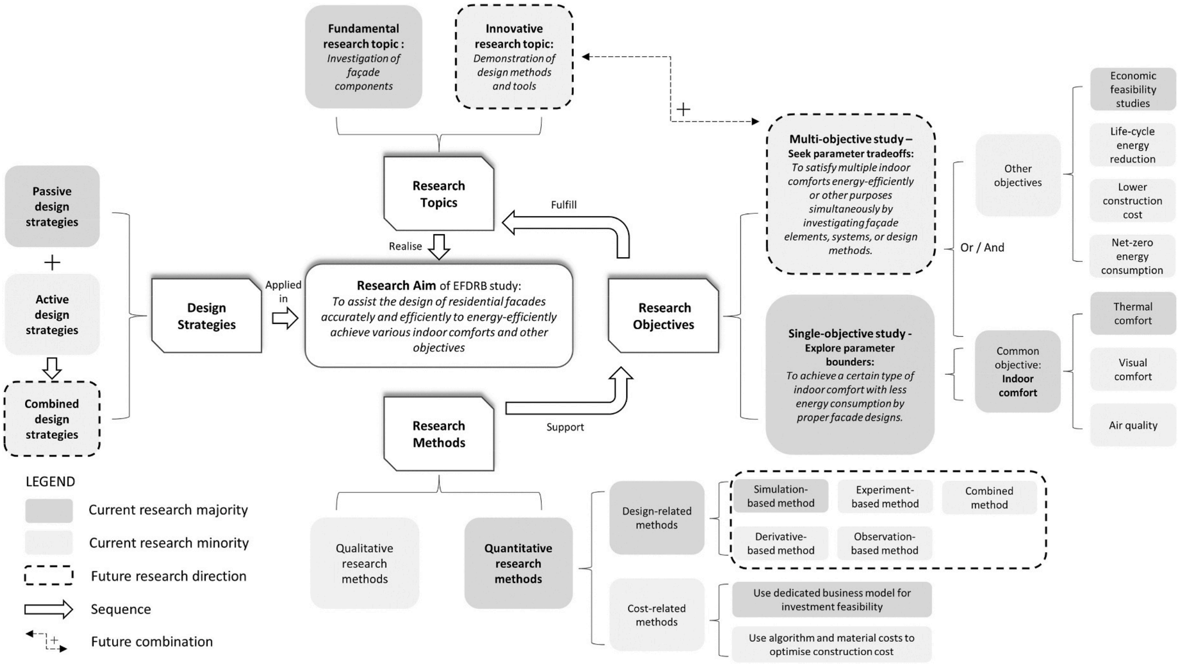


Fig. 10. The domain knowledge map of the current EFDRB study.

grey. Therefore, in addition to expressing the current focuses of the field, this knowledge map also includes the research prospects. The following section will discuss them accordingly.

6. Insights into future directions

In this review, we analyse and discuss the existing literature regarding the EFDRB study from four major themes including research topics, research objectives, research methods, and design strategies. Accordingly, we have clarified the concepts, profile, contents, features, and relationships of the field, and discussed the strengths and shortcomings. Correspondingly, we now propose insights into future directions.

6.1. Application of advanced technologies to achieve multiple objectives

Although the fundamental topic and single-objective studies have explored façade elements in detail and in-depth, they lack synthesis or practicality to guide the actual designs due to the relatively simple research requirements and uncomplicated constraints. On the contrary, the innovative topic and multi-objective studies are more constructive and practical in assisting the actual designs because of the innovative methods and intricate constraints considerations. Thus, we infer that the innovative research topic and multi-objective studies are expected to prosper as designing is a more practical activity intrinsically. Moreover, parameter data is growing as the result of fundamental and single-objective research development, which can form an extensive database to facilitate innovative and multi-objective studies. Therefore, it is foreseeable that innovative topics to achieve multiple objectives will be investigated increasingly in the future.

It is worth noting that the application of advanced technologies in innovative and multi-objective studies is a trend, such as artificial intelligence or building information technologies (Wang et al., 2022). Generally, artificial intelligence (AI) refers to the development of computer systems mimicking human intelligence for tasks requiring cognitive capabilities, using algorithms, machine learning, and other techniques (Kok et al., 2002). In EFDBR research, AI has been applied to optimise design options through algorithms and computations under certain pre-set conditions to assist designers in making decisions more efficiently. Two paper of the reviewed 62 publications have used AI (specifically, the genetic algorithm) to find optimal design solutions for achieving energy-efficiency (Chen et al., 2020; Kalinović et al., 2021). Both studies were published recently (2020 and 2021 respectively), which indicates a future trend of adopting AI in the innovative EFDRB research.

The BIM technology has been employed in multiple studies of the reviewed 62 publications (Watfa et al., 2021; Miller et al., 2014; Chen et al., 2020; Han et al., 2016), taking advantage of its powerful parametric features and program extensibility to facilitate research. Moreover, many other features and advantages of BIM (e.g. compatibility, scalability, or secondary development allowability) can be further utilised in creating innovative design methods or tools (Wang et al., 2013; Wu et al., 2016; Song et al., 2017). For instance, users can use the API or plug-in features in BIM (e.g. Generative Design in Revit) to develop various customised design programs for specific design tasks (Ma et al., 2021; Pantazis and Gerber, 2018; Lim et al., 2018). A notable finding is the combination of BIM and AI, such as (Chen et al., 2020), in which the genetic algorithm was employed in a BIM software for design optimisations. The integration combines the advantages of both technologies, which can improve the parameterization and constructability of the AI-generated design solutions, while enhance the capabilities of BIM in the early design stages (Ma et al., 2021). Therefore, advanced technologies such as BIM and AI will play an increasing role in innovative and multi-objective studies henceforth, although this combination has been rarely applied so far.

6.2. Diversification of quantitative research methods to enhance flexibility and adaptability

More diverse quantitative research methods are suggested to be adopted increasingly to accommodate a wider variety of EFDRB studies. At present, there are several commonly used quantitative methods, but the simulation-based method (especially based on EnergyPlus as Table 3) predominates, which may cause homogeneity. Indeed, the simulation-based method is suitable for many types of studies thanks to its various advantages (Table 4). However, the obvious disadvantages (e.g., skill threshold, time-consuming operation, and ill-adapted nature) may affect its adaptability and prevent wider application. For example, the simulation-based method is not a good option for EFDRB studies on large-scale buildings or for researchers with few simulation program skills. Thus, more diverse quantitative research methods are supposed be developed and applied to enhance methodological flexibility and adaptability.

Other quantitative methods (e.g., derived-based method, experiment-based method, observation-based method, etc.) were also found in the few reviewed publications. Despite the current less adoption, some of these methods offer advantages over simulation-based methods in some respects (Table 4). For example, the derive-based method is quite flexible and scalable and fit many types of design research, as it is mainly based on the existing data sources rather than extensive simulations, experiments, or observations. Also, it can work well with simulation-based method complimenting one another to facilitate broader studies. Thus, we infer that with growing reliable databases being available worldwide (e.g., Energy data - 2020 edition in EU (European Commission, 2020), ASHRAE RP-1365 (Roppel et al., 2011) and ResStock (Wilson, 2017) in North America, and NCC in Australia (Australian Building Codes Board (ABCB), 2019), etc.), the derivative-based method will be increasingly developed and used onward, especially for studies requiring extensive consideration of regional or local regulations. A study (Chen et al., 2020) in which a numerical-based optimizsation method was developed using data drawn from national provisions provided a good example.

6.3. *Integration of active designs with passive designs to reach higher energy-saving goals*

Another research direction, we suggest, is to increasingly integrate passive and active design strategies in future EFDRB research to achieve higher energy-saving (or even net-zero) targets (Rodriguez-Ubinas et al., 2014). According to the discussion above, the application of passive strategies alone may restrict higher energy saving, if equipment (e.g., HVAC systems for heating or cooling) are still required to maintain indoor comforts. In this case, incorporating proper active designs can be an important supplementary strategy because the integration of solar facilities can generate on-site energy to offset external energy supply (Table 5). Although the research complexity may rise, the long-term benefit is significant. Thence, we believe that more integrations of active and passive design strategies will be studied inevitably and increasingly to meet the ultimate goal of net-zero energy consumption (Rodriguez-Ubinas et al., 2014).

Notably, leveraging high technologies into façade systems to enhance solar intervention and usage as an active design strategy has been studied in several reviewed paper and is expected to be an important future focus. For instance, BIPV façade systems were investigated in four paper to discuss the impact on improving energy performance (Strebkov and Filippchenkova, 2020; Hachem-Vermette, 2018; Hachem et al., 2014; Foroughi et al., 2021). Among which, an interactive shading system integrating with photovoltaic panels (i.e., BIPV) was designed to not only generate energy on-site but also blind unwanted solar (Foroughi et al., 2021). Moreover, the BIPV panels can be applied directly on façades as a type of decoration. Thus, integrating active strategies such as BIPV technologies with passive designs are believed to become increasingly popular and will attract more academic and industrial attention (Yang and Zou, 2016; Aguacil et al., 2019).

7. Conclusion

The EFDRB research has drawn increasing academic interest and the current studies are in-depth but mainly focus on the micro level. Moreover, the existing studies cover diverse fields and thus appear to be fragmented, dispersed, and systematic indistinction. This presents a state of contradiction between the importance and systematicity of the EFDRB research, which limits holistic cognition and prospection. Therefore, relevant knowledge needs to be organised structurally to form an integral research picture to understand the development status, inner relationships, and future trends of the field. To this end, this paper conducts an analytical literature review, by carefully selecting 62 highly relevant papers published in the past decade. Based on the dataset, descriptive analysis is conducted to reveal the growing, extensive, but dispersed research status quo. Afterwards, we carry out the thematic analysis and discussion quantitatively on four themes including research topics, research objectives, research methods, and design strategies to understand the profile, contents, and features of the field critically. Correspondingly, an ontological discussion of the EFDRB research with an explicative domain knowledge map is proposed (Fig. 10).

Findings reveal that the essential aim of EFDRB study: to assist the design of residential façades accurately and efficiently to energy-efficiently achieve various indoor comforts and other objectives. To support the research, multiple design strategies, especially various passive designs have been investigated and applied. To realise the essential aim, two major topics have been conducted, e.g., fundamental, and innovative research topics. The fundamental research topic looks into the *Investigation or optimization of residential façade elements or systems*, which is the major topic currently. The innovative research topic focuses on the *Development or demonstration of design methods and tools*, which has great potential. To fulfil these topics, single-objective and multi-objective studies have been carried out, of which the single-objective study is currently dominating. The main feature of a single-objective study is to explore parameter bounders to achieve a certain type of indoor comfort with less energy consumption by proper façade designs. Among them, investigations to meet thermal comfort energy-efficiently have received the most academic attention. To support the objectives, quantitative research methods are mainly used: the simulation-based method and dedicated business models are mostly adopted for design-related and cost-related studies respectively.

Finally, insights into future directions are suggested accordingly, including: (1) Application of advanced technologies to achieve multiple objectives; (2) Diversification of quantitative research methods to enhance flexibility and adaptability; (3) Integration of active designs with passive designs to reach higher energy-saving goals. To sum up, this research could ultimately assist researchers or practitioners to have a holistic understanding of the field, then position their research and determine directions, methods, or design strategies appropriately.

CRediT authorship contribution statement

Wei Ma: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Validation, Writing – original draft, Writing – review & editing. **Xiangyu Wang:** Project administration, Supervision, Writing – review & editing. **Wenchi Shou:** Writing – review & editing. **Jun Wang:** Supervision.

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.

Data availability

Data will be made available on request.

Acknowledgements

This research was supported by an Australian Government Research Training Program (RTP) Scholarship. I would like to extend my sincere thanks to Dr. Yongze Song for his valuable advising and discussion.

References

13790:2008(en), Energy performance of buildings— calculation of energy use for space heating and cooling. International Organization for Standardization. Accessed: February. 11, 2022. [Online]. Available: https://www.iso.org/cms/render/live/en/sites/isoorg/contents/data/standard/04/19/41974.html.

Acosta, I., Campano, M.Á., Molina, J.F., 2016. Window design in architecture: analysis of energy savings for lighting and visual comfort in residential spaces. Appl. Energy 168, 493–506. https://doi.org/10.1016/j.apenergy.2016.02.005.

Aflaki, A., Mahyuddin, N., Al-Cheikh Mahmoud, Z., Baharum, M.R., 2015. A review on natural ventilation applications through building façade components and ventilation openings in tropical climates. Energy Build. 101, 153–162. https://doi.org/10.1016/j.enbuild.2015.04.033.

Afonso, F., 2020. Potential for the design of an energy saving facade system using agglomerated cork: implications in subtropical climates. In: Sustainable Buildings and Structures: Building a Sustainable Tomorrow - Proceedings of the 2nd International Conference in Sustainable Buildings and Structures, ICSBS 2019. SUZHOU, pp. 185–191. https://doi.org/10.1201/9781003000716-24.

Aguacil, S., Lufkin, S., Rey, E., 2019. Active surfaces selection method for building-integrated photovoltaics (BIPV) in renovation projects based on self-consumption and self-sufficiency. Energy Build. 193, 15–28. https://doi.org/10.1016/j.enbuild.2019.03.035.

Ahmed, M.M.S., Abdel-Rahman, A.K., Bady, M., Mahrous, E., 2016. The thermal performance of residential building integrated with adaptive kinetic shading system. Int. Energy J. 16 (3) [Online]. Available: http://rericjournal.ait.ac.th/index.php/reric/article/view/1452. (Accessed 4 January 2022).

Ainurzaman Jamaludin, A., Zalina Mahmood, N., Keumala, N., Rosemary Mohd Ariffin, A., Hussein, H., 2013. Energy audit and prospective energy conservation: studies at residential college buildings in a tropical region. Facilities 31 (3/4), 158–173. https://doi.org/10.1108/02632771311299430.

Aksamija, A., 2013. Sustainable Facades: Design Methods for High-Performance Building Envelopes. New York, UNITED STATES. John Wiley & Sons, Incorporated [Online]. Available: http://ebookcentral.proquest.com/lib/curtin/detail.action?docID=1161961. (Accessed 18 July 2022).

Aksamija, A., 2015. High-performance building envelopes: design methods for energy efficient facades. In: *Building Enclosure Science And Technology (BEST)*, Kansas City, MO: National Institute of Buildings Sciences, p. 15.

Aksamija, A., 2016. Design methods for sustainable, high-performance building facades. Adv. Build. Energy Res. 10 (2), 240–262. https://doi.org/10.1080/17512549.2015.1083885.

Aksoy, U.T., Inalli, M., 2006. Impacts of some building passive design parameters on heating demand for a cold region. Build. Environ. 41 (12), 1742–1754. https://doi.org/10.1016/j.buildenv.2005.07.011.

Al-Azzawi, T., Al-Majidi, Z., 2021. Parametric architecture: the second international style. In: *IOP Conference Series: Materials Science and Engineering,* Kerbala, Iraq, 012019. https://doi.org/10.1088/1757-899X/1067/1/012019.

A. Albertson, 'All Guides: Data Module #1: What is Research Data?: Types of Research Data'. https://libguides.macalester.edu/c.php?g=527786&p=3608643 (accessed Feb. 08, 2022).

Altan, H., Mohelnikova, J., Hofman, P., 2015. Thermal and daylight evaluation of building zones. Energy Proc. 78, 2784–2789. https://doi.org/10.1016/j.egypro.2015.11.626.

Ascione, F., De Masi, R.F., Mastellone, M., Ruggiero, S., Vanoli, G.P., 2022. Improving the building stock sustainability in European Countries: a focus on the Italian case. J. Clean. Prod. 365, 132699 https://doi.org/10.1016/j.jclepro.2022.132699.

Attia, S., Hamdy, M., O'Brien, W., Carlucci, S., 2013. Computational optimisation for zero energy buildings design: interviews results with twenty eight international experts. In: In Proceedings the 13th Conference of International Building Performance Simulation Association, p. 8. Chambery, France.

Australian Building Codes Board (ABCB), 2019. Australia, 2019. National Construction Code Volume Two, Building Code of Australia, 2 [Online]. Available: https://ncc.abcb.gov.au/. (Accessed 14 July 2022).

Australian Government Department of Climate Change, 2022. Energy, the Environment and Water, 'Australian Energy Update 2022', Canberra [Online]. Available: https://www.energy.gov.au/publications/australian-energy-update-2022. (Accessed 20 April 2023).

Aziz, H.A., 2017. Comparison between field research and controlled laboratory research. Arch Clin Biomed Res 1 (2), 101–104. https://doi.org/10.26502/acbr.50170011.

Bogdanovic, V., Randjelovic, D., Vasov, M., Ignjatovic, M., Stevanovic, J., 2018. Improving thermal stability and reduction of energy consumption by implementing Trombe wall construction in the process of building design: the Serbia region. Therm. Sci. 22 (6 Part A), 2355–2365. https://doi.org/10.2298/TSCI180308167B.

Capeluto, I.G., Ochoa, C.E., 2014. Simulation-based method to determine climatic energy strategies of an adaptable building retrofit façade system. Energy 76, 375–384. https://doi.org/10.1016/j.energy.2014.08.028.

Chen, S.-Y., Chu, C.-Y., Cheng, M., Lin, C.-Y., 2009. The autonomous house: a bio-hydrogen based energy self-sufficient approach. Int. J. Environ. Res. Publ. Health 6 (4). https://doi.org/10.3390/ijerph6041515.

Chen, Z., Hammad, A.W.A., Kamardeen, I., Haddad, A., 2020. Optimising window design on residential building facades by considering heat transfer and natural lighting in nontropical regions of Australia. Buildings 10 (11). https://doi.org/10.3390/buildings10110206.

Colombo, I.G., Colombo, M., di Prisco, M., 2015. TRC precast façade SANDWICH panel for energy retrofitting of existing buildings. In: 1st International Workshop on Durability and Sustainability of Concrete Structures, DSCS 2015, Bologna: American Concrete Institute. ACI Special Publication, pp. 30.1–30.10. Jan. 04, 2022. [Online]. Available: https://www.concrete.org/publications/internationalconcreteabstractsportal/m/details/id/51688590.

Drişcu, M.C., 2014. "Renaissance" complex-behind the green building idea - design and technology. In: *14th International Multidisciplinary Scientific Geoconference And EXPO, SGEM 2014*, Albena, pp. 3–10. https://doi.org/10.5593/sgem2014B62.

European Commission, 2020. Statistical office of the European union. Energy Balance Sheets, 2020 edition. Publications Office, LU [Online]. Available: https://data.europa.eu/doi/10.2785/68334. (Accessed 20 April 2023).

Fernandez-Antolin, M.M., del-Río, J.-M., Gonzalez-Lezcano, R.-A., 2019. Influence of solar reflectance and renewable energies on residential heating and cooling demand in sustainable architecture: a case study in different climate zones in Spain considering their urban contexts. Sustainability 11 (23). https://doi.org/10.3390/su11236782.

Foroughi, R., Mc Neil, L., Khazaeli, S., 2021. Designing an interactive and energy efficient building facade using photo voltaic panels. Int. J. Architecton. Spatial, Environ. Des. 15 (1), 71–83. https://doi.org/10.18848/2325-1662/CGP/v15i01/71-83.

Gorantla, K.K., Shaik, S., Puttaranga Settee, A.B.T., 2016. Simulation of various wall and window glass material for energy efficient building design. KEM 692, 9–16. https://doi.org/10.4028/www.scientific.net/KEM.692.9.

Guerrero Delgado, Mc, Sánchez Ramos, J., Álvarez Domínguez, S., Tenorio Ríos, J.A., Cabeza, L.F., 2020. Building thermal storage technology: compensating renewable energy fluctuations. J. Energy Storage 27, 101147. https://doi.org/10.1016/j.est.2019.101147.

Hachem, C., Athienitis, A., Fazio, P., 2014. Energy performance enhancement in multistory residential buildings. Appl. Energy 116, 9–19. https://doi.org/10.1016/j.apenergy.2013.11.018.

Hachem-Vermette, C., 2018. Multistory building envelope: creative design and enhanced performance. Sol. Energy 159, 710–721. https://doi.org/10.1016/j.solener.2017.11.012.

Haggag, M., Hassan, A., Qadir, G., 2017. Energy and economic performance of plant-shaded building façade in hot arid climate. Sustainability 9 (11). https://doi.org/10.3390/su9112026. Art. no. 11.

Halawa, E., et al., 2018. A review on energy conscious designs of building façades in hot and humid climates: lessons for (and from) Kuala Lumpur and Darwin. Renew. Sustain. Energy Rev. 82, 2147–2161. https://doi.org/10.1016/j.rser.2017.08.061.

Han, R., Gao, Y., Shao, D., 2016. Research on the application of building information model technology in the design of urban residential buildings in cold region. IJSH 10 (5), 183–194. https://doi.org/10.14257/ijsh.2016.10.5.17.

Hassan, S.A., 2020. The effect of residential building façade design on energy consumption for hot desert climate. IOP Conf. Ser. Mater. Sci. Eng. 928 (2), 022029 https://doi.org/10.1088/1757-899X/928/2/022029.

Ionescu, C., Baracu, T., Vlad, G.-E., Necula, H., Badea, A., 2015. The historical evolution of the energy efficient buildings. Renew. Sustain. Energy Rev. 49, 243–253. https://doi.org/10.1016/j.rser.2015.04.062.

Jones, G., Bouamane, L., 2012. "Power from sunshine": a business history of solar energy. Harvard Business School Working Paper [Online]. Available: https://core.ac.uk/download/pdf/28939802.pdf.

Kalinović, S.M., Tanikić, D.I., Djoković, J.M., Nikolić, R.R., Hadzima, B., Ulewicz, R., 2021. Optimal solution for an energy efficient construction of a ventilated façade obtained by a genetic algorithm. Energies 14 (11). https://doi.org/10.3390/en14113293.

Khalil, A.-A., Fikry, M., Abdeaal, W., 2018. High technology or low technology for buildings envelopes in residential buildings in Egypt. Alex. Eng. J. 57 (4), 3779–3792. https://doi.org/10.1016/j.aej.2018.11.001.

Kheiri, F., 2018. A review on optimization methods applied in energy-efficient building geometry and envelope design. Renew. Sustain. Energy Rev. 92, 897–920. https://doi.org/10.1016/j.rser.2018.04.080.

Kok, J.N., Boers, E.J.W., Kosters, W.A., van der Putten, P., 2002. Artificial intelligence: definition, trends, techniques and cases. In: Knowledge for Sustainable Development: an Insight into the Encyclopedia of Life Support Systems. EOLSS, France, pp. 1095–1107 [Online]. Available: https://www.eolss.net/Sample-Chapters/C15/E6-44.pdf.

Konstantinou, T., 2015. A methodology to support decision-making towards an energy-efficiency conscious design of residential building envelope retrofitting. Buildings 5 (4). https://doi.org/10.3390/buildings5041221.

Kravanja, S., Premrov, M., Leskovar, V., Lešnik Nedelko, M., 2019. Design optimization of timber-glass upgrade modules from energy efficiency and visual comfort viewpoint. Appl. Energy 270 (C).

Kubečková, D., Vrbová, M., 2021. Biodegradation processes on the facades of residential housing from the point of view of energy savings. cea 9 (3), 899–908. https://doi.org/10.13189/cea.2021.090332.

Lee, E., Selkowitz, S., Inkarojrit, V., Kohler, C., 2002. High-Performance Commercial Building Façades. Lawrence Berkeley National Laboratory, LBNL-50502 [Online]. Available: https://escholarship.org/uc/item/2fp8s9f9.

León-Rodríguez, Á.L., Suárez, R., Bustamante, P., Campano, M.Á., Moreno-Rangel, D., 2017. Design and performance of test cells as an energy evaluation model of facades in a mediterranean building area. Energies 10 (11). https://doi.org/10.3390/en10111816. Art. no. 11.

Li, S., Cui, Y., Banaitienė, N., Liu, C., Luther, M.B., 2021. Sensitivity analysis for carbon emissions of prefabricated residential buildings with window design elements. Energies 14 (19). https://doi.org/10.3390/en14196436. Art. no. 19.

Lim, Y.-W., et al., 2018. BIM and genetic algorithm optimisation for sustainable building envelope design. Int. J. SDP 13 (1), 151–159. https://doi.org/10.2495/SDP-V13-N1-151-159.

Liu, K.-S., Hsueh, S.-L., Wu, W.-C., Chen, Y.-L., 2012. A DFuzzy-DAHP decision-making model for evaluating energy-saving design strategies for residential buildings. Energies 5 (11). https://doi.org/10.3390/en5114462.

Liu, S., Kwok, Y.T., Lau, K.K.-L., Chan, P.W., Ng, E., 2019. Investigating the energy saving potential of applying shading panels on opaque façades: a case study for residential buildings in Hong Kong. Energy Build. 193, 78–91. https://doi.org/10.1016/j.enbuild.2019.03.044.

Loussos, P., Konstantinou, T., Van den Dobbelsteen, A., Bokel, R., 2015. Integrating life cycle energy into the design of façade refurbishment for a post-war residential building in The Netherlands. Buildings 5 (2). https://doi.org/10.3390/buildings5020622.

Ma, W., Wang, X., Wang, J., Xiang, X., Sun, J., 2021. Generative design in building information modelling (BIM): approaches and requirements. Sensors 21 (16). https://doi.org/10.3390/s21165439. Art. no. 16.

Maciel, A.C.F., Carvalho, M.T., 2019. Operational energy of opaque ventilated façades in Brazil. J. Build. Eng. 25, 100775 https://doi.org/10.1016/j.jobe.2019.100775.

Marszal, A.J., et al., 2011. Zero Energy Building – a review of definitions and calculation methodologies. Energy Build. 43 (4), 971–979. https://doi.org/10.1016/j.enbuild.2010.12.022.

Mazria, E., 1979. Passive Solar Energy Book. United States. Rodale Press, Emmaus, PA [Online]. Available: https://www.osti.gov/biblio/5473955. (Accessed 8 May 2023).

McFarquhar, D., 2012. The role of the building façade - curtain walls. In: Building Enclosure Science & Technology (BEST3) Conference. McFarquhaer Group, Inc. Building Enclosure Technology & Environment Council (National Institute of Building Sciences). Nov. 15, 2022. [Online]. Available: https://www.brikbase.org/content/role-building-fa%C3%A7ade-%E2%80%93-curtain-walls.

Meier, A., Olofsson, T., Lamberts, R., 2002. What is an energy efficient building. Presented at the ENTAC 2002 - IX Meeting of Technology in the Built Environment, Foz Do Iguaçu, Brazil, pp. 3–12 [Online]. Available: https://urn.kb.se/resolve?urn=urn:nbn:se:umu:diva-38905.

Mercader-Moyano, P., Anaya-Durán, P., Romero-Cortés, A., 2021. Eco-efficient ventilated facades based on circular economy for residential buildings as an improvement of energy conditions. Energies 14 (21). https://doi.org/10.3390/en14217266.

Mika, P., 2017. Concrete prefabricated elements in a sustainable residential, multi-family housing. In: International Multidisciplinary Scientific GeoConference : *SGEM*, Sofia, p. 9.

Miller, C., et al., 2014. BIM-EXTRACTED energyplus model calibration for retrofit analysis of a historically listed building in Switzerland. In: *Proceedings of the 2014 ASHRAE/IBPSA-USA Building Simulation Conference Atlanta, GA*, Atlanta, pp. 331–338.

Mlakar, J., Štrancar, J., 2013. Temperature and humidity profiles in passive-house building blocks. Build. Environ. 60, 185–193. https://doi.org/10.1016/j.buildenv.2012.11.018.

Nejat, P., Jomehzadeh, F., Taheri, M.M., Gohari, M., Majid, M. Z. Abd, 2015. A global review of energy consumption, CO 2 emissions and policy in the residential sector (with an overview of the top ten CO 2 emitting countries). Renew. Sustain. Energy Rev. 43, 843–862. https://doi.org/10.1016/j.rser.2014.11.066.

Nguyen, A.-T., Reiter, S., Rigo, P., 2014. A review on simulation-based optimization methods applied to building performance analysis. Appl. Energy 113, 1043–1058. https://doi.org/10.1016/j.apenergy.2013.08.061.

Nicholson, S.R., Shohet, R., Fung, A.S., 2019. Modelling of a net-zero energy condo in a cold climate using an interdisciplinary design framework. IOP Conf. Ser. Mater. Sci. Eng. 609 (7), 072041 https://doi.org/10.1088/1757-899X/609/7/072041.

Ochoa, C.E., Capeluto, I.G., 2008. Strategic decision-making for intelligent buildings: comparative impact of passive design strategies and active features in a hot climate. Build. Environ. 43 (11), 1829–1839. https://doi.org/10.1016/j.buildenv.2007.10.018.

Ochoa, C.E., Capeluto, I.G., 2015. Decision methodology for the development of an expert system applied in an adaptable energy retrofit façade system for residential buildings. Renew. Energy 78, 498–508. https://doi.org/10.1016/j.renene.2015.01.036.

Pacheco-Torres, R., López-Alonso, M., Martínez, G., Ordóñez, J., 2015. Efficient design of residential buildings geometry to optimize photovoltaic energy generation and energy demand in a warm Mediterranean climate. Energy Efficiency 8 (1), 65–84. https://doi.org/10.1007/s12053-014-9275-5.

Paiho, S., Ojanen, T., Pinto Seppä, I., Paavola, M., 2019. Critical performance aspects of retrofitting apartment buildings using a multifunctional façade system. Buildings 9 (8). https://doi.org/10.3390/buildings9080184.

Pantazis, E., Gerber, D., 2018. A framework for generating and evaluating façade designs using a multi-agent system approach. Int. J. Architect. Comput. 16 (4), 248–270. https://doi.org/10.1177/1478077118805874.

Pavlov, A., Pavlova, L., Pavlova, L., 2018. Multi-criteria thermal evaluation of wall enclosures of high-rise buildings insulated products based on modified fibers. E3S Web Conf. 33, 02004 https://doi.org/10.1051/e3sconf/20183302004.

Pérez-Lombard, L., Ortiz, J., Pout, C., 2008. A review on buildings energy consumption information. Energy Build. 40 (3), 394–398. https://doi.org/10.1016/j.enbuild.2007.03.007.

Perlova, E., Platonova, M., Pankova, A., Nemova, D., Petrichenko, M., Rakova, X., 2015. The analysis of efficiency using coil meshes with air pockets under plastering composition. In: 26th DAAAM International Symposium on Intelligent Manufacturing and Automation. Zadar, pp. 795–802. https://doi.org/10.2507/26th.daaam.proceedings.111.

Pisello, A.L., Cotana, F., Nicolini, A., Buratti, C., 2014. Effect of dynamic characteristics of building envelope on thermal-energy performance in winter conditions: in field experiment. Energy Build. 80, 218–230. https://doi.org/10.1016/j.enbuild.2014.05.017.

Pyrgou, A., Castaldo, V.L., Pisello, A.L., Cotana, F., Santamouris, M., 2017. On the effect of summer heatwaves and urban overheating on building thermal-energy performance in central Italy. Sustain. Cities Soc. 28, 187–200. https://doi.org/10.1016/j.scs.2016.09.012.

Rais, M., Boumerzoug, A., Baranyai, B., 2021. Energy performance diagnosis for the residential building façade in Algeria. Pollack Period. 16 (2), 136–142. https://doi.org/10.1556/606.2020.00204.

Ramadan, A.M., 2020. Simulation study of trombe wall for passive solar technique of buildings in Egypt. IOP Conf. Ser. Mater. Sci. Eng. 974 (1), 012023 https://doi.org/10.1088/1757-899X/974/1/012023.

Ramadhan, T., Estika, N.D., Widiastuti, I., 2021. The characteristics of secondary skin facade of contemporary house by Indonesian architects. IOP Conf. Ser. Earth Environ. Sci. 738 (1), 012022 https://doi.org/10.1088/1755-1315/738/1/012022.

Reyes-Barajas, K.D., Romero-Moreno, R.A., Luna-León, A., Olvera-García, D., Sotelo-Salas, C., Bojórquez-Morales, G., 2021. Economic feasibility of passive strate gies for energy efficient envelopes of mass-built housing in hot-dry climate. Int. J. EQ 6 (2), 129–142. https://doi.org/10.2495/EQ-V6-N2-129-142.

Rodriguez-Ubinas, E., et al., 2014. Passive design strategies and performance of net energy plus houses. Energy Build. 83, 10–22. https://doi.org/10.1016/j.enbuild.2014.03.074.

Roppel, P., Hershfield, M., Marif, W., NRC, 2011. ASHRAE Research Project Report RP-1365 Thermal Performance of Buildings Envelope Details for Mid and High-Rise Buildings. American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., 1791 Tullie Circle NE, Atlanta, GA, 30329.

Špegelj, T., Žegarac Leskovar, V., Premrov, M., 2016. Application of the timber-glass upgrade module for energy refurbishment of the existing energy-inefficient multi-family buildings. Energy Build. 116, 362–375. https://doi.org/10.1016/j.enbuild.2016.01.013.

Špegelj, T., Premrov, M., Leskovar, V.Ž., 2017. Development of the timber-glass upgrade module for the purpose of its installation on energy-inefficient buildings in the refurbishment process. Energy Efficiency 10 (4), 973–988. https://doi.org/10.1007/s12053-016-9494-z.

Sabini, L., Muzio, D., Alderman, N., 2019. 25 years of “sustainable projects”. What we know and what the literature says. Int. J. Proj. Manag. 37 (6), 820–838. https://doi.org/10.1016/j.ijproman.2019.05.002.

Santamaría, J., Girón, S., Campano, M.A., 2016a. Economic assessments of passive thermal rehabilitations of dwellings in Mediterranean climate. Energy Build. 128, 772–784. https://doi.org/10.1016/j.enbuild.2016.07.035.

Santamaría, J., Campano, M.A., Girón, S., 2016b. Method for the economic profitability of energy rehabilitation operations: application to residential dwellings in seville. Procedia Comput. Sci. 83, 742–749. https://doi.org/10.1016/j.procs.2016.04.162.

Sari, D.P., Chiou, Y.-S., 2019. Do energy conservation strategies limit the freedom of architecture design? A case study of minsheng community, Taipei, Taiwan. Sustainability 11 (7). https://doi.org/10.3390/su11072003. Art. no. 7.

Schnieders, J., Feist, W., Rongen, L., 2015. Passive Houses for different climate zones. Energy Build. 105, 71–87. https://doi.org/10.1016/j.enbuild.2015.07.032.

Sesana, M.M., Salvalai, G., Esposito, F., 2011. A sensitivity analysis approach: simulation tools as support at the early stages of low energy housing design. In: 27th International Conference on Passive and Low Energy Architecture: Architecture and Sustainable Development. PLEA, pp. 223–228.

Seuring, S., Gold, S., 2012. Conducting content-analysis based literature reviews in supply chain management. Supply Chain Manag.: Int. J. 17 (5), 544–555. https://doi.org/10.1108/13598541211258609.

Shen, J., et al., 2016. The early design stage of a novel solar thermal façade (STF) for building integration: energy performance simulation and socio-economic analysis. Energy Proc. 96, 55–66. https://doi.org/10.1016/j.egypro.2016.09.099.

Shou, W., Wang, J., Wang, X., Chong, H.Y., 2015. A comparative review of building information modelling implementation in building and infrastructure industries. Arch. Comput. Methods Eng. 22 (2), 291–308. https://doi.org/10.1007/s11831-014-9125-9.

Siddiq, M., 2014. Establishing energy efficient building codes in developing nations: an analysis of window characteristics suited to hot-dry climates through a study of the residential byelaws of Lahore, Pakistan. In: 30th International PLEA Conference: Sustainable Habitat for Developing Societies: Choosing the Way Forward - Proceedings, Ahmedabad, pp. 583–590.

Singh, P., Devadutt, S., Mantha, P., 2015. Early stage building environmental analysis case study of a large residential community in India. In: 14th Conference of International Building Performance Simulation Association, BS 2015, Hyderabad, pp. 488–495.

Song, Y., et al., 2017. Trends and opportunities of BIM-GIS integration in the architecture, engineering and construction industry: a review from a spatio-temporal statistical perspective. IJGI 6 (12), 397. https://doi.org/10.3390/ijgi6120397.

Spacey, J., 2016. Design: passive vs active. Simplicable. https://simplicable.com/new/passive-design-vs-active-design. Nov. 29, 2021.

Strebkov, D.S., Filippchenkova, N.S., 2020. Results of an experimental study of a solar photovoltaic-thermal module. Appl. Sol. Energy 56 (6), 442–448. https://doi.org/10.3103/S0003701X20060110.

Thalfeldt, M., Pikas, E., Kurnitski, J., Voll, H., 2013. Facade design principles for nearly zero energy buildings in a cold climate. Energy Build. 67, 309–321. https://doi.org/10.1016/j.enbuild.2013.08.027.

Tian, Z., Zhang, X., Jin, X., Zhou, X., Si, B., Shi, X., 2018. Towards adoption of building energy simulation and optimization for passive building design: a survey and a review. Energy Build. 158, 1306–1316. https://doi.org/10.1016/j.enbuild.2017.11.022.

Tong, S., Wen, J., Wong, N.H., Tan, E., 2021. Impact of façade design on indoor air temperatures and cooling loads in residential buildings in the tropical climate. Energy Build. 243, 110972 https://doi.org/10.1016/j.enbuild.2021.110972.

Vijay Kumar, D.R., Sandeep Kumar, N., Narsimha, K., Shiva Ram Reddy, K., Vamsee Krishna, E., 2020. Spatial Day light autonomy and energy analysis of a residential building for different climatic conditions and window-to-wall ratios. In: 2nd International Conference on Design and Manufacturing Aspects for Sustainable Energy, ICMED 2020. Hyderabad. https://doi.org/10.1051/e3sconf/202018401117.

Wang, X., Love, P.E.D., Kim, M.J., Park, C.-S., Sing, C.-P., Hou, L., 2013. A conceptual framework for integrating building information modeling with augmented reality. Autom. ConStruct. 34, 37–44. https://doi.org/10.1016/j.autcon.2012.10.012.

Wang, Y., et al., 2021. Mineralized supramolecular hydrogel as thermo-responsive smart window. J. Mater. Sci. 56 (11), 6955–6965. https://doi.org/10.1007/s10853-020-05710-3.

Wang, X., Wang, J., Wu, C., Xu, S., Ma, W., 2022. Engineering brain: metaverse for future engineering. AI Civ. Eng. 1 (1), 2. https://doi.org/10.1007/s43503-022-00001-z.

Watfa, M.K., Hawash, A.E., Jaafar, K., 2021. Using building information & energy modelling for energy efficient designs. ITcon 26, 427–440. https://doi.org/10.36680/j.itcon.2021.023.

Webb, M., 2021. Biomimetic building facades demonstrate potential to reduce energy consumption for different building typologies in different climate zones. Clean Technol. Environ. Policy. https://doi.org/10.1007/s10098-021-02183-z.

Welzenbach, R.. Research guides: research impact metrics: citation analysis: Scopus. https://guides.lib.umich.edu/citation/Scopus. (Accessed 18 December 2021).

Wilkinson, S., Stoller, P., Ralph, P., Hamdorf, B., Catana, L.N., Kuzava, G.S., 2017. Exploring the feasibility of algae building technology in NSW. Procedia Eng. 180, 1121–1130. https://doi.org/10.1016/j.proeng.2017.04.272.

Wilson, A., 1979. THERMAL STORAGE WALL DESIGN MANUAL. NEW MEXICO SOLAR ENERGY ASSOCIATION, Albuquerque [Online]. Available: https://www.builditsolar.com/Projects/SpaceHeating/ThermalStorageWallDesignManual.pdf.

Wilson, E.J., 2017. ResStock - Targeting Energy and Cost Savings for U.S. Homes', National Renewable Energy Lab. (NREL), Golden, CO (United States). NREL/FS-5500-68653 [Online]. Available: https://www.osti.gov/biblio/1398250. (Accessed 21 September 2023).

Wong, I., Baldwin, A.N., 2016. Investigating the potential of applying vertical green walls to high-rise residential buildings for energy-saving in sub-tropical region. Build. Environ. 97, 34–39. https://doi.org/10.1016/j.buildenv.2015.11.028.

Wu, P., Wang, J., Wang, X., 2016. A critical review of the use of 3-D printing in the construction industry. Autom. ConStruct. 68, 21–31. https://doi.org/10.1016/j.autcon.2016.04.005.

Xue, P., Mak, C.M., Huang, Y., 2016. Quantification of luminous comfort with dynamic daylight metrics in residential buildings. Energy Build. 117, 99–108. https://doi.org/10.1016/j.enbuild.2016.02.026.

Yang, R.J., Zou, P.X.W., 2016. Building integrated photovoltaics (BIPV): costs, benefits, risks, barriers and improvement strategy. International Journal of Construction Management 16 (1), 39–53. https://doi.org/10.1080/15623599.2015.1117709.

Yimprayoon, C., Tuaychareon, N., Chuancheang, N., Kornisaranukul, W., Tavasit, P., 2017. Air conditioning electricity use simulation in low-cost residential housings after daylighting redesign. In: Proceedings of 33rd PLEA International Conference: Design to Thrive. PLEA, pp. 3451–3457, 2017, Edinburgh.

Zhang, X., et al., 2015. The early design stage for building renovation with a novel loop-heat-pipe based solar thermal facade (LHP-STF) heat pump water heating system: techno-economic analysis in three European climates. Energy Convers. Manag. 106, 964–986. https://doi.org/10.1016/j.enconman.2015.10.034.

'Content - How Scopus Works - Scopus - | Elsevier solutions'. https://www.elsevier.com/solutions/scopus/how-scopus-works/content (accessed December. 18, 2021).

DesignBuilder software Ltd - 3-D BIM import (gbXML). https://designbuilder.co.uk/22-training/certification-training/139-designbuilder-epcs-and-part-l. (Accessed 24 January 2022).

'Multifunctional Energy Efficient Façade System for Building Retrofitting | MEEFS RETROFITTING Project | Fact Sheet | FP7', *CORDIS* | European Commission. https://cordis.europa.eu/project/id/285411 (accessed Aug. 23, 2022).

Sustainable • Healthy, High-Performance, and Energy-Efficient Architecture — Strategies', Sustainable • Healthy, High-Performance, and Energy-Efficient Architecture. https://www.sustainable.to/strategies (accessed Feb. 18, 2022).