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State-of-the-art and future trends

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DOI
10.1016/j.buildenv.2024.111184

Publication date
2024

Document Version
Final published version

Published in
Building and Environment

Citation (APA)
Bianchi, S., Andriotis, C., Klein, T., & Overend, M. (2024). Multi-criteria design methods in façade engineering: State-of-the-art and future trends. *Building and Environment*, *250*, Article 111184. https://doi.org/10.1016/j.buildenv.2024.111184

Building and Environment 250 (2024) 111184

Contents lists available at ScienceDirect

Building and Environment

journal homepage: www.elsevier.com/locate/buildenv

Multi-criteria design methods in façade engineering: State-of-the-art and future trends

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ARTICLE INFO

Keywords:
Façade design
Performance-based
Decision-making
Multi-criteria
Multi-objective
Optimization

ABSTRACT

Façade engineering is facing an era of extraordinary challenge to meet the surge in demand for buildings that are environmentally sustainable and enhance occupant wellbeing. Facades, also known as building envelopes, play a major role in the resource-efficiency of buildings and the quality of its indoor environment. Consequently, the development of effective design approaches is crucial for generating appropriate façade solutions. Façade design is complex and multi-disciplinary involving several and oftentimes conflicting performance criteria. Systematic and holistic design procedures are, therefore, required to achieve optimal trade-offs. Over the last decades, researchers in this field have used computational tools and power to address this challenging problem within the context of multi-criteria design approaches. This paper reviews the existing research in this field, and presents the state-of-the-art review from simple to advanced decision-making procedures currently used at the early design stages, where decisions have a disproportionally large impact on the façade performance. The paper provides a complete description of the design variables and objectives typically involved. Alternative multi-criteria design methodologies regarding discrete decisions and automated optimization are reviewed, each with salient pros/cons, and overall conclusions are drawn. Finally, the paper discusses ongoing trends and research needs, namely, the development of uncertainty-based procedures to enable more informed decision-making; the inclusion of structural/seismic safety considerations in the design process to achieve higher socio-economic benefits; the integration of smart building information modeling and processing technologies to facilitate smarter design decisions; and the adoption of integrated design approaches to promote climate-adaptive solutions that enhance resilience.

1. Introduction

Facades, also known as building envelopes, act as filters between the building's interior and exterior environments. They are connected to the main load-bearing structure and provide the external architectural expression of the building. Fig. 1 provides an overview of the primary typologies currently employed. Facades can be classified based on the panel modularity and connection details. Panel modularity includes mono-panels, as in infill walls, and multi-panels, comprising both vertical and/or horizontal panels as in curtain and cladding walls. Connection details refer to how the panel is connected to the primary structure, through interface elements such as mortar filling for masonry infills, continuous elements for timber/steel infills, or discrete bracketry for curtain and cladding walls. Alternative systems have also emerged due to the development of different materials, construction processes and architectural designs. Moreover, to meet ever stricter energy performance requirements [1,2], facades have become integrated multi-material, multi-functional components, often with some integrated adaptive features.

Facades are, therefore, complex systems designed for several performance criteria associated with their multiple functions. They have significant impact on the functional and economic aspects of the entire building (accounting for up to the 30 % of the total cost of a building [3]) and play a paramount role in its aesthetics. Their ultimate functional aim is to provide an indoor environment, which is safe and comfortable for building occupants in an aesthetically pleasing and resource-efficient manner. In doing so, facades control (i) heat and mass transfer, water, acoustic and light transmission between the inner and outer environment which have a direct impact on the operational energy demand and occupant comfort; and (ii) resist wind, impact, earthquake, fire and other actions which have a direct impact on embodied energy and occupant safety. This leads to multiple and conflicting objectives during the design process. For instance, a high window-to-wall ratio reduces

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https://doi.org/10.1016/j.buildenv.2024.111184
Received 29 September 2023; Received in revised form 14 December 2023; Accepted 8 January 2024

Abbreviations

AHP	Analytic Hierarchy Process
AI	Artificial Intelligence
ANN	Artificial Neural Networks
ANP	Analytic Network Process
BIM	Building Information Modelling
COPRAS	COmplex PRoportional Assessment
DE	Differential Evolution
DRL	Deep Reinforcement Learning
ELECTRE	ELimination Et Choix Traduisant la REalité
GA	Genetic Algorithm
GAN	Generative Adversarial Network
NSGA-II	Non-dominated Sorting Genetic Algorithm
MADM	Multi-Attribute Decision-Making
MAS	Multi Agent Systems
MCDM	Multi-Criteria Decision-Making
MODM	Multi-Objective Decision Making
PROMETHEE	Preference Ranking Organization Method for Enrichment Evaluation
PSO	Particle Swarm Optimization
SPEA-2	Strength Pareto Evolutionary Algorithm
TOPSIS	Technique for Order of Preference by Similarity to Ideal Solution
WASPA	Weighted Aggregated Sum Product Assessment
WPM	Weighted Product Method
WSM	Weighted Sum Method

artificial lighting demand but may cause overheating during the cooling season due to increased solar heat gain. Similarly, enlarging internal gaps enhances façade dynamic behavior during earthquakes but may compromise acoustic performance.

Façade design consists of a whole process characterized by increasing levels of detail [4]. This process begins with a conceptual design, which involves exploring various design options. The next stage involves creating a detailed façade design, that includes the selection of materials and buildup, as well as accurate evaluations of the overall performance and cost. The final stage is the technical design, which involves creating a detailed production plan that outlines the specific steps required to bring the façade design to life. The design process is multi-objective and considers many design variables, each of them likely to affect several performance indicators. Therefore, the different design variables should be properly combined to achieve the optimal trade-offs among all the performance indicators. This makes design decisions difficult, and the difficulty is further increased if the uncertainties of the design variables are taken into account and a proper quantification of the relative impacts of the design variables is needed [5,6].

The complex and multi-disciplinary design process has been plagued by inefficient design and operational stages in the past, leading to an increasing negative impact on the environment. To address this, the development of effective design tools and methods has become crucial in targeting higher levels of energy efficiency for building envelopes and fulfilling current sustainability requirements. Façade engineering is therefore facing an extraordinary challenging era to achieve this goal. Early research efforts focused on the development of computer-aided design tools to automate the drawing production by generating efficient geometrical building models (since late 1960). This was followed by parametric and performance-based design procedures that have emerged (since late 1980) as an integrated approach to combine several design parameters from the early design stage [7]. Parametric design,

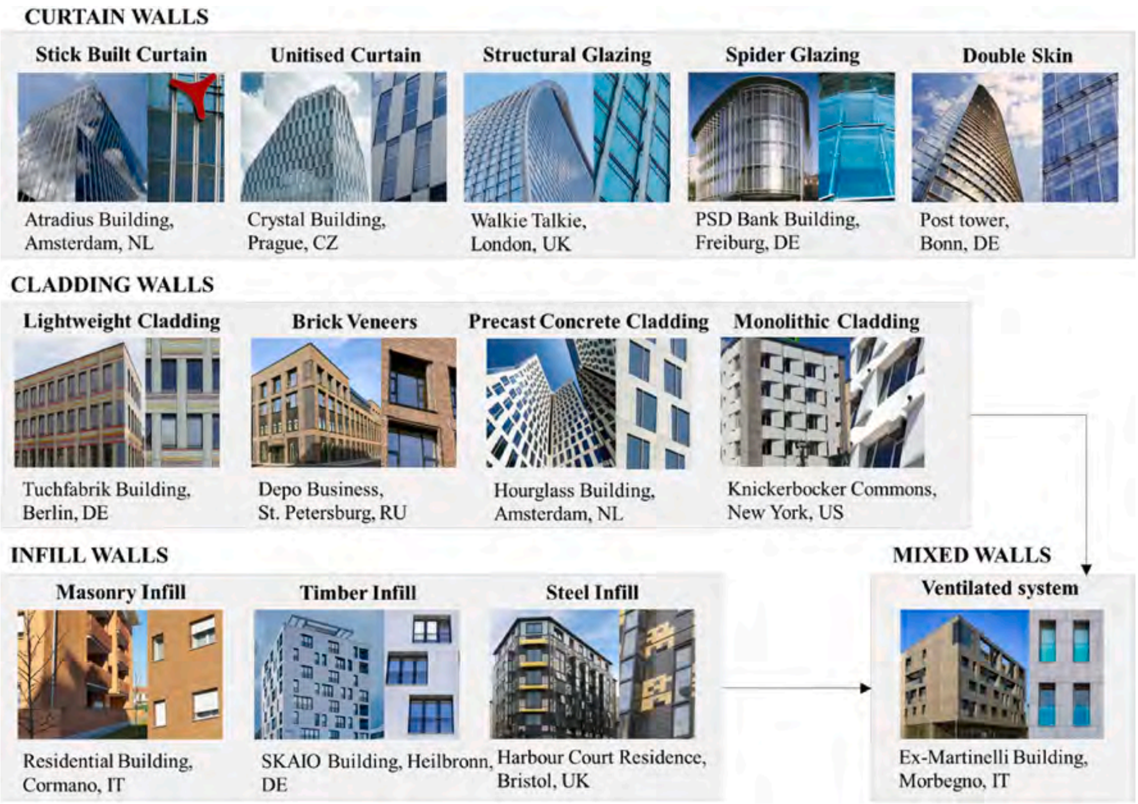

Fig. 1. Spectrum of façade typologies.

coupled with building simulation tools, streamlines the assessment and selection of optimal solutions for multi-dimensional problems, establishing it as the predominant modeling process in façade design.

The rapid advancement of digital technologies has given rise to an extensive range of computational approaches and techniques available to designers, enabling them to produce and rationalize design processes and outputs. Particularly, computational advancements can provide designers with a more methodological approach to address façade design problems. Designers are now able to predict the building/façade behavior, explore the full realm of parameters affecting the models, manage the conflicting design objectives and generate multiple and/or optimal design alternatives by coupling various parameters with performance metrics. To provide a comprehensive understanding of this topic, this paper aims to present a systematic state-of-the-art review of simplified-to-comprehensive methods that integrate computational performance simulation in the façade design process. A significant research effort by a growing number of researchers has been made in this research field, particularly in recent years, focusing on the development of early-stage design tools, decision-making procedures and automated optimization, as well as accounting for various design variables and objectives. This state-of-art review first provides an overview of the various façade performance aspects that need to be considered in the design (Section 2). The paper then presents alternative multi-criteria design methodologies, regarding discrete and continuous decision spaces, and related advantages/disadvantages, which might be applied in façade design problems (Section 3). The paper finally discusses ongoing research and new perspectives in façade engineering (Section 4).

2. Façade performance criteria

Building facades are subject to various loads and displacements during their whole life. In addition to imposed and variable loads, either the external/internal environment or accidental events, such as earthquakes or fires, cause actions which may affect the functionality of the building envelope. A façade system should be designed to account for all the possible impacts on its components and risks threatening its life cycle performance. This leads to multiple functions described as performance requirements (or criteria) a façade needs to fulfil. Many authors provide a comprehensive list of performance requirements [8–11] and these generally fall into three categories: functional (structural safety, human comfort, durability), environmental (energy and material efficiency) and financial (cost effectiveness) (Fig. 2).

2.1. Functional: Structural safety

Facades must support their self-weight and allow for differential deformations caused by moisture, temperature and structural movements, e.g. floor slab deflections. Additionally, they need to withstand environmental loads, such as rain, wind and, for sloped facades, snow. The structural design is not limited to the principal façade components (e.g., glass panel and framing for curtain walls), but also includes the connections between these components as well as the connections between the façade and the primary load-bearing structure. These connections must safely transfer loads and accommodate necessary deformation flexibility, while providing construction tolerances. Furthermore, facades must have adequate fire resistance capacity to prevent failure, and ensure safe escape routes and access for rescue crews during a fire. This requires limiting the probability of fire propagation and providing proper mechanical resistance, integrity and insulation against heat, flames, smoke.

Designing building facades also involves addressing man-made (blast loading) and natural hazards (earthquakes). To prevent serious injuries to people in the event of an explosion, the glass should absorb and disperse the impact pressure wave while retaining broken glass and debris [12]. Additionally, façade design should consider blast-related pressures, impulse and load duration. During earthquakes, even low-intensity events can cause functional loss or serious damage to facades [13]. To reduce vulnerability, seismic demand parameters (accelerations, displacements) should be properly evaluated and considered in designing construction details and anchorage systems to the primary structure.

2.2. Functional: Human comfort

Facades create visual and physical connections to the outside and have major impact on the appearance of the building and the streetscape. Exterior envelopes provide access to daylight, and have positive

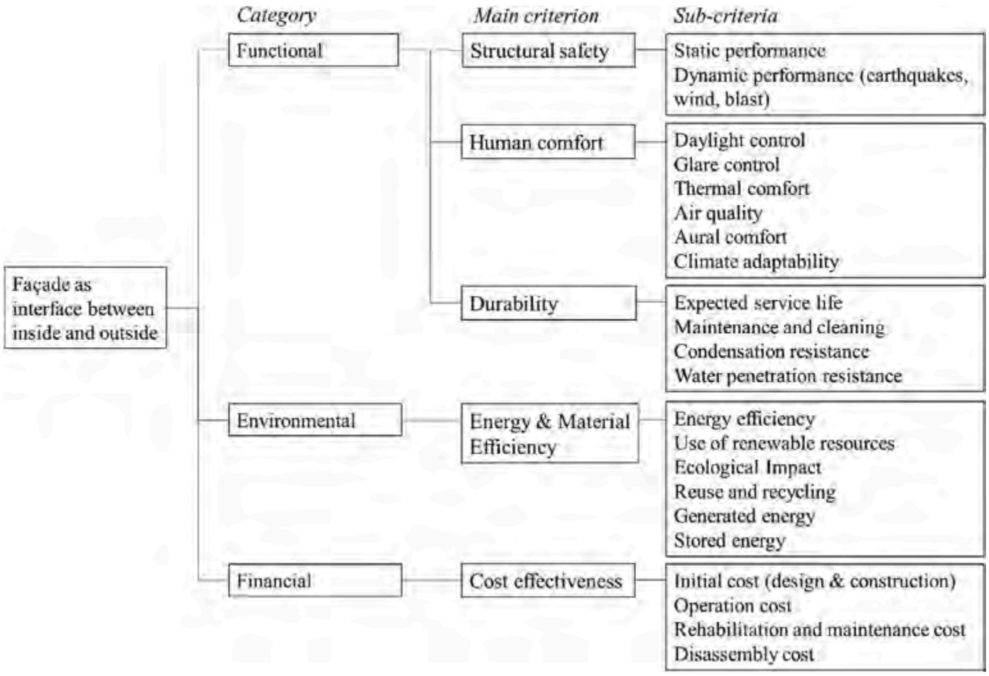

Fig. 2. Main façade performance criteria.

impact on occupant satisfaction and wellbeing. Although predicting the influence of façade design on visual comfort and lighting energy use can be challenging, attaining a well-daylit space is a crucial design objective. However, daylight can also cause discomfort, e.g. solar glare and very high luminance reflections on display screens, therefore, all of these factors need to be considered in daylighting building design [14]. Meeting the heating and cooling needs of the occupants, controlling the building thermal environment, supporting occupant comfort, productivity and well-being, are other fundamental roles of facades. Furthermore, facades are designed to control natural ventilation and indoor air quality, e.g. by using proper ventilation devices and strategies along with minimizing air leakage through the building envelope. Another important function of the building envelope is noise mitigation, consequently, facades should provide adequate acoustic performance. Building facades are indeed the primary surfaces upon which the sound from the external environment is reflected and the reduction of noise level over their fronts is fundamental and must be addressed, e.g. by adopting alternative façade shapes and materials [15,16].

2.3. *Functional: Durability*

Facades, as all the building components, have a natural reduction in performance over time. This is due to their sensitivity to weathering and consequent degradation, inevitably leading to loss of functionality. The capacity of a façade to perform its functions during a specified time period, under the influence of the actions expected for the building operation, is captured by the durability and expressed in terms of service life [17]. Facades must provide an adequate durability by resisting condensation and water penetration, as well as facilitating the migration of excess humidity from inside the building to the outside [18]. To ensure façade durability, the designer must properly account for the building use, the environment conditions, the shape and details of the components and the quality of installation. Protective measures and maintenance operations must be planned to allow the system to maintain its performance and aesthetic features.

2.4. *Environmental: Energy & material efficiency*

Due to climate change concerns, the building industry is putting a major effort in increasing the sustainability level of our built environment and fulfilling energy efficiency targets. This focus on sustainable development is crucial to mitigate negative environmental, economic and social impact on future generations [19]. Facades have a disproportionate impact on the sustainability of buildings, therefore, the use of natural and manufactured resources throughout the design, construction and operation phases should be carefully planned during a project. Facades are able to reduce energy consumption and energy demand through the optimal use of daylight, allowing natural air circulation, avoiding moisture transfer and controlling heat transfer. Lifecycle-based assessment and design methodologies can be utilized to gauge the sustainability of a façade, and numerous tools have been developed to address this aspect [20]. These imply defining all the environmental implications during the whole life-cycle encompassing the extraction and processing of raw materials, the fabrication phase, transportation and distribution, use and eventually re-use, the storage, recovery and final disposal of façade systems.

2.5. *Financial: Cost effectiveness*

The economic analysis plays a fundamental role when comparing alternative solutions or exploring the benefits of a product. Rather than focusing solely on investment costs, life-cycle cost analyses must consider the entire cost spectrum, including design, construction, operation, maintenance, upgrades and demolition. The design objective should aim to minimize all these costs. Consequently, the considerable upfront investment in high-performance facades can be offset by lower operational and maintenance costs over its lifespan, resulting in more cost-effective solutions. For example, employing damage-control technologies to create "earthquake-proof" systems may involve higher initial costs compared to conventional solutions. However, economically feasible payback periods can be identified, allowing for the recovery of invested funds and yielding significant savings by the end of the service life [21]. Moreover, long-term cost efficiency can be maximized by integrating various technologies, such as facades embedding air conditioning systems. This may result in a multi-layer and multi-material high-performance solution, but poses challenges for disassembly and re-use/recycling at the end of its life [22].

3. Façade design process

Façade design is a complex multi-disciplinary process involving different stakeholders and domains of expertise. The overall process consists of the combination of architectural design, execution design and product design and their overlaps. Architects and engineers are regularly involved in consulting the client during the project development phase, while the façade builder and system provider try to establish long term relations with clients and architects or consultants [3]. These relationships are vital for the design and construction of a façade, as they enable a more collaborative and iterative process that can lead to better outcomes. The whole process of a traditional route for façade design and construction are described in detail in the process mapping developed by Voss et al. [23]. Although an interactive and integrated design approach is desirable, a traditional sequential design procedure is still employed. The design evolves through increasing complexity levels which are intrinsically interdependent: the initial design choices have a significant impact on subsequent steps, while later steps play a role in driving the initial design choices, particularly when it comes to meeting production-related constraints [24].

Focusing on the architectural design, three main design stages can be identified: (a) building early design, (b) façade preliminary design, and (c) façade detailed design (Fig. 3). Before starting the design process, the designer must decide on the importance of each performance criterion, since this prioritization will influence the decisions throughout the overall process. Project limitations and constraints, e.g. available budget and material type for the building façade, are identified at the earliest design stage. A conceptual workflow is firstly developed to define basic geometrical features, building massing, orientation and performance criteria for the overall building. This initial stage has a significant impact (around 80 % [25]) on all subsequent design decisions and involves the definition of performance indicators, optimization and performance prediction. Then, (often several) preliminary design options are developed to satisfy all the intended design criteria and the most appropriate design is selected for the project. Finally, a detailed design of the façade is carried out to determine detailed information for production and installation. This later stage involves comprehensive assessments through numerical modelling to study the façade behavior at a system-level (whole façade) and at local level (members and joints/connections). During the overall process, verifications are implemented to check that the proposed design is code-compliant and it satisfies project-related design requirements in terms of manufacturability, cost and performance. Moreover, additional considerations need attention, including accommodating construction alterations, addressing durability concerns for both the façade and its connections, optimizing construction processes for efficiency, and developing a comprehensive plan for maintenance, inspection and end-of-life management of the envelope [26]. This highlights the need for a proper communication between professionals and decision makers, and the seamless integration of all façade design stages. Building Information Modelling (BIM) is nowadays applied to facilitate this integration, particularly to monitor life-cycle decisions from conception to demolition, by providing accurate information and three-dimensional visualizations throughout the project.

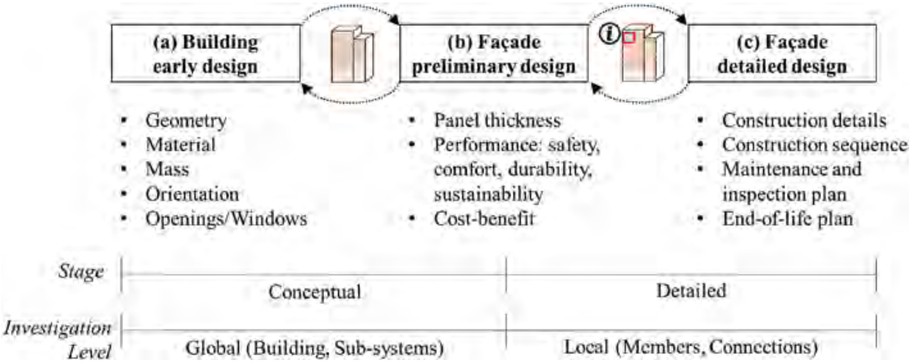

Fig. 3. Façade design process.

Within this overall design procedure, selecting the proper façade system for each project is the most important decision to make. In addition to project goals, limitations and constraints, the designer must identify all the key performance design aspects, that is, not only structural integrity and energy efficiency as typically happens, but all the decisive criteria. The design objective should not merely be to define a façade system with acceptable performance levels: instead, the aim should be to seek for an optimal solution. Since some performance criteria are conflicting with each other, the façade design leads to Pareto decisions meaning that there is no single solution achieving the highest score on each of the performance criteria, but one that establishes efficient trade-offs among the criteria. The choice of trade-off will lead a different (optimal) solution on the Pareto front (see Section 3.2). However, most designers presently tend to use design methods that are optimized with respect to only a few objectives, due to a limited understanding of the complex interactions among different design variables or due to the prioritization of certain project-related objectives. However, the goal should be to maximize the overall performance accounting for the interactions and correlations between the design criteria. To achieve this, it is essential to implement a systematic design method that can help identify, assess and integrate various performance criteria.

Given the importance of a holistic design approach, several studies have focused on developing simplified procedures to guide stakeholders. One of the early research in this direction was carried out by Ramachandran [27], who developed an integrated tool to support façade design by referring to existing practices and knowledge-based technologies. Additional research on analytical-based approaches has emerged in the last decade. Donato et al. [28] developed a parametric and multi-disciplinary procedure to investigate the relationships between envelope features and cooling strategies. Kültür et al. [29] proposed a supporting holistic tool based upon an extensive literature review and providing the impacts of design decisions on different façade functional aspects (safety, health-related, well-being). To define a systematic approach for energy retrofitting, Pracucci et al. [30] developed a simple multi-criteria decision matrix to support the façade technology selection. This qualitative method provides an overall score based on the simple sum of each project requirements to each current market components. Focusing on public buildings, Vullo et al. [31] proposed a conceptual methodology to drive procurement procedures based on the overall building performance, rather than tenders based on single façade properties. While it is true that these tools rely on simplified investigations and/or literature-based information, and may require the integration of additional façade functions and typologies, they can still be valuable resources. Designers can save time, reduce labor costs and minimize expenses associated with time-consuming analyses, stakeholders can gain awareness of the impact of design variations on building performance and make more informed decisions from the very early stage.

Although simplified methods can be useful for certain applications, more refined procedures should be applied at the early stages of façade design to achieve high-performance multi-functional systems. To this end, Multi-Criteria Decision-Making (MCDM) methods have gained increasing attention in recent years [32]. Building on existing literature, this section presents a review of the MCDM approaches adopted in façade engineering, with their potential benefits and limitations. MCDM is branch of operational research that employs techniques and mathematical tools to facilitate the analysis and selection of alternatives based on pre-selected criteria. MCDM involves Multi-Attribute Decision Making (MADM) and Multi-Objective Decision Making (MODM) [33]. MADM concentrates on problems with discrete decision spaces, while MODM involves mathematical optimization with several competing objectives to be optimized simultaneously. These performance-based design methods provide a solution to the challenges especially faced in the conceptual design stage of building facades.

3.1. Multi-Attribute Decision Making

MADM is a valuable selection technique currently used in a wide variety of disciplines, such as management science, industrial engineering, economics, and civil engineering [34]. Although the application of MADM in façade engineering is relatively recent, research efforts have demonstrated the potential benefits of this method in enhancing façade performance by empowering designers to make informed decisions on design parameters based on contextual conditions. Fig. 4 presents a schematic of the overall MADM process. In order to select the optimal façade among a set of predetermined alternatives, all the required qualitative and quantitative performance criteria need to be identified. Several feasible design options are considered and evaluated by assigning a rating and a weight to each criterion. Subsequently, a final score is assigned to the overall performance of each alternative to identify the best solution. The procedure can account for all the design attributes and their interdependence, resulting in more accurate evaluations of the performance of each design solution.

MADM methods can be generally classified into: (i) compensatory methods, producing a single score for each design option, enabling the identification of the best solution through a process of trading-off or ranking of the importance of the individual criteria, as for the simple Weighted Sum Method (WSM), the Analytic Hierarchy Process (AHP) [35], the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) [36] and the COmplex PRoportional Assessment (COPRAS) [37]; (ii) non-compensatory methods, making individual comparisons of all possible pairs of design options through matrices that show how one option outranks another (pair-wise comparison), without the need for explicit trading-off, as the ELimination Et Choix Traduisant la REalité (ELECTRE) [38] and the Preference Ranking Organization Method for Enrichment Evaluation (PROMETHEE) [39]. This paper does not present the technical details of the alternative approaches, however, it discusses the use of MADM in façade design and the main advantages and disadvantages of each method.

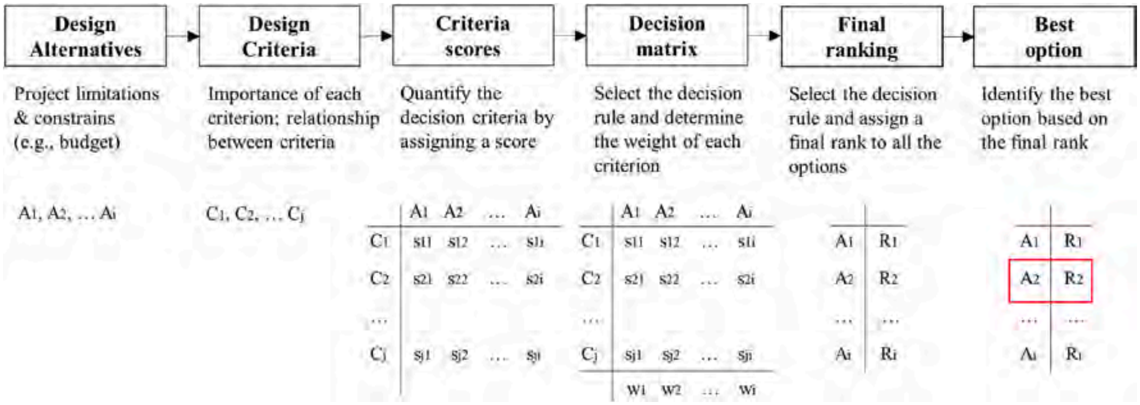

Fig. 4. General model of the MADM procedure.

Table 1 summarizes the research efforts of various authors who have worked on validating these MADM procedures in the context of façade design problems. One of the early applications was conducted by Rey [40], who applied the ELECTRE method, which is based on partial aggregation and offering a ranking process similar to the thought processes of decision makers. The author adopted this method to assess the overall efficiency of various retrofit façade strategies, considering environmental, sociocultural and economic criteria. Zavsdskas et al. [41] tested the reliability of alternative approaches, i.e. WSM, Weighted Product Method (WPM) and Weighted Aggregated Sum Product Assessment (WASPA) [42], to rank façade solutions of public and commercial buildings. Rogulj et al. [43] used PROMETHEE method to compare alternative glass facades by identifying a priority ranking list of alternatives which enables the investor to select the appropriate solution. Akbari et al. [44] examined the functions of a façade in terms of its role as a connector and barrier for both the interior and exterior of a home. Using the fuzzy TOPSIS technique [45], they ranked these functions across different interior spaces of the home and identified that control of natural ventilation and air flow were the most significant façade functions for the living room, while providing sufficient daylight was deemed crucial for the kitchen. Many authors adopted and tested the application of AHP, most widely applied and well-known technique in sustainable energy planning of buildings [46–48]. E.g., Moussavi Nadoushiani et al. [46] applied the AHP method to estimate the relative weights and rank façade alternatives through a systematic procedure that accounts for economic and environmental impacts, along with often overlooked social impacts. The method was employed to identify the most suitable system to replace an existing old façade. AHP enables stakeholders to rank decision criteria based on their relative importance and evaluate alternative solutions through pair-wise comparisons. AHP assumes that decision problems can be hierarchically structured, with a one-directional relation between decision levels. By breaking down a complex decision problem into smaller, more manageable sub-problems, AHP aids stakeholders in identifying the most critical criteria for a specific context and making well-informed decisions that strike a balance between multiple objectives.

Nevertheless, recognizing the distinct strengths and limitations of individual MADM methods, a hybrid approach that combines different techniques is gaining popularity [49–51]. This approach aims to enhance the efficiency of the decision-making procedure by leveraging the advantages of multiple methods. Particularly, the AHP method is generally used to calculate the weighted criteria, while the decision variants are ranked through other approaches, such as (i) TOPSIS, where the alternatives are selected based on their shortest distance from the ideal solution, which represents the desired outcome, while the performance of decision alternatives is measured by comparing their relative distances to both the ideal and worst solutions; or (ii) COPRAS, which uses a stepwise ranking and evaluation procedure of the alternatives based on performance index values, resulting in reduced computational time. For instance, Ilter et al. [50] applied the AHP in conjunction with both TOPSIS and COPRAS in the performance evaluation of a glass panel system, taking into account experimental results to establish the hierarchical structure. The study revealed that the TOPSIS method yielded more reliable and consistent results compared to the COPRAS method.

Moreover, different authors sought to develop and apply enhanced MADM methods. Elkhayat et al. [47] proposed a systematic approach to rank high performance glazing systems for an existing building by applying a weighting method based on LEED (Leadership in Energy and Environmental Design) green building rating system [52]. The weights of matched criteria in LEED are used as a scale of the relative importance for the AHP pairwise comparison for establishing the final weight of criteria. Chen [53] developed a decision-making tool to facilitate technological innovation and lifecycle environmental sustainability by using the Analytic Network Process (ANP) [54], a general theory of relative measurement and generalization of the AHP method. Unlike other methods, ANP accounts for relative interdependences among criteria, however, it is very subjective and time-consuming when a large number of criteria is involved. Moghatadernejad et al. [55] compared MADM implementation methodologies and suggested that Choquet integral [56] is the most appropriate and reliable approach for façade design. The Choquet method addresses the interdependence among decision criteria through fuzzy measures, allowing for the consideration of both quantitative and qualitative measures. When integrated with the AHP method, it facilitates the generation of consistent preferences, enabling a comprehensive approach to decision-making. The principal challenge with the Choquet integral is the identification of the fuzzy measures when a high number of decision criteria is involved. This can be achieved either by supervised approaches, if information on the ranking or the total score of design options is available, or non-supervised approaches, when judgements from the decision makers are not required. Moghatadernejad et al. [57,58] presented different methodologies to derive the fuzzy measures and validate the application of the method in façade design. The authors highlight that (i) even minor interactions among criteria can impact the final ranking of design alternatives; and (ii) supervised methods offer valuable insights into the relationships among design criteria, providing valuable guidance when evaluating new design alternatives. Nevertheless, to establish reliable fuzzy measures, it is essential to employ a more extensive database. Additionally, there is a need to develop an easy-to-use framework that simplifies the application of the approach.

The capacity of MADM methods to handle complex decision problems and offer structured and intuitive decision-making processes makes them highly suitable for addressing the multifaceted nature of façade design and selection. However, it is important to acknowledge that the different MADM procedures have their own strengths and limitations.

Table 1
MADM applications in façade design.

Method	Authors	Aim of the study	Decision criteria
WSM	Leśniak et al. [59]	Evaluate variants of façade finishing technologies for one-storey commercial buildings	5 criteria (cost, frost resistance, maintenance, warranty period, assembly time)
WSM, WPM, WASPA	Zavadskas et al. [41]	Test the reliability of different methodologies. Select the best design solution for facades of public and commercial buildings	12 criteria (installation cost, labour intensity, user friendliness, durability, warranty, environmental friendliness, recovery, aesthetics, weight of structure, thickness of structure, sound isolation, fire resistance)
AHP	Moussavi Nadoushiani et al. [46]	Identify the most sustainable facade system to replace the existing worn façade of a building	17 criteria (embodied energy and carbon emission, heating load, cooling load, resource sustainability, material cost, labour cost, transport cost, maintenance cost, design cost, weight, thermal resistance, thermal mass, acoustic insulation, resistance to decay, aesthetics, suitability to location and to climate)
	Elkhayat et al. [47]	Select the most suitable high-performance glazing system. Propose a new weighting method based on LEED rating system to prioritize the alternatives	4 criteria (sustainability, environmental, economic, social), 20 sub-criteria
	Dement'eva [48]	Compare different hinged ventilated facades used in major repairs and reconstruction of buildings. Develop a decision making algorithm to choose the optimal solution	5 criteria (cost, maintainability, life time of service, complexity of mounting, adaptability)
AHP, AHP + TOPSIS	Moghtadernejad et al. [55]	Review of decision-making methods for façade design. Test the efficiency of alternative approaches in a simplified façade selection	8 criteria (aesthetics, weight, fire resistance, acoustics, environmental impacts, ease of construction, durability, initial costs)
AHP + TOPSIS, AHP + COPRAS	Ilter et al. [50]	Multi-performance testing on glass panel façade systems. Use the experimental results in a multi-criteria evaluation process to determine the performance levels	5 criteria (frontal deflection, air infiltration, air infiltration difference after seismic test, air infiltration difference after wind test, air infiltration difference between first and last air infiltration test)
AHP + TOPSIS, Fuzzy AHP + Modified Fuzzy TOPSIS	Mukhamet et al. [51]	Develop and validate a multi-criteria methodology for ranking phase change materials for building façade applications	13 criteria (thermal conductivity, latent heat of fusion, phase change temperature, specific heat, density, cycling stability, supercooling, initial cost, toxicity, flammability, corrosiveness, recyclability, embodied energy)
AHP + PROMETHEE	Rogulj et al. [43]	Support decisions in selecting the type of and solution for glass facades of a residential-commercial building	9 criteria (construction cost, maintenance cost, energy budget, construction complexity, aesthetics, functionality of use, safety, heat transfer, energy savings)
AHP + Choquet integral	Moghtadernejad et al. [57]	Propose and validate a systematic approach to support the design of optimal façade systems	15 criteria (thickness, weight, fire rating, vapour resistance, thermal resistance, noise reduction, window performance, ease of construction, energy consumptions, effect on environment, expected service life, initial cost, operation and maintenance cost, decommissioning cost, aesthetics)
Fuzzy TOPSIS	Akbari et al. [44]	Investigate and rank the façade functions in relation to the inside and outside of a home as a connector and barrier. Find the importance of façade functions for indoor spaces	7 criteria (visual access, natural ventilation and air flow, daylight, safety and security, privacy, noise pollution, climate issues)
COPRAS	Kaklauskas et al. [37]	Develop a method (COPRAS) to select the optimal window system for the retrofit of public buildings	14 criteria (mechanical strength and stiffness, reliability, thermal transmittance of profile and unit, emission ability, sound reduction, air permeability, water tightness, warranty period, durability, light transmittance, duration of works, number of windows with openings and closing infiltration air vent)
ELECTRE	Rey [40]	Develop a multi-criteria method for office retrofitting projects	9 criteria (annual energy use for heating, annual electricity use, annual emissions, summer thermal comfort, acoustic comfort, visual comfort - natural and artificial lighting -, renovation costs, annual on-going charges)
ANP	Chen [53]	Develop a multi-criteria model to select the most appropriate building façade taking into account design, construction and operation	37 criteria in 6 clusters (adaptability, affordability, durability, energy, intelligence, well-being)
	Yitmen et al. [60]	Evaluate the performance of adaptive façade systems in complex commercial buildings	19 criteria in 5 clusters (energy efficiency and environment, indoor comfort conditions, performance-related functions, maintenance and life cycle, adaptability)

- WSM is the simplest decision-making approach, well-suited for single-criteria decisions. In design problems with the same unit ranges across multiple criteria, WSM can be effective and easily applicable. However, if the different criteria are measured using different units, the problem becomes difficult to handle [61]. WPM is similar to WSM with the main difference being a product instead of a sum. WPM is a dimensionless analysis where each alternative is compared through a multiplication of ratios related to each criterion. Therefore, WPM is suitable for both single and multi-dimensional cases, but it prioritizes the alternatives based on the distance from the average. WASPA is a combination of both methods and has the ability to increase the accuracy of ranking. WASPA involves the optimization of the weighted aggregated function, thereby being able to reach a higher estimation of accuracy than WPM and WSM alone [42].
- AHP is the most commonly used MADM method in façade design due to (i) its use of hierarchies, enabling decomposition of complex problems into simpler sub-problems, reducing the overall complexity; (ii) its adaptability without significantly increasing computational demands; and (iii) its ability to handle both quantitative and qualitative criteria [55]. Furthermore, the AHP method, through its mathematical framework and the use of pairwise comparisons, provides the most consistent weighting judgments and offers mechanisms to verify data inconsistencies, which significantly enhances its reliability in decision-making processes. Additionally, the method can be easily combined with other MADM methods, allowing for a more robust decision-making process. However AHP

(i) can produce inconsistent ratings when a new alternative is added to the decision problem at a later stage, as the method is unable to change the ranking of previously evaluated alternatives [62]; (ii) has a subjective nature of the modeling process, meaning that the methodology cannot guarantee definitely true decisions; and (iii) building the model takes significantly more time and effort when the number of the levels in the hierarchy (i.e. the number of pair comparisons) increases [63]. Moreover, AHP assumes that there are no dependencies among the criteria, and this limitation can result in double-counting in the comparisons. It is worth mentioning that the ANP method, a more generalized form of the AHP method, can account for interdependency in the hierarchy by introducing network relationships. However, ANP is very subjective and scalability issues when a large number of criteria is involved, due to the sheer volume of pair-wise comparison combinations required.

- As discussed above, the AHP method is generally applied in a hybrid fashion: AHP is used to compute the weighted criteria, while the rank of decision variants is developed through other methods, particularly TOPSIS and COPRAS. TOPSIS has many advantages, including simplicity, computational efficiency and ability to measure the relative performance of each alternative using a straightforward mathematical function that calculates their distance from an ideal solution. The most significant disadvantage is the high subjectivity of the method, which stems from the reliance on subjective judgments and preferences in the process of assigning weights and determining the ideal solution [64]. When AHP is used in conjunction with COPRAS, it requires less calculation than when used with TOPSIS. The AHP-COPRAS combination also enhances the evaluation of both qualitative and quantitative criteria, due to COPRAS's ability to handle multi-criteria problems including those with imprecise or vague information. The main advantage of COPRAS is that the method is able to show the degree of utility, representing how well a given façade design satisfies the criteria or requirements established by the decision-maker, by comparing the analyzed façade with the most efficient one. However, COPRAS is less stable than TOPSIS and the calculation may be sensitive to the data variation [65]. PROMETHEE is also applied in combination with the AHP model in one of the studies reviewed. Through this method, the decision maker can express their preferences between two façade alternatives on all criteria using ratio scales [66], enabling more accurate evaluation of each alternative's performance against each criterion. PROMETHEE therefore facilitates group-level decision making by allowing the simultaneous evaluation of multiple alternatives against multiple criteria. However, the PROMETHEE method is known to be complex and time-consuming, especially when dealing with large or complex decision problems.
- Although the aforementioned decision-making methods have proven useful in selecting the best solution from alternatives, they share a common limitation: they do not account for the correlation among criteria. In many decision-making processes, the correlation among criteria is a critical factor that must be considered to avoid difficulties in selecting the best solution when the final decision scores are similar. The Choquet integral is an effective method to account for this interaction and it can be integrated with AHP to improve consistency in the design selection. The Choquet integral can also deal with uncertainties associated with decision makers' judgements. It is worth noting that these uncertainties can be handled by the other MADM procedures through the integration of fuzzy sets theory, thereby describing the subjective judgments of decision makers in a quantitative manner. The Choquet integral has been applied recently in façade design [55,57]. However, its main complexity lies in defining the fuzzy measures that describe the interaction among criteria. This process typically requires inputs from a panel of experts and can be impractical, especially when dealing with a large number of criteria. Consequently, the utilization of the Choquet integral may pose limitations in certain façade decision-making contexts, making it impractical or challenging to implement.

3.2. Multi-Objective Decision Making

Multi-Objective Decision Making (MODM) relies on the use of optimization algorithms coupled with numerical simulation to aid designers in exploring a large number of design options. Building performance simulation does not generate design solutions, but quantifies the performance of design candidates; while, optimization is a method for finding the best scenario(s) with highest achievable performance under certain constraints and variables. In general terms, optimization seeks the minimum or maximum value of an objective function by identifying the best set of variables within pre-defined constraints. In the context of façade design, the objective function represents a performance indicator, often computed through simulation. The process consists of (i) defining design variables and constraints for the specific problem; (ii) analyzing the performance of these solutions through computational simulation tools or mathematical equations; (iii) iterating this approach until convergence to the optimal solution, in terms of a pre-defined set of performance criteria, is attained. The time and resources required to complete the process mainly depends on the time needed to evaluate the alternatives by simulation tools. When conflicting goals are involved, multi-objective optimization algorithms are employed to identify a set of "non-dominated" solutions or "Pareto frontier" (Fig. 5), meaning that there is no other feasible solution that improves one objective without deteriorating at least another one [67].

Optimization tools for façade design consist of programmed algorithms (typically developed in MATLAB or Python), specific optimization solvers (such as Octopus in Grasshopper algorithmic modelling) and general optimization packages (such as GenOpt [69]). Although many types of optimization techniques exist, performance optimization frequently employs stochastic population-based algorithms, particularly Genetic Algorithm (GA) [70]. GAs broadly belong to the gradient-free optimization family: unlike gradient-based optimization algorithms that rely on the calculation of gradients or derivatives, GAs do not require explicit gradient information. GAs draw motivation from processes of natural evolution, using mechanisms such as selection, crossover and mutation to iteratively explore and search the solution space. This characteristic grants them scalability and ease of use, particularly when dealing with discrete variables. The algorithm can efficiently handle non-linear problems with discontinuities and many local minima. However, they lack the crucial information captured by gradients and Hessians of the objectives and constraints, which affects their convergence, optimality and stability properties. GA-based multi-objective optimization methods commonly used in façade research include Non-dominated Sorting Genetic Algorithm (NSGA-II) [71] and Strength Pareto Evolutionary Algorithm (SPEA-2) [72]. Empirical performance and evaluations suggest that NSGA-II is able to ensure both the convergence of the population and its spreading (i.e. to maintain a diverse set of solutions in the population), while SPEA-2 represents an improved algorithm which can have advantages over NSGA-II in multi-dimensional spaces. However, several limitations affect the GA-based methods, such as the high computational demand due to the large number of simulations to be run. Moreover, despite their ability to escape local optima, identifying global ones is often still elusive in practical large-scale applications. On one hand, micro-GA algorithm have been developed [73] to allow for a fast converging algorithm with low computational cost by reducing the population size and number of generations to converge. On the other hand, it is worth noting that finding a global optimum may not be necessary, as identifying a set of alternatives can suffice as an initial design rather than a final one.

Evolutionary GA-based methods represent the most widely adopted procedures in façade design, particularly because they handle discrete variables effectively. Many authors used GA processes in single objective problems, targeting: (i) natural ventilation, to optimize the shape and position of façade openings [74,75]; (ii) energy efficiency, to optimize the building envelope, and orientation, shape, or both shape and orientation [76,77]; and (iii) illuminance, in order to optimize shape, number, position and properties of openings or shading louvers [78–80]. However, to better solve the complex façade design problem and achieve a high impact on the final outcomes (e.g. highest performance, lowest cost, etc.), several studies have focused on multiple objective GA-based optimization at early stage design. These investigations involved different performance aspects in the objective functions, such as: (i) natural ventilation with energy consumption and visual comfort [81,82], (ii) heating and cooling performance with daylighting [83–86], (iii) illuminance and glare [78,87]. Due to the importance of both cost optimality and environmental sustainability in façade design, other authors embedded either cost effectiveness [88,89] or environmental impact [90] or both [83,91] within their multi-objective façade optimization. Particularly, Jin and Overend [91] developed a comprehensive methodology based on a whole-life value approach accounting for social, economic and environmental aspects associated with all the different stages of the façade life-cycle.

These GA-based investigations traditionally employ a fixed geometry for the building, while variables for optimization usually include physical properties of materials and construction systems. However, the building form or geometry is one of the most important decisions at early-stage design, influencing aesthetics and building functions whilst greatly affecting solar radiation receipt, natural light and heat transfer. Therefore, further studies have focused on building form and facade optimization in order to minimize the energy consumption while simultaneously increasing thermal and visual comfort based on solar radiation or natural light penetration [92–98]. In this context, Jalali et al. [99] investigated the effect of building envelope changes on the interior space of the building, rarely taken into account and evaluated on the basis of the building geometry. Nevertheless, all the cited GA applications focused on finding one or more solutions for a problem defined by a limited number of simplified constraints. This contrasts with the requirements of façade design which typically involves a large spectrum of design and manufacturing criteria. Taking this into account, Montali et al. [100] proposed an interactive procedure allowing for a properly-constrained optimization accounting for both physical features of the product and the underlying design and manufacturing knowledge along the lines of a design-for-manufacture-and-assembly approach.

An overview of published research on the use of GA multi-objective optimization methods in façade design, showing the multiple objectives, the design variables and, when specified, the type of GA-based method involved, is shown in Table 2.

Hybrid algorithms, involving the implementation of more than one optimization algorithms in a hybrid operation, are also widely used in building design research. The typical procedure consists of (i) adopting a global search algorithm to find a near-optimal solution; and (ii) using the result as a starting point for a local optimizer. A good example of this operation is implemented in GenOpt [69], a generic optimization program for the minimization of a cost function that is evaluated by an external simulation software, such as EnergyPlus or TRNSYS. The hybrid algorithm in GenOpt consists of a Particle Swarm Optimization (PSO) [102], another nature inspired computational intelligence method, which starts searching for a global minimum region, while the Hooke-Jeeves direct search method [103] continues searching in order to refine the position of the minimum. Focusing on façade design problems, the use of hybrid optimization through GenOpt can be found in various studies involving energy consumptions and daylight or the life-cycle cost [104,105] as functions to be optimized, and mainly looking at the design of curtain wall facades for new office buildings [106,107]. Within the nature-inspired algorithms, Chatzikonstantinou et al. [108] tested the applicability of Differential Evolution (DE) [109] to design a diagrid façade considering interior daylight distribution and panel construction cost in the objective functions, showing that DE can be another effective tool for façade design problems.

Concluding, MODM can be used to extensively explore the full realm of design possibilities and generate optimal solutions. By coupling building performance simulation and optimization, and accounting for multiple performance objectives and project-related constraints, high-performance solutions can be identified at the early stages of the design process.

- Initial MODM applications in façade design focused on single-objective problems. However, single-objective optimization is driven by dominating contributions, which can be controlled by weighting averages over individual contributions [110]. Therefore, this approach suffers from various drawbacks, such as the a-priori selection of weights and the convergence to a single solution which is affected by this weight selection.
- Evolutionary algorithms are the most popular methods for solving multi-objective façade optimization. Most of the authors employed GA, an efficient family of algorithms for searching in a guided manner the state space to find near-optimal solutions. GA is a stochastic algorithm that can handle both discrete and continuous problems. However, the method is computationally expensive due to the large amount of simulations to be run to ensure optimality of the final solution, and it typically lacks convergence guarantees. To address this issue, some researchers have employed the micro-GA algorithm, which utilizes small populations that are more efficient at identifying promising areas of the search space [111]. Although small populations may face challenges in preserving diversity over multiple generations, it is possible to retain the best-fit individuals and restart the population when diversity is lost.
- Within the evolutionary algorithms, the DE method has also been tested in the context of façade design. DE is a population-based stochastic algorithm with multiple advantages, such as simplicity due to few control parameters, local searching properties, and fast convergence. Moreover, it has been demonstrated that DE is often able to explore the decision space more efficiently than GA [112].

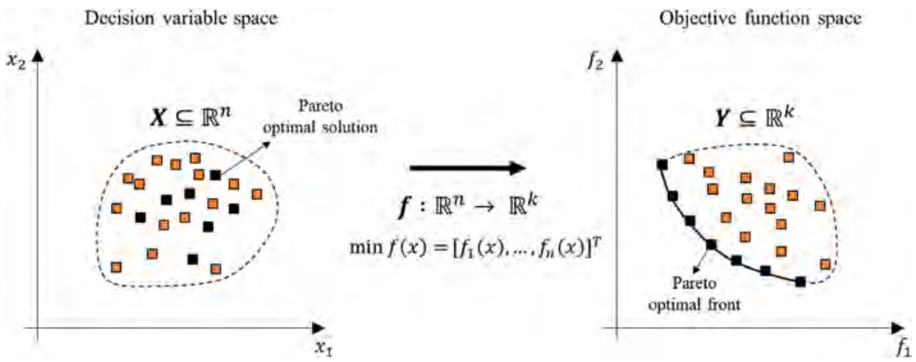

Fig. 5. Pareto frontier (modified after López Jaimes et al. [68]).

Table 2
GA-based multi-objective applications in façade design.

Method	Authors	Aim of the study	Objectives	Variables
Micro-GA	Caldas [83]	Develop an evolutionary-based generative design method to achieve energy-efficient and sustainable solutions	Case 1: annual illumination Case 2: natural lighting and energy performance Case 3: energy consumptions, construction costs, embodied energy Case 4: daylight use and thermal performance Case 5: energy efficiency, Case 6: heating energy and daylight	Case 1: geometrical description of spaces, facades, roofs and other elements, Case 2: alternative façade solutions, Case 3: building materials Case 4: as Case 1 Case 5: architectural form, Case 6: shape generation
	Gagne and Andersen [78]	Explore facade design based on illuminance and/or glare objectives	Illuminance, Daylighting glare probability	10 variables: Window-to-Wall ratio, number of windows, aspect ratio, vertical and horizontal location, window distribution, overhang, fins, length of shading devices, total glass transmissivity, percent transmission
GA	Torres and Sakamoto [81]	Determine the applicability of a GA for the optimization of daylighting systems	Visual discomfort and daylight penetration	21 variables encoding size, number, position of windows and fixed protections, reflectance of surfaces
	Shan [88]	Provide a method for optimizing building facade to achieve the minimum annual energy cost	Heating, cooling and lighting loads, total cost	Dimensions of window grids, depth of the shading system
	Marzban et al. [82]	Optimize single-sided naturally ventilated residential buildings	Ventilation efficiency, cooling/heating load and number of discomfort hours, and visual comfort	13 variables related to openings geometry and types, balconies geometry, type of shading, construction and insulation types, neighboring units
	Montali et al. [100]	Develop and validate a process to build product-oriented knowledge bases and design tools and help designers find optimal façade solutions	Operational and embodied carbon	Panel height and width, position of panels, air layer thickness, window position and height, concrete infill position and height
NSGA-II	Evins et al. [101]	Derive the best configuration and control of Double-Skin Facades	Cooling and heating load	20 variables related to cooling and heating mode, control glazing
	Chantrelle et al. [90]	Develop and validate a multi-criteria tool for the optimization of renovation operations	Cooling, heating, lighting, ventilation, thermal discomfort, environmental impact	Variables related to control strategies and HVAC systems; 6 variables for the building envelope: external wall type, roof type, ground floor type, intermediate floor type, partition wall type, window type
	Kasinalis et al. [84]	Develop a framework for design and performance analysis of climate adaptive building shells with optimal seasonal adaptation strategies	Heating, artificial lighting, indoor environmental quality	Density, specific heat, thermal conductivity, external surface absorbance, window-to-wall ratio, glazing ID
	Jin and Overend [91]	Develop a prototype whole-life value optimization tool for façade design; test the tool on a real-world façade design project	Whole-life cost, Whole-life carbon emissions	8 variables related to: glazed facade geometric parameters, glazing types, spandrel panel type
	Méndez Echenaguci et al. [85]	Develop an integrative approach to obtain detailed information on energy efficient envelope configurations	Heating, cooling and lighting energy	Thickness of the masonry wall; number, shape and placement of windows; glazing characteristics of the windows
	Yang et al. [89]	Apply multi-objective optimization to design green building envelope material	Envelope construction cost and energy performance, window opening rate	Number of windows, window length, window width, window glass material, wall material, glass curtain material, roof material, sunshade type, sunshade board size
	Li et al. [80]	Develop an approach combining machine learning and computer-aided design methods for adaptive facades	Daylight illuminance, daylight autonomy, daylight glare probability	Unit type, unit width, unit height, unit distance, rotation angle, room width, room length, room height
	Wen et al. [87]	Develop a parameterization method for the selection and design of a shading strategy	Spatial glare autonomy, spatial daylight vote autonomy	Hole diameters, rotation angle, slat width, slat number, extension length
	Nazari et al. [98]	Optimize a commercial (retail stores and supermarkets) building envelope	Heating and cooling energy, Indoor environmental quality	Orientation, diameter ratio (ratio of the building large diameter to its small diameter), window-to-wall ratio
SPEA-2	Jin and Joeng [93]	Define an optimization process for a free-form building shape in the early design stage	Envelope heat gain, heat loss and solar heat gain	Shape and footprint of the building
	Moraes and Pereira [94]	Develop a process to optimize building facades for solar irradiation	Economic viability of the photovoltaic installation	4 variables related to building shape
	Zhang et al. [95]	Optimize the thermal and daylight performance of school buildings	Energy use for heating and lighting	Orientation, room depth and corridor depth, window-to-wall ratio of different interfaces, glazing materials and shading types
	Fathy and Fareed [96]	Optimize the design of a parametric double skin façade to maintain sufficient daylighting conditions to meet LEED requirements while maximizing energy savings	Illuminance intensity, energy loads from cooling and heating	Distance between the outer skin and the inner skin, depth of the outer skin, openness factor in the outer façade, scale factor of the opened cells
	Fang and Cho [97]	Develop and test an optimization process to evaluate the daylighting and energy performance of design options and generate optimized design	Daylight illuminance, energy use	Building depth, roof ridge location, skylight width, skylight length, skylight location, south window width, louver length, north window width, and skylight orientation
	Jalali et al. [99]	Optimize an office building facade through a genetic algorithm with the sustainability approach	Thermal load; useful space inside the building; shape coefficient; amount of natural light	Changes in angles, form rotation, lengths and widths, building heights, and number of floors
	Kim and Clayton [86]	Develop a multi-objective optimization framework to support the climate-adaptive building envelope	Cooling load, daylighting performance in summer season	Operation scenarios in the climate adaptive building envelope system

(*continued on next page*)

Table 2 (*continued*)

Method	Authors	Aim of the study	Objectives	Variables
		design decision-making process using a parametric behavior map		
	Fan et al. [98]	Develop a multi-objective facade optimization method for stadium design, using image density atlas	Daylight illuminance, solar radiation load and daylight glare probability	Opening and closing degree of the gymnasium facade

However, the efficiency of the search for the global minimum is very sensitive to the choice of the control parameters and can be disadvantageous in some global optimization problems [113].

- Several authors adopted existing optimization software packages in their multi-objective studies, such as Octopus plug-in for Grasshopper environment and GenOpt [69], a general optimization program which can be easily coupled with any simulation software. Octopus is based on SPEA-2 algorithm, a GA-based method able to keep the desired convergence properties and to maintain a good distribution of solutions. GenOpt involves a hybrid algorithm combining PSO with direct search methods. PSO is known to have difficulty in finding the global optimum in high-dimensional spaces and can have a low convergence rate in the iterative process [114]. Direct search methods, on the other hand, can improve solutions as long as they overcome small discontinuities in the cost function and small local optima. By combining both methods, GenOpt aims to achieve better performance in terms of finding the global optimum while overcoming the limitations of each individual method. These existing tools provide ease of access to optimization processes and ease of application for the majority of designers who are not experts in computational optimization.
- In multi-objective optimization for façade design, it is important to consider constraints related to manufacturability in addition to the design optimization problem. However, many research studies tend to focus solely on the optimization problem without taking into account manufacturability constraints. To address this issue, advanced performance modeling methods have been developed that incorporate both design and manufacturing knowledge, resulting in a more reliable and practical optimization-based design process. These new design processes involve iterative optimization procedures that are constrained by the physical features of the product, allowing for the identification of solutions that are both optimal and manufacturable [100].

3.3. Role of machine learning methods

Building/façade optimization typically involves a large-number of computationally intensive simulations. For instance, for an energy efficiency assessment, multiple calls may be required to cover energy performance over a meteorological year, whereas, in a seismic vulnerability/fragility assessment, a large number of nonlinear dynamic analyses is necessary to adequately quantify safety-related risks. A way to address this challenge is by combining machine learning methods with multi-objective optimization techniques. Surrogate models built on simulation data, such as Artificial Neural Networks (ANNs) [115], are often used to expedite the process. ANNs, inspired by the biological nervous system, map inputs to outputs through layers of connected neurons. Training ANNs involves adjusting weights by backpropagating errors until predicted outputs match pre-specified targets. Once properly trained and validated, ANNs act as surrogate models, substituting external simulation programs. Coupled with multi-objective algorithms, they can assess objective and constraint functions faster within acceptable accuracy losses. However, quality outcomes depend on the data used during the learning phase, typically requiring substantially large datasets of carefully selected features for effective training through numerous offline simulations. Finding optimal ANN structures and hyperparameters also involves a significant component of trial-and-error by the user, in order to strike a balance between computational demand and accuracy. Proper training, validation, and testing are crucial for ANNs generalization to new unseen data. This is particularly important when coupling surrogates, such as ANNs, with optimization methods, since optimal designs may lie outside the limited subspace captured by the training data.

The implementation of ANNs coupled with optimization in façade problems has mainly emerged in recent years. Particularly, the efficiency and advantage of applying ANN-based performance simulation with GA has been studied in different problems involving annual energy load and summer thermal comfort [116], cooling energy with thermal comfort and indoor air quality [117], thermal and visual comfort with both energy consumptions and energy costs, daylight and energy [87,118,119], energy and cost objectives [121]. Physics-informed neural networks are also emerging in building design (e.g. [120]) as they combine data-driven approaches with the mathematical properties inherent in physics-based problems. Consequently, these networks typically require less data while still capturing the underlying physics accurately. The above-described ANN implementations, either under their purely data-driven or physics-informed instances, belong to the general family of supervised learning approaches.

Reinforcement learning [122] is another machine learning family that is gaining attraction in the context of sequential decision-making and control optimization for facades/buildings. Deep Reinforcement Learning (DRL) is an extended version combining classical reinforcement learning principles with ANN parametrizations. This paradigm empowers a computer program (agent) to learn decision-making strategies that achieve specific goals. In traditional reinforcement learning, the agent learns by interacting with its environment and taking actions to earn rewards. DRL enhances this process since neutral networks allow us to handle more complex state and decision spaces. Training DRL agents can be, however, often computationally intensive due to the need for numerous simulations and interactions with the environment. An example of DRL applications in façade/building optimization can be found in the work of Han et al. [123], where the technique is used to optimize the timing of window opening/closing by observing and learning from the environment. Another application can be found in Park et al. [124], who utilize DRL to learn individual occupant behaviors and indoor environmental conditions, adapting control parameters accordingly through personalized set-points.

Furthermore, initial research is being further conducted on Multi-Agent Systems (MAS) approaches within the reinforcement learning agent-based paradigm. Multi-agent-based design allows modeling different domains as agents to support design exploration through heuristic search. It facilitates adjusting parameters and identifying façade alternatives based on preferences and performance goals. However, MAS presents challenges in emergent behavior, system robustness, and reliability [125]. Emergent behavior arises when the system's overall behavior is not a simple sum of individual agents' actions, leading to hard-to-control and unexpected outcomes. System robustness deals with the ability to function despite agent or component failures. System reliability, on the other hand, refers to the system's correct and consistent performance over time. Initial research towards the integration of performance-based goals with geometric formation through a decentralized and agent-based approach can be found in the research developed by Gerber et al. [126] and Pantazis and Gerber [127]. The authors developed a MAS-based design tool for daylighting design and optimization. This approach allows for customization to align with the specific needs of designers. The software works through generative agents and behaviors initially acting alone to develop design alternatives. The alternatives are subsequently analyzed by a set of specialist and user preference agents, that communicate their data back to the generative agents to adjust parameters and regenerate design alternatives based on specific preferences and performance goals.

Apart from reinforcement learning, generative artificial methods are also emerging for façade and building mass generation. Deep generative design, within the unsupervised learning family, leverages deep learning techniques like neural networks to autonomously generate and optimize designs, effectively automating and enhancing the design process through the integration of generative algorithms. However, deep generative design often requires a large amount of design data, which may not always be accessible, and the resulting designs may lack clear explanations, making it challenging to understand and validate the design process. Within these methods, various authors have implemented Generative Adversarial Networks (GANs) [128] in the context of façade applications. In the context of urban renovation, Yu et al. [129] applied GAN technology in the context of urban renovation for façade recognition and generation, showcasing its potential for façade review, digital design, drawing assistance and for expanding creative work using AI. Sun et al. [130] developed a GAN-based decision-support tool to automatically generate stylized facades, evaluated its effectiveness through quantitative and qualitative assessments, and demonstrated its significant potential for enhancing the conventional design process for historic urban area renovation.

3.4. Conclusions from the reviewed studies

Based on the collected publications, the literature data are further analyzed to identify the dominant performance criteria and the types of applications that have been explored in these research studies (Fig. 6). Energy efficiency and daylight control (in 33 and 35 studies, respectively) are the predominant aspects identified as important criteria or objective functions in MADM or MODM. Specifically, optimization mainly focuses on minimizing the cooling energy and the total energy consumptions and maximizing visual comfort for occupants. Several studies also account for the initial cost and thermal comfort (each in 18 studies) as primary performance aspects for façade design, with the thermal comfort typically expressed in terms of Predicted Percentage of people Dissatisfied. Moreover, both structural performance, i.e. the verification of allowable stresses and/or displacements, and the environmental footprint, particularly in terms of embodied energy, are involved in many works (16 studies). Focusing on the functional category, different MCDM works also aimed at glare control (13 studies), air quality (13 studies) and aural comfort (11 studies), to target an optimized comfort for building occupants. Particularly, these studies focused on satisfying Indoor Environmental Quality within their MCDM procedures. Durability is also involved in different MADM procedures by evaluating the expected service life of the façade system (8 studies), while few researchers accounted for water penetration resistance (4 studies) and condensation resistance (2 studies) as additional durability criteria. Regarding the cost-effectiveness, rehabilitation and maintenance cost are also involved (11 studies) in MADM approaches, while operation cost (8 studies) and disassembly cost (5 studies) are considered when full life-cycle analysis are conducted. It is worth noticing that fire protection is also investigated in some MADM investigations (6 studies), while both blast resistance and dynamic performance are absent in the reviewed papers. Finally, due to the increasingly strong sensitivity to the environment, recent MADM investigations also account for reuse and recycling (3 studies), use of renewable resources (2 studies) and climate adaptability (3 studies) to select the best façade amongst alternatives. The data also indicate that the majority of papers (73 %) utilize MCDM procedures for new designs, with a particular emphasis on selecting the optimal façade for office buildings (42 %). The remaining studies reviewed (27 %) focus on façade retrofitting/refurbishment, primarily examining public structures such as school buildings (29 %).

Referring to the implemented methodologies, Fig. 7 provides an inclusive overview of all the MCDM approaches (where main categories are depicted by rectangular shapes, while dashed lines indicate the integration of techniques) adopted in the reviewed papers discussed earlier. MCDM offers a structured approach to evaluate and rank alternatives based on predefined criteria, aiding informed choices by considering design attributes' relative importance. In contrast, MODM provides a comprehensive approach, exploring the full range of possibilities by considering multiple conflicting objectives simultaneously. MODM facilitates the search for Pareto-optimal solutions that balance competing design objectives through trade-offs. The choice between MADM and MODM depends on specific requirements and the solution space each method can explore, taking into account design space complexity and desired levels of exploration and optimization. MADM is effective for scenarios with a predefined set of facade solutions, enabling decision-makers to prioritize selection based on predefined criteria. MODM is more appropriate when there is a need to optimize the design space. Combining MADM and MODM provides a comprehensive decision-making framework, encompassing both predefined options and design space exploration. If the MADM space is smaller than the MODM space, a designer can start with an MADM solution for a quicker identification and then initiate MODM optimization based on that initial 'guess,' or vice versa.

Despite the exploration and comparison of various MCDM methods in the literature, further investigation is needed to determine the most suitable method for façade design. Stakeholders' requirements greatly influence the selection of an optimal façade design, and the choice of optimality criteria can yield different outcomes with different methods. With regard to MADM methods, there is still a need to identify a reliable and user-friendly design support tool that can effectively combine quantitative and qualitative data while accounting for attribute correlation. This will facilitate a shift from traditional façade selection processes to performance-based decision-making processes that embed design priorities for the specific case-study scenario. In MODM methods, defining a real design problem in a mathematical domain has some limitations. However, by using MODM tools and algorithms in combination with their expert knowledge, designers can improve façade performance compared to common practices that do not involve optimization. Designers can reduce the solution space or steer the search in the right direction by using MODM tools and algorithms. Moreover, the integration of machine learning techniques can further improve the efficiency and effectiveness of the design optimization, opening up new possibilities for creative and high-performance façades (see Section 3.3). As such, research is ongoing to integrate optimization into real-world façade design processes effectively. This involves identifying suitable approaches tailored to specific façade problems, considering factors like design complexity and optimization objectives. Furthermore, there is a need to explore and develop techniques for reducing simulation time when optimizing alongside building energy simulations.

4. Opportunities and research challenges

Recent developments and drivers largely from outside the field of façade engineering present notable opportunities and associated research challenges for multi-criteria methods in façade design. These are identified and discussed in turn in this section.

4.1. Uncertainties and risk analysis

The robustness of a design decision is unknown unless uncertainty is considered explicitly in the design process. In this way the performance-based design solution not only fulfills the pre-established performance requirements, but also provides acceptable performance under uncertainty. However, multi-criteria façade design typically neglects the influence of uncertainty (modelling and hazard-related) as well as the risk attitude of stakeholders in decision making.

In the literature, there are initial studies that deal with uncertainty in MADM methods. Hopfe et al. [62] highlighted the effectiveness of including uncertainty in a AHP process in order to inform the design team about the predicted building performance and its risks, thus addressing a rational decision. Muin et al. [131] developed a decision making framework involving uncertainty quantification (for light, thermal energy consumptions and initial costs) and probabilistic analysis to assess the performance of conventional vs. innovative facades. Homaei and Hamdy [132] proposed a new decision making method, the “T-approach”, integrating robustness assessment and defining a multi-target key performance indicator based on the building performance and deviations from performance targets. Moschetti et al. [133] validated an extension of this approach to identify the most robust responsive building envelope.

Focusing on optimization problems, uncertainty in design variables, environmental parameters, and noise in the output and constraints should be considered to develop a robust multi-criteria optimization [134], which leads to the identification of a global robust Pareto front. Despite not focusing on façade only, an initial application of a robust optimization can be found in the recent work developed by Chang et al. [135], who proposed a GA-based multi-objective algorithm accounting for uncertainties in the objective functions. The authors aimed to identify the optimal building envelope renovation options to satisfy indoor thermal comfort, energy balance, environmental emissions and economic aspects. However, embedding all the different sources of uncertainty would lead to a highly computationally intensive process, therefore, sensitivity analysis should be carried out to identify the most sensitive design variables. Furthermore, to reduce simulation time and assess robustness more quickly, meta-models or surrogates can be utilized to approximate the objective function. For instance, Hopfe et al. [136] employed the highly accurate Kriging metamodel for the design optimization of an office building, while Li et al. [137] utilized ANNs as the building performance model in their robust design optimization of entire zero/low energy buildings, which included both the building envelope and services.

Selecting a robust high-performance solution is challenging, and inaccurate descriptions of uncertainty in design parameters can result in improper uncertainty analysis. However, a risk-based MCDM procedure that involves performance evaluation and uncertainty assessment could be effective to address investment decisions in façade design. Uncertainty quantification should encompass both epistemic uncertainties associated with the specific design problem, such as mechanical properties, loading/mass values, design variations (e.g., equipment density, load people, heating and cooling set points, etc.) and aleatoric uncertainties associated with the specific hazard, such as earthquakes or hurricanes [138,139]. Accounting for all these uncertainties is essential for developing a robust assessment framework, potentially enabling the definition of uncertainty factors for use in simpler and more practical analyses. This can result in solutions with better performance and reduced cost when compared to (semi-) deterministic design [140]. It is therefore essential to explore uncertainty-based MCDM methods, striking a balance between computational time and analysis complexity, to enable decision-makers to robustly evaluate design alternatives.

4.2. Seismic safety considerations

Although simplified or advanced multi-criteria design approaches have been proposed, none includes the seismic safety within the performance indicators. Seismic performance is hardly mentioned when defining the general design framework, while no practical application involving seismic safety of building facades can be found in the literature, when the majority of the buildings investigated in the reviewed papers are located in seismic-prone areas (Fig. 8a).

Facades may lose functionality even in low-intensity earthquakes, and can be seriously damaged or destroyed in moderate-to-high intensity events (Fig. 8b). This poses a potential life-safety threat to building occupants and pedestrians, while leading to substantial socio-economic losses (even greater than the structural losses), negative impact to the environment, and market disruption. Moreover, building facades represent a large portion of the construction investment in buildings, e.g. unitized systems can account for 20–30 % of the total cost and this percentage could even increase when more functions such as the active contribution to the building services is considered [3].

As such, the development of innovative damage-control or earthquake-proof technologies for facades is crucial for enhancing community resilience in seismic hazard zones [143,144]. However, it is equally important to incorporate the seismic performance of facades

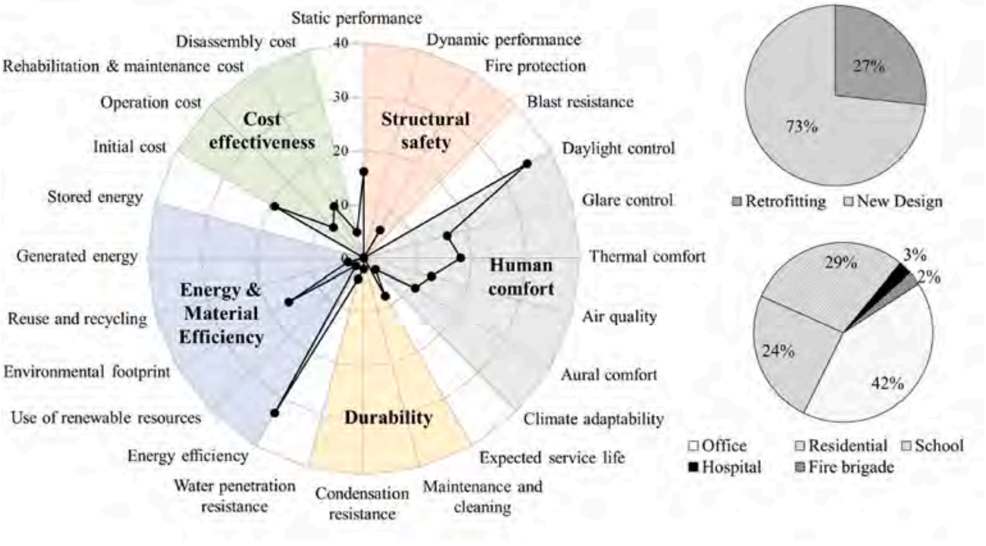

Fig. 6. Performance criteria and type of application investigated in the reviewed papers.

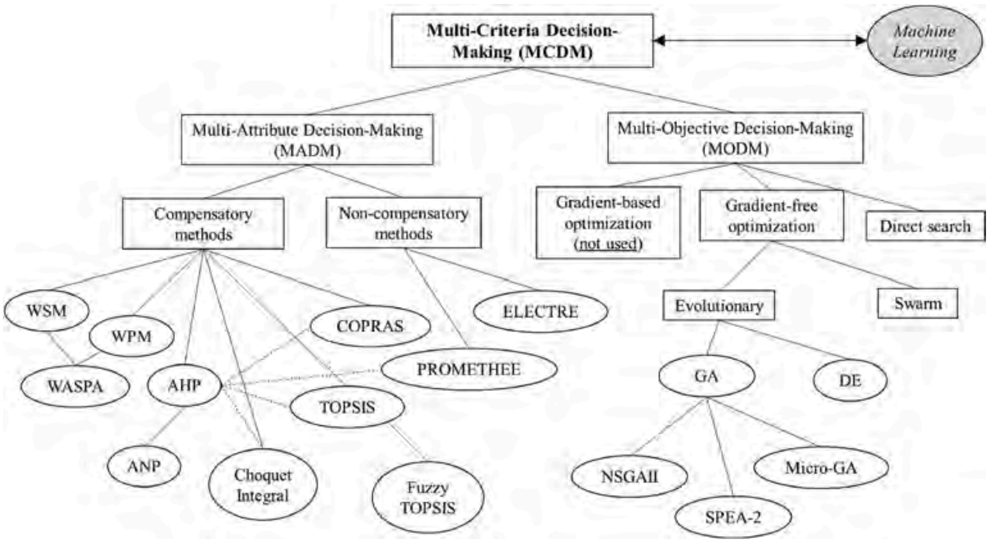

Fig. 7. MCDM façade engineering methods applied in the reviewed papers.

into the decision-making process from the early stages of design. By doing so, stakeholders can select high-performance and safer solutions, thereby preventing severe economic losses and business interruption due to severe damage after earthquakes. Initial research efforts are acknowledged towards the development of integrated approaches combining seismic safety, environmental sustainability and cost effectiveness for retrofit/refurbishment interventions [e.g. [145,146]]. However, these investigations have mainly focused on simplified procedures and global building-level assessments. Moreover, a consolidated framework for façade design and retrofitting that integrates seismic safety with other performance measures, based on MADM or MODM or a combination of both, is still lacking. A design procedure and tool should be developed to support the selection of resilient façade technologies and interventions in earthquake-prone regions. Furthermore, while this paper specifically focuses on seismic safety, the integration of safety considerations is applicable to other natural disasters or extreme events, such as hurricanes or floods, based on the specific multi-hazard local scenario.

4.3. *Smart building information modeling*

BIM is a powerful tool that facilitates cross-disciplinary collaboration and knowledge sharing among stakeholders involved in the design, construction and operation of a building. BIM is a multi-dimensional model that improves work efficiency, enhances quality, and minimizes the risk of data loss. Applying BIM from the early design phase can provide positive impact to a project, being cheaper and better to make changes earlier than in a later design phase [147]. Additionally, integrating BIM and MCDM procedures certainly represents another important step forward to enhance façade design and facilitate the application of decision-making methods to designers, enabling stakeholders to collaborate across their value chains. Efforts to integrate BIM and façade optimization can be seen in the initial research conducted by Gagne and Andersen [78]. The authors integrated GA methods with BIM to allow designers to customize both the design and the performance goals through building models, automatically generated during the GA process. Recent investigations [e.g.148-150] have focused on the development and validation of BIM-based frameworks to enable designers to explore design options through a visual programming user interface (e.g., Dynamo in Autodesk Revit), by generating models of the alternative solutions, assessing the performance of the models and searching for the optimal design. All of these studies demonstrate that using BIM in the decision-making process provides several benefits, including: (i) increased confidence in the generated solution by balancing construction and production constraints with design requirements, (ii) visualization of the effect of changes in the model and planning process for designers and clients, and (iii) enhanced level of automation. Additionally, BIM-based simulations can account for other dimensions such as schedule management, allowing for better control of overall façade performance from a life-cycle perspective. As more information is integrated into the BIM model, a more holistic process and optimization can be achieved.

Looking at automatization procedures within the Industry 4.0 technologies, integrating MCDM with Augmented Reality (AR) presents an exciting opportunity in façade design. This integration could provide a simpler and more accessible way for building users, customers and suppliers to interact with the design process. One of the first applications and proofs of the advantages of this integrated method can be found in the work developed by Sangiorgio et al. [151]. They proposed an AR-based decision-making procedure based on the hierarchical structure of AHP. The authors validated the method for precast concrete panels accounting for alternative criteria such as aesthetics, production and executive needs, thermal behavior, and costs. The AR-based approach was found to be fast and intuitive, allowing the decision-maker to carry out a comparison of the design parameters through a simple procedure. Specific models helped in understanding the problem parameters, and consistency tests were conducted according to the AHP theory. Therefore, the main advantage of an AR-based approach is its ability to communicate and involve non-expert decision makers. However, this approach may only be effective when certain performance criteria are involved, while other criteria may require more advanced simulations and procedures to identify the best solution. Consequently, more studies are required to investigate the effectiveness of this approach for a wider range of criteria and design scenarios, and investigate its potential in real-life design and construction projects.

4.4. *Climate-resilient façade design*

The built environment is increasingly facing events due to climate change, such as high temperatures, strong winds and heavy rainfall. Buildings have not been designed for these climate-related extremes and they are vulnerable and non-resilient to such events (insured losses for climatological events alone are 7–16 % of the total economic losses in Europe [152]). As a result, building systems often struggle to fulfill their primary functions, such as ensuring structural safety, as well as operational functions like providing comfortable environments for occupants.

These climate-related events add another series of hazards to the other disruptive events such as earthquakes or explosions. Altogether these hazards have significant consequences on the resilience of the overall building and, in particular, of the building facades. Building a resilient society is therefore increasingly recognized as a socio-economic and political priority and the overarching goal of risk reduction and management policies. Within the building industry, this means that building components should be able to absorb and recover from the effects of an external event as well as to adapt to the changing environment. The concept of resilience is defined differently depending on the research field, however it is typically expressed as the capacity of a system to "bounce back" to an equilibrium state (or "bounce forward") within a recovery time, after absorbing the impact of an external, natural or man-made, event [153]. Resilience refers to both strength and flexibility of a building, and facades certainly play a critical role to reduce the risk of sub-standard performance levels.

Although research is increasingly moving towards the study of climate change impacts on building facades (e.g. [154,155]), research efforts are needed to develop effective frameworks and tools for assessing and mitigating the overall multi-hazard risk of building facades. Such frameworks must account for the short- and long-term consequences associated with weather variations and extreme events. Furthermore, to support the design of resilient facades, resilience considerations should be included in multi-criteria decision making from the early stage design, where key decisions are made to target high-performance designs. This would help stakeholders to identify appropriate designs or mitigation measures based on their positive impact in terms of resilience. However, in order to be included in the design process, a quantifiable resilience index/measure should be first identified. While there are emerging concepts, definitions and initial frameworks for assessing thermal resilience in the literature [156–158], defining facade resilience requires an indicator or curve that accounts for all potential events that may occur over the lifespan of the facade. This includes the impacts of both gradual environmental changes and disruptive events (Fig. 9). The long-term effect of climate change has impact on the façade *Robustness*, its inherent strength to withstand external demands without degradation or loss of functionality, and *Redundancy*, defining the inclusion of redundant elements or properties to provide backup or alternate options when subjected to stresses or failures. In case of an extreme event, *Resourcefulness*, meaning the capacity to manage operation and/or resources and services under emergency conditions, and *Rapidity*, at which disruption can be overcome, are also mobilized. These represent the four principles of resilience or the so-called 4R's following the framework defined by Bruneau et al. [159]. Concluding, an integrated resilience indicator should be identified and embedded as design parameter and/or target objective in the early stage design of building facades to define robust, adaptive and less vulnerable solutions.

5. Conclusions

Developing effective design methods is crucial for achieving high-performance facades. Today, designers have access to a wide range of computation-based approaches and techniques, enabling automation and enhancement of the design process, especially at the early stages. Facade design is intricate, involving numerous variables and conflicting performance criteria that require complex decisions. Complexity is amplified by project goals, limitations, and constraints specific to each case study. Optimal facade solutions should not merely meet requirements but aim to maximize the overall performance and consider interactions among various criteria.

To develop an integrated approach for façade design, research efforts to-date have largely focused on the identification of key performance criteria, and the definition and validation of decision-making methods to support the façade selection. Referring to several publications on this topic, the paper has provided an overview of the main methodologies currently employed in façade design. The description has focused on Multi-Criteria Decision Making (MCDM) procedures, including both Multi-Attribute Decision Making (MADM) and Multi-Objective Decision Making (MODM). The paper has also explored the integration of machine learning within MCDM, which is increasingly recognized as a method to streamline the design process and empower architects to make informed data-driven decisions. The investigation has revealed that many MCDM procedures tend to address energy efficiency and daylight control. MADM is a valuable technique to support the choice of the best solution from a set of predetermined alternatives. Despite being affected by the subjective preferences of decision makers, there are some promising trends in MADM. First, hybrid approaches combining different methods are becoming increasingly popular. Second, there is a growing interest in methods that account for the correlation among attributes, such as the Choquet integral, and for uncertainties in the design criteria, often by using fuzzy set theory. However, MODM offers a more rigorous framework at early stage design, enabling to explore the full realm of design possibilities and target optimal solution(s). In façade design MODM mainly considers nature-inspired algorithms, often combined with metamodels that mimic the behavior of external simulation programs to reduce the computational time. Notwithstanding the tendency to focus primarily on the mathematical optimization problem and the difficulty of achieving a real optimal solution, research efforts are further aiming at enhanced design procedures that account for manufacturer knowledge or consider the interaction between the different expertise involved. However, further investigations are needed to establish design criteria and objective functions based on the case-study scenario (i.e. type of application and building use) and identify the most appropriate MADM and MODM (or their combination) approach to be implemented for a specific façade problem. This will provide a useful guideline to designers, thus facilitating the integration of these design approaches in the common practice.

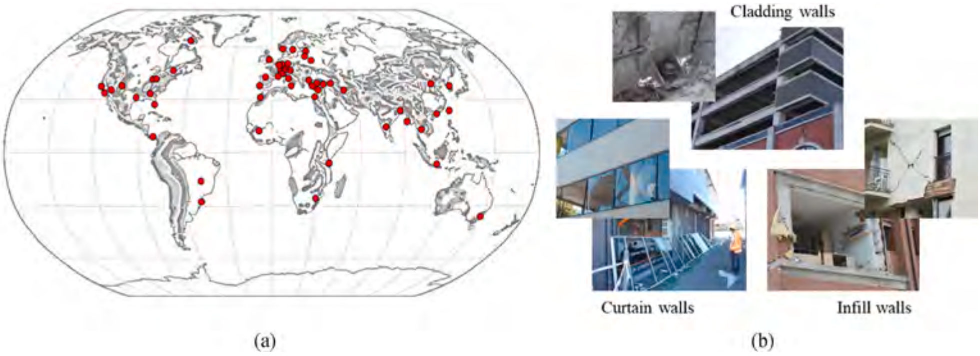

Fig. 8. (a) Map indicating the seismic zones (light-to-dark grey areas, representing low-to-very high seismicity) and locations involved in the reviewed MCDM studies; (b) Damage to building facades [141,142].

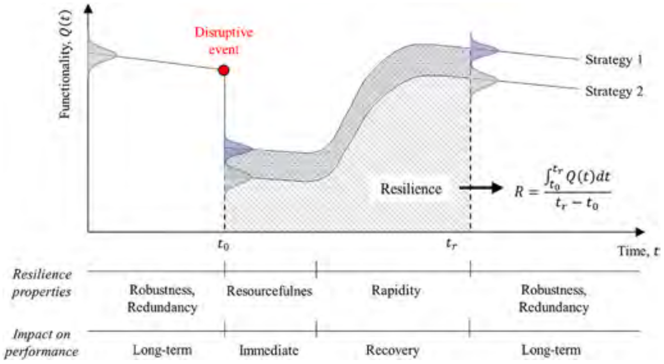

Fig. 9. Resilience definition, by referring to the description provided in Bruneau et al. [156].

To capture latest developments, the paper has also discussed ongoing trends that are likely to affect the future of façade design. Particularly, robust multi-criteria design processes accounting for different sources of uncertainties are needed to increase effectiveness and provide the reliability/risks associated with a specific façade. Although the majority of the buildings investigated in literature are located in seismic-prone countries, none of the applications involve seismic safety as decisive criterion. However, seismic considerations should be integrated to create safer systems and reduce the negative socio-economic-environmental impact of earthquakes. To further enhance the design, automation should be used to increase quality and facilitate the application of multi-criteria methods and the interaction with stakeholders. Furthermore, due to the vulnerability of facades to climate-induced extremes, the urgent need for resilient solutions is being increasingly recognized. The principal challenge here is to quantify resilience and integrate resilience considerations into the design process. This includes incorporating resilience as a key objective in multi-objective design methods, to ensure that the resulting facades are not only resource-efficient and user-centered, but also capable of withstanding a range of environmental stresses and hazards.

CRediT authorship contribution statement

Simona Bianchi: Writing – original draft, Visualization, Investigation, Funding acquisition, Conceptualization. **Charalampos Andriotis:** Writing – review & editing. **Tillman Klein:** Writing – review & editing. **Mauro Overend:** Writing – review & editing, Conceptualization.

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

No data was used for the research described in the article.

Acknowledgements

This study has received funding from the European Union's Horizon 2020 research and innovation program under the Marie Skłodowska-Curie grant agreement No. 101029605 (H2020-MSCA–IF–2020 - SAFE-FACE - Seismic SAFety and Energy efficiency: Integrated technologies and multi-criteria performance-based design for building FACadEs) for Dr. Bianchi. Dr. Andriotis would further acknowledge the support by the TU Delft AI Labs program.

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