Combining energy dynamic simulation and multi-criteria analysis for supporting investment decisions on smart shading devices in office buildings

Combining energy dynamic simulation and multi-criteria analysis for supporting investment decisions on smart shading devices in office buildings

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Abstract: In the framework of the current energy transition, the building sector is experiencing a smart revolution, recognizing how the adoption of advanced control strategies and smart management systems can increase buildings energy efficiency and improve occupants' comfort. As a key element for smart buildings, solar shading devices coupled with effective control systems need to be strategically assessed. The investment decision-making process for selecting the proper shading systems is influenced by the existence of potential conflicts from economic, environmental, social, and energy standpoints, thus asking to be supported by innovative methodological approaches able to include all these aspects in the decisional framework. To this purpose, the work aims to propose a multi-disciplinary methodological framework to support decision-makers in ranking a set of solar shading device and relative control strategy, integrating energy dynamic simulations with multi-criteria decision analysis techniques. The analysis focuses on office buildings, recognizing their huge impact in terms of energy consumptions and the need to guarantee proper indoor conditions to increase employees' productivity and wellbeing. To test the applicability of the multi-step methodology for this building category, the proposed approach is applied to an office building located in the North-West of Italy, aiming to assess and compare different alternative combinations of shadings devices and management strategies. The advanced features of building energy modelling and simulation and the application of PROMETHEE II (Preference Ranking Organization METHod for Enrichment Evaluation II) method as multi-criteria analysis allows to provide recommendations to decision-makers to identify the systems to be installed, able to guarantee the best trade-off between internal comfort, operational energy, and environmental costs for the building under investigation.

Keywords: smart buildings, solar shading devices, building management, dynamic energy simulation, multi-criteria decision analysis (MCDA), PROMETHEE II method.

1. Introduction

Being recognized as optimal agents in the energy transition framework (Cabeza and Ürge-Vorsatz, 2020), the promotion of smart and efficient buildings is a key priority to effectively drive the decarbonization of the entire sector (Santamouris and Vasilakopoulou, 2021). The 2018 revision of the Energy Performance of Building Directive (EPBD) has recognized smartness as crucial enabler for the building sector to achieve its emission targets (European Commission, 2018); pushing for the adoption of smart solutions, the Smart Readiness Indicator (SRI) is also introduced, as a valuable tool to evaluate the capability of buildings to adapt to both energy systems and occupants' needs (Becchio et al., 2021). Moreover, the apparent consequences of climate change and global warming phenomena, especially in terms of external temperature increases, is affecting buildings air conditioning demands, asking them to be equipped with efficient HVAC systems for heating and cooling provision (Crespi et al., 2021) and with advanced solutions for improving their passive characteristics. In line with the above, to reduce the space cooling demands and to enhance the natural lighting conditions of indoor spaces, well-designed solar shading devices represent an effective design strategy (Prowler, 2016). Recognized as valuable instruments to dynamically respond to solar radiation, there exists a wide range of solar shading solutions, varying in terms of installation (e.g., external, internal, or between-glass systems) or of type of use (e.g., fixed or movable solutions) (Bellia et al., 2014). If adequately installed and managed, solar shadings allow to reduce both heating and cooling needs, maximizing solar gains in winter, and reducing loads in summer; indeed, coupled with proper building automation mechanisms, these systems may help achieving significant energy savings (Bustamante et al., 2017;

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Becchio et al., 2021). Moreover, the use of smart solar shadings can effectively influence occupants' comfort, in terms of both visual and thermal performances (Van Den Wymelenberg, 2012; Bustamante et al., 2017; De Loyola Ramos Garcia et al., 2021). Solar shading devices can be manually operated by occupants according to their comfort perceptions or be automatically controlled through an efficient combination of sensors and actuators, which can enable the opening or closing of the different shading systems according to specific variables (e.g., internal temperature, external temperature, external solar radiation on window, etc.). In line with this, the use of smart automation and control strategies can increase their capability of optimizing the use of energy resources and building systems (Becchio et al., 2021). Indeed, monitoring and supervision, and user, grid and climate responses are defined as the basic features of a smart building, which must be equipped with proper technological solutions able to enhance its flexibility and capability to react against external variables, like weather and grid conditions, or internal factors, like users' interactions (Al Dankheel et al., 2020).

Despite the well-recognized energy-related benefits that shading installations may guarantee, the investment decision-making process is profoundly influenced by other aspects, reflecting the perspective of the stakeholders potentially involved in the decision context (Jafari et al., 2018). In this regard, building investments are typically evaluated according to the private investor's perspective, whose needs and interests are mainly influenced by the financial attractiveness of the analysed solutions. However, it is becoming increasingly important to include into the decision-making process also other objectives, which are spreading, mainly at policy scale, to push the market towards more environmental-friendly solutions, responding to the ambitious efforts requested to the building sector to reduce its impact over time (Crespi et al., 2020), and technologies able to respond to occupants' needs. From one side, to make environmental-friendly solutions more attractive to private investors, proper policy measures have been promoted. In line with the scope of the paper, specific incentive mechanisms to support interventions in new and existing buildings exist; for the sake of exemplification, in Italy, the "2020 Relaunch Decree" allows to implement energy efficiency interventions in buildings with a 110% tax deduction (Ministry of Economic Development, 2020), including the installation of shading systems, recognizing their benefits in terms of energy and emissions savings. From the other side, due to the actual concerns related to the need to make buildings healthier and more comfortable, a human-centred approach is required in the attempt to include occupant-related criteria into building investment decision-making processes. In line with this, purely techno-economic-based decisions are no longer enough for building analyses, neglecting various non-technical aspects, which conversely should play a not trivial role in the decisional framework.

In the light of the above, according to Jafari et al. (2018), the evaluation and definition of the most suitable option for buildings can be defined as a multi-objective optimization problem, with different criteria entering the decisional process. When analysing the selection of the most appropriate system to be installed in a building, it is important to look at the investment decision-making issue from a multi-dimensional standpoint, aiming to consider all the factors (i.e., belonging to economic, environmental, social, energy, architectural, and daylighting domains) that can influence the choice of shading devices. Therefore, to tackle the intrinsic complexity of energy investment-related choices, proper decision-support methods are required, with the final goal of identifying the shading systems and associated management and control strategies representing the best compromises between the conflicting criteria. In this context, the coupling of dynamic energy simulation software with decision-support methods can be beneficial, allowing to identify the best compromises between the different compared alternative strategies, also according to decision-makers' preferences and judgements (Jalilzadehazhari et al., 2019; Dell'Anna et al., 2020; Cinelli et al. 2021). In line with this, the work aims to propose a decision-making framework based on a multi-disciplinary methodological approach, capable of coupling multi-criteria decision analysis with energy modelling and simulation, to evaluate the performances of different shading options according to various criteria of interest. Specifically, the work focuses on office buildings, recognizing the role that solar shadings can play for this building category, considering that well-designed shading systems can improve indoor environmental conditions, positively influencing occupants' comfort and productivity. The proposed multi-step methodological approach is applied to the Energy Center building, a newly constructed office building located in Turin (North-West of Italy), for which several options of solar shading systems coupled with automated mechanisms are assessed, aiming to identify the best performing alternative among the ones at disposal.

The paper is organized as follows: section 2 is dedicated to a literature review on the deployment of decision support models in the building sector, aiming to identify the methods and tools usually used for supporting energy investments, giving attention to shading devices selection. Section 3 describes the methodological proposal defined

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for the selection of the most appropriate shading device and related control strategy for office buildings. Then, the case study is presented in section 4, focusing on the identification and assessment of the multi-domain criteria and on the judgements of the involved experts, while the main results and outputs of the application are discussed in section 5. Finally, section 6 summarizes the main conclusions and future perspectives of the work.

2. Decision support systems for shading devices: a review

This section aims to highlight the most recent trends and challenges in the framework of the assessment and selection of shading systems in the building sector. A review on the exploitation of decision support systems in the energy field is developed, focusing on their application for supporting solar shading assessments and investments. Moreover, a brief deepening on the most adopted energy simulation tools to analyse and assess the use of diverse solar shadings and their effects on buildings energy consumptions and occupants' comfort is developed, especially when integrated with decision support methods.

Focusing on the application of decision support systems, the literature has shown that the most used approaches in the field of energy investment decision problems are Life Cycle Assessment (LCA) and Life Cycle Cost (LCC), Discounted Cash Flow Analysis (DCFA) and Cost-Benefit Analysis (CBA), Environmental Impact Assessment (EIA) and Multi-Criteria Decision Analysis (MCDA) (Strantzali and Aravossis, 2016; Bottero et al., 2021). Although the variety of assessment tools makes it possible to analyse all aspects of sustainability, the diversity of approaches does not always lead to consistent assessment results (Hoogmartens et al., 2014). This review aims to identify the advantages and disadvantages of these approaches in the context of supporting investment decisions related to shading systems installations in buildings, focusing on LCA, LCC and MCDA, which are recognized as the most exploited approaches in this application area.

LCA approach falls within the more traditional Life Cycle Thinking (LCT) techniques, which are defined as useful tools to assess project impacts, considering the related activities throughout the entire life cycle of a project (Fregonara, 2017). In detail, the LCA assesses the energy and environmental loads of a product, activity, or management process during its whole existence to determine its global cost (Bonoli et al., 2021). The literature presents a large number of studies assessing the environmental impact of retrofit projects (including shading systems) on public (Pushkar, 2016), residential (Babaizadeh et al., 2015a; Babaizadeh et al., 2015b), and office (Ghose et al., 2017; Pushkar and Verbitsky , 2017; Ylitalo et al., 2017) buildings. Hu (2020) has determined the life-cycle environmental impacts associated with energy retrofit strategies on an urban scale applying a LCA integrated into a building information model (BIM). In detail, the author proposes an LCA-based model for evaluating different retrofit strategies (e.g., building envelope with additional insulation, replacement of windows and exterior doors, shading, replacement of the primary mechanical system and replacement of the lighting system) for a university campus, demonstrating how LCA approach could be used as a quantitative evaluation method for assessing and comparing large-scale energy retrofits (Hu, 2020). Moreover, Pushkar (2016) has assessed through LCA both the environmental damage (caused by the production and construction phases of shading devices) and the savings benefits (i.e., decrease of operational energy associated to the shadings installation) associated to the selection of external shading devices for office buildings. Despite the interesting applications of LCA for supporting building-related investments, the LCA model can be very resource- and time-consuming; moreover, depending on the degree of detail of the project, the collection and availability of input data may be problematic and can heavily influence the accuracy of the results.

Furthermore, within the LCT models, also the Life Cycle Costing (LCC) model can be cited (ISO 15686, 2008), which represents the life cycle analysis of a product from a purely economic standpoint. LCC, being able to give a snapshot of the Life Cycle Cost of products or services, has been used as the basis of the Global Cost technique proposed by the 2010 EPBD recast and typically used to compare diverse retrofit interventions for buildings to identify the cost-optimal level, according to both financial and energy perspectives (European Commission, 2010). As an example, Jaber and Ajib (2011) have applied LCC to find the optimal solution in terms of best building orientation, window size, thermal insulation thickness from an energy and economic point of view for a typical residential building located in the Mediterranean region. The authors have stated that LCC is useful for identifying the solutions capable of guaranteeing thermal comfort to occupants at minimum cost and that the application of energy-saving measures from the initial design phase can be significant in achieving this goal (Jaber and Ajib,

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2011). However, when considering the application of LCC, the results are limited to the financial dimension, providing an underestimation of the benefits provided by these solutions.

Finally, MCDA is an evaluation method that simultaneously considers a variety of qualitative and quantitative criteria to highlight the diverse points of view of the actors participating in the decision-making process (Figueira et al., 2005; Figueira et al., 2010). According to the MCDA theory, the process of criteria weighting allows to account stakeholders' opinions, which would otherwise be ignored using standard evaluation methods as LCA and LCC (Tsoukias et al., 1994; Figueira et al., 2002; Mustajoki et al., 2005; Bragolusi and D'Alpaos, 2022). For the sake of exemplification, Stamatakis et al. (2016) have applied an MCDA technique based on the PROMETHEE (Preference Ranking Organization METHod for Enrichment Evaluation) method for analysing 13 solutions of shading systems combined with photovoltaic (PV) plants, based on four quantitative (i.e., PV power generation, heating, cooling, and lighting) and three qualitative (i.e., Aesthetic, View, Glare) criteria. In addition, the study has introduced several stakeholders, chosen since they are generally involved in either the use (i.e., users of office buildings), the construction (i.e., installers of photovoltaic systems), the study (i.e., architects, academic researchers) or the control (i.e., building and energy inspectors) of the building. Moreover, Fontenelle and Bastos (2014) have developed an ELECTRE III model to choose among six proposed window solutions that differ in size, glass type, and sun protection devices, based on three criteria: landscape view, daylight level on work plan, and energy efficiency. Finally, Jalilzadehazhari et al. (2019) have proposed an integrated model for optimum window and blind selection in buildings, considering potential conflicts between visual comfort, thermal comfort, energy consumption, and life cycle cost, using the Analytic Hierarchy Process (AHP) method (Saaty, 1980).

The review shows that linking energy efficiency to environmental benefits through the application of LCA has demonstrated the ability to consider not only energy performance but also environmental benefits, accounting for several factors related to the choice of building materials and construction methods, as well as building systems and components (Chua and Chou, 2010). As for the LCC analysis, instead, it only calculates the economic cost of the whole life cycle of an investment, starting from the pre-production phases until its final disposal, limiting the scope of the assessment. The two LCT approaches mentioned above, indeed, provide a partial performance assessment, and often require input data that are difficult to obtain in the preliminary stages of the project; in this sense, they are of little use in providing support to professionals, investors and building managers. On the other hand, MCDA has proven to be a flexible evaluation model allowing multi-domain criteria (both qualitative and quantitative) to be included and evaluated with the goal of providing decision-makers with preliminary data. Furthermore, the MCDA allows to involve various stakeholders (e.g., building owner, building management, tenants, etc.) during the criteria weighting phase, to develop an evaluation that is as shared as possible.

The literature review has also deepened on applications coupling financial and economic evaluation approaches with energy simulation models, when dealing with building analyses. Building interventions are usually evaluated by performing a whole-building-level study (Li et al., 2020), exploiting energy simulation. There exist several building energy simulation tools, characterized by different levels of complexity and possibility to exploit optional variables of interest; depending on the application and requirements, a certain software can be exploited to simulate an existing building or a project (Sousa, 2012). As the most recognized, it is important to cite EnergyPlus (Department of Energy), IDA-ICE (EQUA), Transient System Simulation Tool (TRNSYS) (TESS) and IES-VE (IES). Among the mentioned tools, EnergyPlus is surely one of the most known energy simulation software, and it is widely exploited to support energy-related investments, including the selection and installation of solar shading systems (Atzeri et al., 2013; Huang et al., 2014; Khoroshiltseva et al., 2016; Singh et al., 2016; Bustamante et al., 2017; Jalilzadehazhari et al., 2019; De Almeida Rocha et al., 2020; Tabadkani et al., 2020; Becchio et al., 2021; Tabadkani et al., 2021). Developed and funded by the U.S. Department of Energy (DOE), it is an open-source software, widely used all over the world, in both academic and commercial contexts, for building and HVAC system design and dynamic simulation. EnergyPlus application is quite wide and ranges from the study of building envelope facade to the study of ventilation strategies or of specific building systems, allowing the energy assessment of different building types. It is an energy modelling and thermal load simulation program, able to provide energy- and comfort-related outputs, conducting simulations with an hourly or sub-hourly resolution and making use of location-specific information of solar radiation and external air details.

Focusing on investment decisions linked to shading device selection and relative control tactics, energy simulation tools are undeniably powerful tools for evaluating their energy, environmental, and comfort performance when implemented in a specific building. However, their application in decision-making is frequently limited to a single

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criterion at a time, rather than discovering the solution that represents the optimum trade-off between multiple multi-domain criteria (Jalilzadehazhari et al., 2019). In this context, some authors have stressed the importance of developing integrated decision support models capable of integrating energy performances with other domains (i.e., economic, social, or environmental), especially when considering building-related analysis, including the selection of shading devices, which is of interest in the work. An example can be found in the work of Jaber and Ajib (2011), who have used TRNSYS in combination with the LCC method; similarly, Mifsud et al. (2020) have analysed two shading devices and shutters from a whole life perspective, combining dynamic energy simulation using IES-VE tool and impact estimation through LCA method. EnergyPlus tool is exploited in the work of Jalilzadehazhari et al. (2019), which represent a relevant example of combination of evaluation methods with dynamic energy simulations; specifically, the authors have coupled dynamic energy simulations with AHP to create a decision support model (Saaty, 1980), according to which various combinations of exterior shading systems and window glazing types are assessed and compared on a multi-domain basis. As reported in (Jalilzadehazhari et al., 2019), indeed, the integration of multi-criteria methods with dynamic energy simulation tools is beneficial for obtaining the most accurate assessment of buildings energy performance, as well as of visual (e.g., amount of light, glare, uniformity, light intensity distribution) and thermal comfort (e.g., Fanger's thermal comfort model, long-term percentage dissatisfaction, temperature) and LCC (e.g., investment, consumption, maintenance) performance.

The work of Jalilzadehazhari et al. (2019) has put in the spotlight the combination of energy simulations with MCDA technologies, highlight how this integration can help decision-makers to identify the optimal options among the alternatives at disposal. Given the above, in light of the findings of the literature review and recognizing the potential of multi-criteria techniques in the energy field, this paper proposes an evaluation model blending EnergyPlus-based dynamic energy simulation with a PROMETHEE II-based multi-criteria (Brans et al., 1984, Brans et al., 1986; Brans et al., 1994; Andreopoulou et al., 2018). In particular, the study aims to propose a multi-disciplinary and multi-step methodological approach to assist decision-makers in choosing the solar shading device and related control strategy for an office building, ranking a set of alternative solutions, based on a wide range of multi-domain criteria, belonging to energy, environmental, economic, and social spheres. In detail, on the one side, EnergyPlus tool is exploited to investigate the office building under assessment and estimate its performances, in both its current state and in case different shading devices and control strategies are installed, recognizing it as "the most frequently used simulation tool for evaluating thermal comfort, energy consumption and LCC" (Jalilzadehazhari et al., 2019). On the other side, PROMETHEE II approach, defined as an outranking method that pairwise compares similar alternatives to rank them against a set of often contradictory criteria, is used as MCDA technique; the choice is facilitated by the advantages of PROMETHEE II, which does not necessitate the normalization of the quantitative data of the assessment items, allowing them to be used in their original units, it does not exhibit the risk of compensating between criteria, and it allows to include diverse stakeholders' judgments in the evaluation framework, to take into account the possible interests and perspectives involved in the energy investment decision-making process (Dell'Anna et al., 2020; Sward et al., 2021).

3. Methodology

Aiming to support the choice of an appropriate solar shading device and relative control strategy for an office building, the paper proposes a multi-step methodological approach, coupling the energy-related assessment of the performances of the different alternatives at disposal with multi-criteria techniques, as reported in **Fig. 1**.

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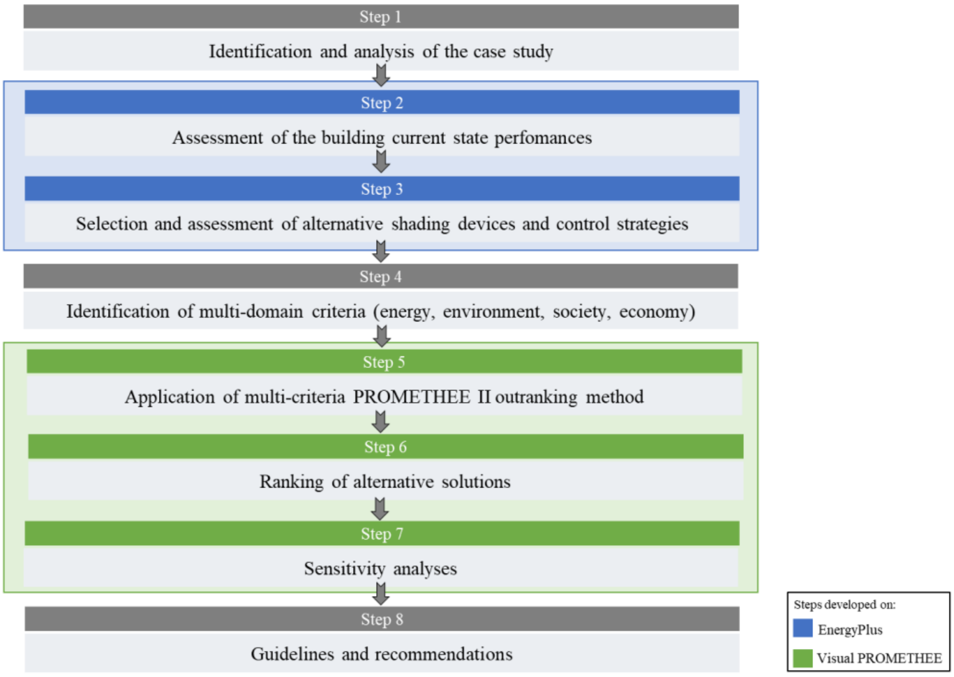

***Fig. 1**. Proposal of the multi-step methodological workflow.*

Specifically, after having identified and analysed from the energy point of view the case study, a preliminary assessment of the performances in its current state (i.e., no shading devices installed) is developed, through the energy dynamic simulation of the building model elaborated on EnergyPlus software. Then, after having selected diverse shading devices, combined with proper automation and control strategies, these alternatives are integrated in the office building model and their performances are assessed through EnergyPlus. Exploiting the simulation outcomes, the alternatives are evaluated and compared according to a set of multi-domain criteria, belonging to social, energy, economic and environmental spheres, to be able to express different stakeholders' perspectives and interests when choosing the adequate solutions for an office building. Then, by using Visual PROMETHEE software (Mareschal, 2011), the PROMETHEE II multi-criteria method is developed (see section 3.1), through the involvement of a panel of experts able to identify the appropriate preference functions and to weight the involved criteria, leading to a first scoring and ranking of the alternatives at disposal. Finally, proper sensitivity analyses are elaborated, to evaluate the stability of the rankings when varying the weighting coefficients coming from the involved experts' judgements. As previously mentioned, the proposed multi-disciplinary method aims to support energy investment decision-making, coupling energy-related assessment through dynamic modelling and simulation with multi-criteria methods; in particular, thanks to the combination of methods belonging to diverse disciplines (i.e., energy dynamic simulations and multi-criteria techniques), the integrated approach has the final goal of providing guidelines and recommendations to the stakeholders involved in the decisional process.

3.1 The PROMETHEE II multi-criteria method

PROMETHEE II is a multi-criteria method, usually exploited to assess and compare diverse alternative options, including diverse experts' judgements (Brans et al., 1986). PROMETHEE II is an outranking method, performing the comparison between the alternatives N = $\{a, b, \dots n\}$ according to the set of criteria J = $\{1, \dots k\}$, defining per each criterion an appropriate preference function (i.e., Usual, U-shape, V-shape, level criterion, linear, and Gaussian).
The PROMETHEE II method is organized around the following steps (Brans et al., 1986):

1) Development of an impact matrix, which is a double-entry table linking the alternatives (on the rows) to the evaluation criteria (on the columns).

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2) Identification of a preference function $P_j(a,b)$ for each j-th criterion, to express the relative preference between each pair of alternatives a and b. Each preference function ranges from 0 to 1, with 1 meaning that there is a strong preference for an alternative over the other, while 0 expresses the indifference of the expert between the two. Depending on the selected preference functions, it is required to identify proper indifference (q) and preference (p) thresholds.
3) Quantification of the global preference of the alternative a over b; the preference index $\Pi(a,b)$ (see Eq. 1) is introduced to aggregate all the preferences $P_j(a,b)$ for each j-th criterion considering each w_j weight (dependent on experts' judgements).

$$\prod(a,b) = \sum_{j=1}^{k} w_j * P_j(a,b) \tag{1}$$

The definition of the criteria weighting coefficients is performed through personal interviews with experts, according to the Simos-Roy-Figueira (SRF) approach (Figueira and Roy, 2002). It consists of a simple procedure that, making use of a set of cards, each representing a criterion, allows to indirectly determine the numerical values needed to weight the criteria under assessment. Each interviewed expert is asked to rank the cards (i.e., criteria) according to his/her preferences, from the least important to the most important, and to eventually introduce "white cards" between successive criteria to increase their relative distance in importance. The SRF approach can be developed in person or remotely, using DEC-Space web tool (Decspace).
4) Computation of the outranking flows for each alternative n∈N, in terms of entering (Φ^+) and leaving (Φ^-) flows, as reported in Eq. 2 and 3.

$$\Phi^+(a) = \frac{1}{(n-1)} * \sum_b \prod(a,b) \tag{2}$$

$$\Phi^-(a) = \frac{1}{(n-1)} * \sum_b \prod(b,a) \tag{3}$$

where n is the total number of alternatives.
5) Calculation of the net flows Φ per each alternative (see Eq. 4), according to which the complete ranking of the set of alternatives can be defined, based on each expert's judgements. The higher the net flow Φ, the better the alternative is, according to experts' judgements.

$$\Phi(a) = \Phi^+(a) - \phi^-(a) \tag{4}$$

4. Application

The multi-step methodology described in section 3 is applied to an existing office building, to test the capability of the proposed method to support the investment decision-making process. After a brief description of the case study (section 4.1), this section summarizes the main assumptions done for the construction of the model through the EnergyPlus software (section 4.2), the description of the analysed alternatives, each represented by the coupling of a shading system with a management and control strategy (section 4.3), and the hypotheses made for the multi-criteria assessment (section 4.4).

4.1 Identification and analysis of the case study

Non-residential buildings, specifically offices, are of interest to apply the proposed methodological approach, especially new office constructions. Indeed, this category of buildings is interesting for its envelope characteristics, typically equipped with large windows, and for its specific energy requirements and users' needs. Moreover, especially for new constructions, the exploitation of advanced monitoring and control systems may help reducing

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their huge energy consumption, while improving workers' productivity and comfort. For this reason, the Energy Center building of Politecnico di Torino, located in the North-West of Italy, is selected as case study (**Fig. 2**). It is well representative of newly constructed office buildings of North Italy. It is a five-stories office building completed in 2017, with the aim of creating a space where public and private entities can meet and work, sharing knowledge and pursuing together innovation in the energy and environmental fields (Borchiellini et al., 2017). The Energy Center is constituted of a basement, a ground floor hosting an auditorium and a full-eight exposition hall, and three floors of offices and meeting rooms for enterprises and university researchers. Concerning the building energy needs, the district heating network is exploited for space heating, while during summer a geothermal polyvalent heat pump satisfies cooling needs. Two on-field renewable sources are also present: a 47 kW_p photovoltaic (PV) system and a 30 m^2 solar thermal plant for domestic hot water production.

Fig. 2*. A view on the Energy Center building located in Turin.*

The building is selected for the study due to its peculiarities and innovative features. Indeed, the Energy Center represents a multi-energy environment, where different energy production systems and resources are integrated, to meet current energy needs, as well as for research purposes. Moreover, an advanced monitoring system and control was developed to achieve an efficient and smart management of the entire building (Becchio et al., 2021). Therefore, the smart-ready features of the building allow an evaluation on the possibility of integrating solar shading systems with diverse levels of automation, to further improve building energy behaviour and occupants' satisfaction.

4.2 Assessment of the building current state performances

The Energy Center model reflecting its current state conditions is developed on EnergyPlus software. The building presents a heated area of approximately 5'500 m^2 and a cooled area of 4'460 m^2, and it is modelled according to an L-shape, with the long side oriented to North-West (NW) and South-East (SE), and a window-to-wall ratio of 20.3%. To distinguish the characteristics of the different internal spaces, 41 thermal zones are modelled, taking care of their differences in terms of conditioning settings (e.g., presence of heating and/or cooling systems, internal temperature, and relative humidity settings, etc.) and introducing proper schedules for equipment and occupants' needs and usage (Becchio et al., 2021). The current state model does not include any shading systems. The AutoCAD output of the EnergyPlus model is reported in **Fig. 3**.
Annual simulations, with a sub-hourly time step, are run, using the climate characteristics by DOE Weather for Energy Calculation Database of Climatic Data (DOE); specifically, the IWEC weather file of Turin is exploited. Concerning the internal gains for occupancy, lighting, and electric equipment, UNI 10339 (1995), UNI EN ISO 7730 (2006), UNI EN 16798-1 (2019) are used, tailoring the related schedules on the specific thermal zones. All zones follow a set-point of 20 °C (set-back of 18 °C) in the heating season, while a set point of 26 °C is set for the summer period (set-back of 28 °C), during the occupied hours (offices are closed on Saturdays afternoon and on Sundays). Moreover, natural ventilation is simulated, distinguishing among the different thermal zones, while a constant 0.1 ach infiltration rate is set for each zone.

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For this work, the simulation does not account for the modelling of the existing HVAC systems, aiming to estimate the building space heating and cooling needs; to this purpose, an Ideal Loads Air System is modelled on EnergyPlus. Based on the obtained annual needs for space heating and cooling, energy consumptions are preliminary estimated assuming average generation, emission, distribution, and regulation efficiencies, derived from the available project documentation on the installed systems. The average global seasonal efficiencies are equal to 1.64 and 5.24, for heating and cooling systems, respectively. It is important to specify that, in this work, the energy consumption calculation is performed considering only heating and cooling uses, without assessing the consumptions associated to other services (i.e., domestic hot water, lighting and appliances). Moreover, the amount of renewable electricity produced by the PV plant installed on the Energy Center roof and hall façades is not considered.

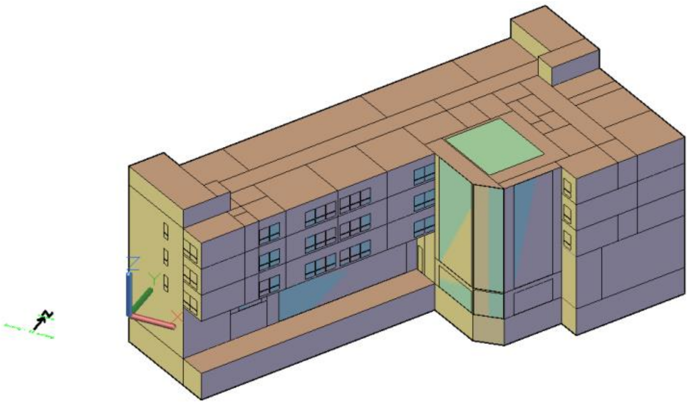

Fig. 3*. A view on the geometric model of the Energy Center developed on EnergyPlus (Becchio et al., 2021).*

4.3 Selection and assessment of alternative shading devices and control strategies

The multi-step method allows the comparison of diverse alternatives for the Energy Center building; specifically, different types of systems and control strategies available for installation are considered, each adequately simulated on EnergyPlus and then assessed through the selected MCDA. For this application, venetian blinds and shades (curtains) are selected, for both exterior and interior installation, leading to the definition of four possible shading solutions. Moreover, three different automation and control strategies are proposed for each shading system, considering the possible use of shading systems during the cooling season: i) a control strategy A, according to which occupants can manually act on the installed shading systems when in discomfort (i.e., when the indoor temperature is higher than the internal set point fixed at 26°C); ii) a control strategy B, in which the manual operation is substituted by the intervention of an automatic opening or closing of the shading devices, dependent on the variation of the indoor temperature with respect to the internal set point; and iii) a control strategy C, in which the automatic opening or closing of the shading devices is controlled thanks to the use of a detector for the solar radiation incident on the windows. According to the combination of the 4 typologies of solar shadings with the 3 possible control strategies, 12 alternatives are defined for the study, as shown in **Fig. 4**.

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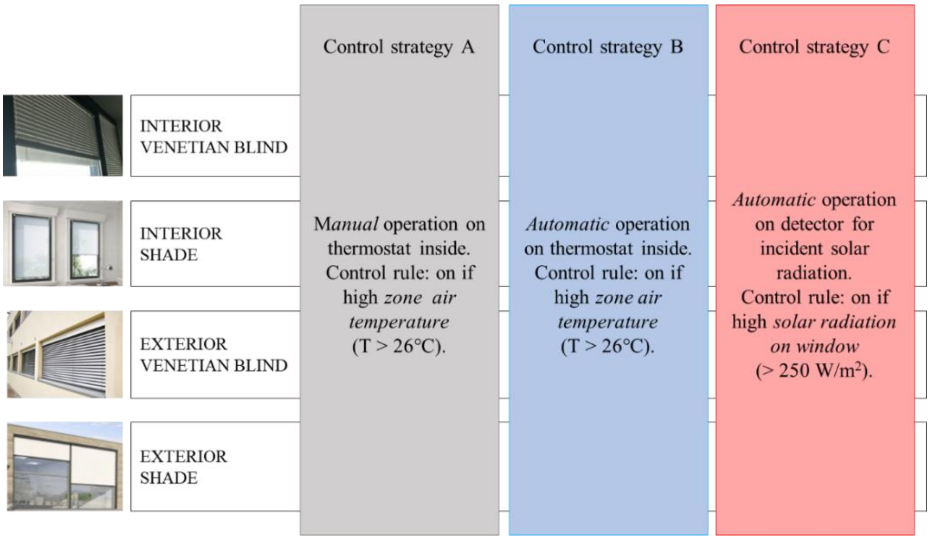

Fig. 4. *The 12 alternatives to be assessed by the multi-step methodology.*

All 12 combinations of shading device and control strategy are modelled on EnergyPlus software. Specifically, the "blind with medium reflectivity slats" object is selected to simulate exterior and interior blinds, while the "medium reflectivity–medium transmittance shade" is chosen to model interior and exterior shades. The shading devices are assumed to be located only in offices, auditorium, and laboratory, considering these zones as the most occupied spaces of the Energy Center. **Tab. 1** shows the number and size of the windows on which the related shading devices are installed, covering approximately 634 m^2 of transparent area (approximately 54% of the total surface covered by windows).

Tab. 1. *Details on shaded windows.*

Window type	Window dimension [m x m]	Number of windows
Office – Window 1	1.7 x 2.48	3
Office – Window 2	3.4 x 2.48	27
Office – Window 3	5.1 x 2.48	12
Laboratory	20.85 x 7.2	1
Auditorium	12.7 x 7.2	1

Moreover, the control strategies are modelled only for the summer season, considering it the most critical due to higher external solar stresses. Specifically, the manual operation on the zones thermostats (control strategy A) is modelled by setting 26°C as upper limit temperature for closing solar devices, allowing the action of the devices only when the occupancy schedule is not zero; for the control strategy B, instead, the schedule allows to activate shadings all day long, without constraints on occupants' presence (assuming it to be automatic, and not dependent on occupants' manual actions); thus, according to this automatic operation, shading devices are closed/opened also in unoccupied periods, including weekends and holidays, to improve the building performance, reducing the risk of overheating during the whole summer season. Finally, the control strategy C, which is the most advanced solution, assumes the use of an external detector for measuring solar radiation on the interested windows, which controls the opening and closing of shading devices considering a threshold value of 250 W/m^2 (option "On if high solar on window" on EnergyPlus); when the detector measures a value equal or higher than the threshold, the shading systems are immediately closed and maintained in this condition, until the measured value decreases below 250 W/m^2.

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4.4 Identification of multi-domain criteria

To apply the multi-criteria approach for comparing and ranking the selected alternatives of solar shading devices and automation and control strategies to be installed in the Energy Center building, a set of multi-domain criteria is selected for the analysis (see **Tab. 2**), aiming to reflect the different aspects potentially of interest in the investment decision-making process. The considered criteria are all in the form of quantitative metrics, with the sole exception of the visual impact criterion, which is a qualitative indicator measured on a 1-to-5 scale. Some of these criteria are assessed using EnergyPlus simulations, while others are computed using external data sources, coming from literature sources.

Tab. 2*. The selected multi-domain criteria for the assessment.*

Domain	Symbol	Criterion	Unit of measure
Energy	EN1	Cooling needs savings	%
	EN2	Primary energy consumption for heating and cooling	$kWh/m^2/y$
Environment	ENV1	CO_2 emissions for heating and cooling	$kg/m^2/y$
	ENV2	PM emissions for heating and cooling	$g/m^2/y$
Economy	ECO1	Investment cost	€/m^2
	ECO2	Maintenance cost	€/m^2
Society	S1	Percentage of occupied hours in thermal comfort	%
	S2	Percentage of occupied hours in visual comfort	%
	S3	Visual impact	Qualitative scale 1-5

Starting from the energy domain, recognizing the potential impact of solar shading installations on buildings cooling needs, a specific criterion of cooling needs savings (EN1) is considered, to estimate the effects that solar shading devices coupled with smart control strategies can have on the building cooling performances. Having modelled each alternative on the software, space cooling needs are extrapolated, and savings are calculated with respect to the building current state performances, with no shadings installed (section 4.2). EN2 criterion refers to the building primary energy consumption for heating and cooling; this indicator is computed starting from the energy consumption of the Energy Center building and using appropriate conversion factors per each used energy carrier (i.e., district heating and electricity for heating and cooling purposes, respectively). A similar approach is adopted for the two criteria belonging to the environmental domain, ENV1 and ENV2, which are calculated starting from the district heating and electricity consumptions of the building under study, using proper CO_2 (ISO 52000-1, 2017) and PM (EEA, 2019; ISPRA, 2021) emission factors.

Besides energy and environmental aspects, the alternative strategies are assessed in economic terms, comparing them according to investment (ECO1) and maintenance (ECO2) cost. The former considers the total costs necessary for the installation of shading systems and related accessories for automation and control, when required; this indicator is calculated based on Piedmont regional price list (2022) and on market prices. Using the same sources, the maintenance costs (both ordinary and extraordinary) are assessed for the different options on a life-cycle basis, considering a 30-years lifetime and a 3% discount rate (European Commission, 2012).

Finally, attention is devoted to assessing the impact that shading devices can have on employees, in terms of thermal and visual comfort. With this objective in mind, among the social criteria, two quantitative indicators are selected for evaluating these aspects, both computed based on the hourly simulations of the alternatives through EnergyPlus software. Specifically, thermal comfort is assessed in terms of the Predicted Percentage of Dissatisfied (PPD) index, defined by Fanger (ISO 7730, 2006) and representing the percentage of occupants not satisfied by the thermal conditions of the indoor spaces (Liu et al., 2015). The PPD computation is referred to the estimation of the Predicted Mean Vote (PMV) metric, which considers the average vote of thermal sensation expressed by a large group of people, on a scale from +3 (hot) to -3 (cold) (ISO 7730, 2016). Specifically, according to Fanger, a PMV value ranging between -0.5 and +0.5 corresponds to a thermal comfort condition, which in turn means having a PPD lower than 10%. Therefore, obtaining the hourly PMV and PPD values from the energy simulations, S1 is calculated as the percentage of occupied hours in which PPD is lower than 10% on a year. Similarly, S2 criterion refers to the visual comfort and is assessed in terms of glare index, which is used to evaluate the presence of glare due to opening areas within a confined environment. Considering the EnergyPlus-based default value of 22 as maximum allowable discomfort glare index (DOE), S2 is calculated as the percentage of occupied hours in which the glare index is lower than 22 during an entire year of simulation. Furthermore, the social domain includes also a qualitative criterion analysing the visual impact (S3) of the alternatives, assessed on a 1-to-5 scale, where 1 corresponds to a low impact and 5 to a high impact on the external urban environment (i.e., the lower, the better). The visual impact criterion allows considering the increasingly crucial need of integrating buildings within the urban environment, taking care of the specific characteristics and specificities of the external environment where the considered building is located, aiming not to compromise it. With this in mind, the alternatives are estimated according to their aesthetical impact on the building and on the environment, based on experts' opinions.

4.5 Application of multi-criteria PROMETHEE II outranking method

Once criteria and alternatives are defined, the first step consists of creating the impact matrix (as shown in **Tab. 3**), which reports the performances of all alternatives according to each selected criterion. At this point, the direction of preference needs to be defined (meaning that, according to the criteria definition, it is required to indicate if the preferred alternatives per each criterion are those with minimum or maximum values), together with the exploited preference functions, and their associated indifference (*q*) and preference (*p*) thresholds, if required.

Tab. 3. *Input parameters of the impact matrix.*

	EN1	***EN2***	***ENV1***	***ENV2***	***ECO1***	***ECO2***	***S1***	***S2***	***S3***
	%	*kWh/m²/y*	$Kg_{CO2}/m^2/y$	$g_{PM}/m^2/y$	*€/m²*	*€/m²*	*%*	*%*	*1-5*
Direction of preference	max	min	min	min	min	min	max	max	min
Preference function	linear	U-shape	usual	usual	linear	linear	V-shape	V-shape	U-shape
Indifference threshold (q)	3.5%	1.5 kWh/m²	n/a	n/a	15 €/m²	12 €/m²	n/a	n/a	n/a
Preference threshold (p)	10%	n/a	n/a	n/a	60 €/m²	55 €/m²	5%	17%	1
Interior shade control strategy A	1.60%	27.46	4.76	0.027	69.32	32.31	68%	61%	1
Interior blind control strategy A	0.61%	27.57	4.78	0.027	71.75	34.98	68%	75%	1
Exterior shade control strategy A	3.72%	27.22	4.72	0.027	96.98	87.86	68%	61%	4
Exterior blind control strategy A	5.99%	26.96	4.68	0.026	90.43	93.62	70%	77%	4
Interior shade control strategy B	4.30%	27.15	4.71	0.027	96.25	40.81	69%	61%	1
Interior blind control strategy B	2.05%	27.41	4.75	0.027	98.68	43.48	69%	75%	1
Exterior shade control strategy B	9.14%	26.60	4.61	0.026	113.26	87.86	68%	61%	4
Exterior blind control strategy B	14.32%	26.00	4.51	0.025	106.71	93.62	72%	77%	4
Interior shade control strategy C	4.01%	27.19	4.72	0.027	131.72	60.10	76%	58%	2
Interior blind control strategy C	1.92%	27.43	4.76	0.027	134.15	62.77	76%	89%	2
Exterior shade control strategy C	10.03%	26.51	4.60	0.026	148.73	107.15	73%	58%	5
Exterior blind control strategy C	16.82%	25.74	4.46	0.024	142.18	112.91	79%	89%	5

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To define the proper preference functions and thresholds, different multi-disciplinary experts are involved, among which practitioners and researchers in the field of building physics and energy performance, economic analyses, and occupants' behaviour. Specifically, for the EN1 criterion, the linear shape is selected as preference function, with an indifference threshold q of 3.5% and a preference threshold p of 10%, considering that the average saving is of 6.21% for the considered alternatives, while the U-shape is chosen for EN2, with an indifference threshold q of 1.5 kWh/m^2, due to the little variation between the alternatives performances. Concerning the two environmental criteria, the usual preference function is applied for both cases, because of the very small range obtained for the emission values of the alternatives. For the economic criteria, the linear shape is selected; specifically, for ECO1 (i.e., investment costs) q is set to 15 €/m^2 and p to 60 €/m^2, while for ECO2 (i.e., maintenance costs) q is equal to 12 €/m^2 and p to 55 €/m^2. The thresholds are defined in such a way as to favour alternatives that provide significant cost-effectiveness in terms of investment costs and low maintenance costs. To conclude, for the social domain, the V-shape is selected for S1 and S2 and the U-shape for the qualitative criterion S3; in particular, based on the alternatives performances, S1 is evaluated through a preference threshold of 5%, while S2 with a p of 17%. The indifference threshold for S3 U-shape is set to 1, to give importance also to the unitary difference in the 1-to-5 scale associated to this criterion.

4.5.1 Importance of weightings: multi-actors analysis

A crucial step of the multi-criteria techniques concerns the assignment of weights to criteria. Generally, going through the determination of weights means involving diverse experts, whose opinions can help improving the quality of decisions, determining a more explicit, rational, and efficient decision-making process (Bottero et al., 2020; Bottero et al., 2021). Specifically, several actors can be involved, with different background and interests, using their judgements to create separate scenarios for the multi-criteria analysis.
In this work, three experts are involved, having expertise related to buildings energy performances, occupants' comfort and well-being, and economy. The experts are asked to express their preferences in relation to the criteria importance, and this step is developed using the SRF method. As a result of the experts' judgements, **Fig. 5** summarizes the weighting coefficients of the criteria, according to three scenarios (one per each interviewed expert) (Figueira and Roy, 2002; Decspace).

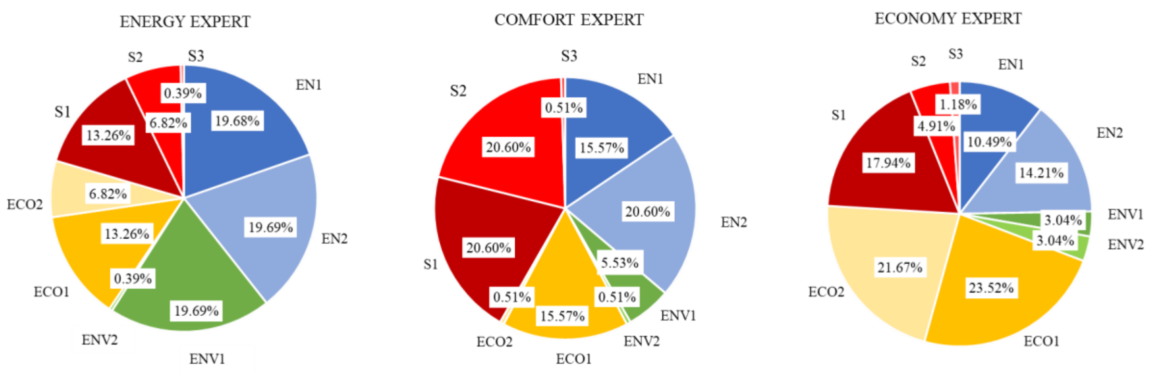

Fig. 5*. Criteria weightings assigned by the three experts involved in the assessment.*

It is interesting to note that a similar perception on the importance of the energy criteria for the selection of the appropriate shading system for an office building is expressed by the energy and comfort experts. Moreover, the energy expert gives equal importance to both energy criteria and to the environmental criterion on CO_2 emission, while the comfort analyst gives greater importance to social criteria, and specifically to thermal and visual comfort ones. Conversely, the economy expert's weights stress about the importance of costs (both investment and maintenance voices). Finally, a similar consideration between the three experts regards the visual impact criterion (S3), which obtains the lowest preference in all scenarios (0.31% for the energy expert, 0.51% for the comfort expert, 1.18% for the economy one). Despite the importance of architectural integration when assessing possible buildings intervention, this criterion is profoundly influenced by the location of the building; according to experts' opinions, indeed, the relevance of this criterion increases when considering buildings located in historical areas or

city-centers, which is not the case for the Energy Center, which is in a commercial area, closed to the university campus.
In addition to the three scenarios (i.e., energy, comfort, and economy), an average scenario is built, setting the criteria weightings as the average between the three experts' weights (shown in **Fig. 5**). This scenario makes it possible to take into consideration the opinions of all experts and to define a ranking of solutions consistent with all points of view.

5. Results and discussion

By means of EnergyPlus simulations, the heating and cooling needs of the Energy Center in the current state are estimated, equal to approximately 17 kWh/m^2 and 31 kWh/m^2, respectively, Moreover, by introducing the combinations of shading devices and control strategies in the EnergyPlus software, the 12 alternatives are assessed in energy, environmental, and social terms. Specifically, focusing on energy aspects, **Fig. 6** compares the alternative combinations of shading devices (interior/exterior blinds/shades) and control strategies in terms of guaranteed savings of space cooling needs, with respect to the Energy Center current state.

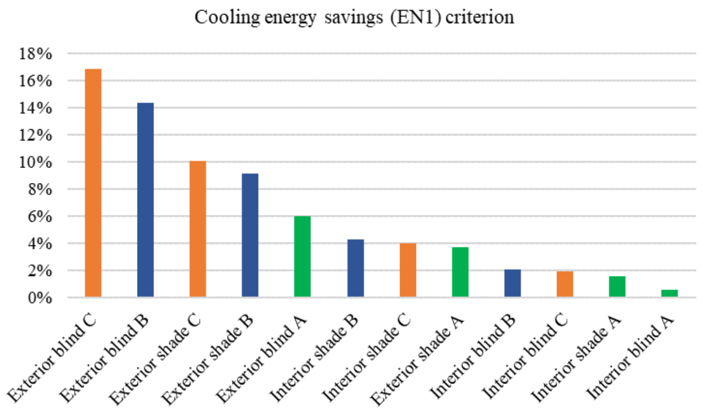

***Fig. 6**. Comparison of the cooling needs savings (EN1) criterion for the 12 alternatives.*

From the graph, it clearly appears how the exterior solutions represent the best options to reduce space cooling needs in the building, being able to better reduce the external solar stresses; moreover, the automatic control strategies (i.e., B and C) have a stronger impact on energy needs, with respect to the manual operation, not being dependent on occupants' presence and, thus, allowing to reduce the overheating of the building, also when not occupied. According to the EN1 criterion, the exterior blind with control strategy C is the best candidate, reaching a 17% reduction of space cooling needs.
Moving to the multi-criteria analysis, the PROMETHEE II application provides a ranking of the 12 alternatives, through the estimation of their net flows Φ (through Eq. 4). **Fig. 7**, elaborated based on the outputs of Visual PROMETHEE (Mareschal, 2011), presents the obtained rankings for the four developed scenarios. Specifically, indicators are used to represent the different type of shading (i.e., circle for shades and square for blinds), while lines indicate their installation (i.e., exterior installations are shown through dotted lines, while interior ones with continuous ones). Finally, colours are used to differentiate the control strategies, using green for strategy A, blue for strategy B and orange for the most advanced control strategy C.

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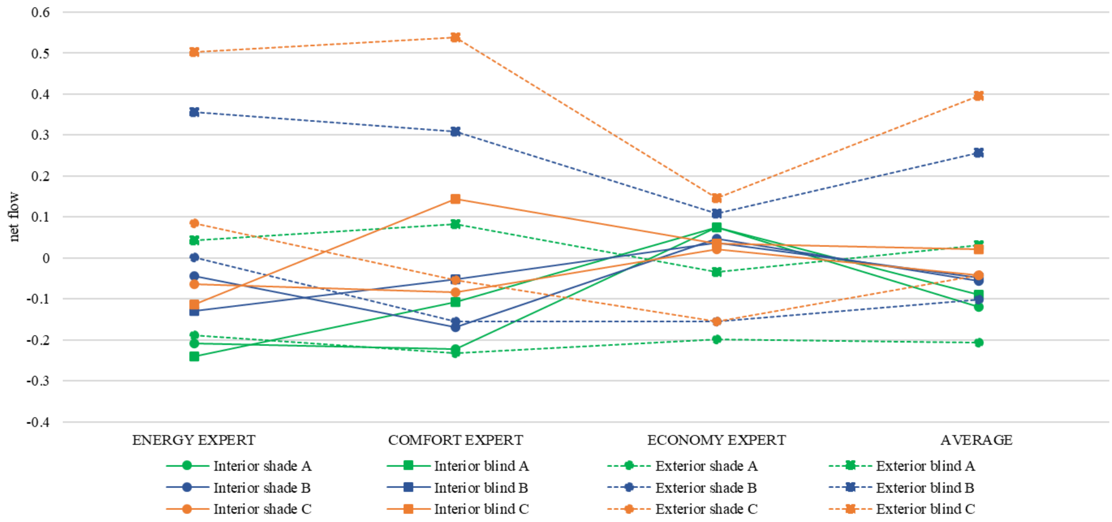

Fig. 7. *Ranking of the alternatives resulting from the application of PROMETHEE II method according to the experts' preferences and the resulting average case.*

The best performing option for the four scenarios is always the exterior blind system coupled with the control strategy C (orange dotted line with squared indicator), which requires the installation of a detector for solar radiation able to automatically act on the shading systems. The result is not unexpected, since the control strategy C is the best performing in terms of energy savings, environmental impact, thermal and visual comfort, even if more expensive than the other options. Concerning the choice among shades and blinds, the latter guarantee higher energy savings and a lower environmental impact, especially if installed externally. Even though for the best option there is no difference in the multi-scenario analysis, the same consideration is not valid for the other ranking positions. This is the case of the interior venetian blind coupled with control strategy C (orange continuous line with squared indicator), which ranks in 8th position according to the energy expert and in the 7th for the economy one, while jumps to the 3rd position according to the comfort scenario; indeed, on the one hand, this alternative is very performing from the thermal comfort point of view, which is identified as a strategic element for the comfort expert, while, on the other hand, it has a lower performance in terms of the energy criteria, which are relevant for the energy expert. Due to its scarce energy performance, the interior venetian blind with control strategy A (i.e., manual operation) is the worst solution (green continuous line with squared indicator) for the energy expert; instead, for the economy scenario this option goes up to the 3rd position, considering its lower cost with respect to other combinations. Moreover, the conflicting nature of the energy and economic criteria is understandable also looking at the 3rd position of the energy scenario, occupied by the exterior shade with control strategy C (orange dotted line with circular indicator), which instead obtains the second last position in the ranking of the economy expert. Finally, looking at the ranking of the average scenario, the results appear to be coherent with the outputs of the three experts' preferences; specifically, the 1st and 2nd positions are identical to the other scenarios, and the worst alternative is identified in the exterior shade with control strategy A (green dotted line with circular indicator), as for the comfort and economy experts' rankings. It is interesting to note that, for the average case, with the exception of the first positions, the gap among the net flows of the alternatives is reduced if compared to the experts' scenarios.

The results of the application are also analyzed according to the Rainbow representation, available in Visual PROMETHEE (Mareschal, 2011). The example for the energy expert's scenario is shown in **Fig. 8**. The Rainbow graph is a disaggregated representation of the complete ranking of each scenario, which distributes the alternatives from the most to the least preferred, from left to right, showing their performances according to the considered criteria (each color represents a domain family). Specifically, each slice shows the contribution of each criterion to the net flow of the alternative, representing the flow value times the weighting coefficient associated to the specific criterion by the expert involved. For the sake of exemplification, the winning alternative for the energy scenario (i.e., the exterior venetian blind with control strategy C) performs well in terms of energy, environmental and social criteria, while showing some weaknesses with reference to the visual impact S3 and to the economic criteria (both investment and maintenance costs). In an opposite way, the worst alternative according to this

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scenario presents positive performances only for economic and social criteria, including S3, while is penalized by its low performance in energy and environmental terms.

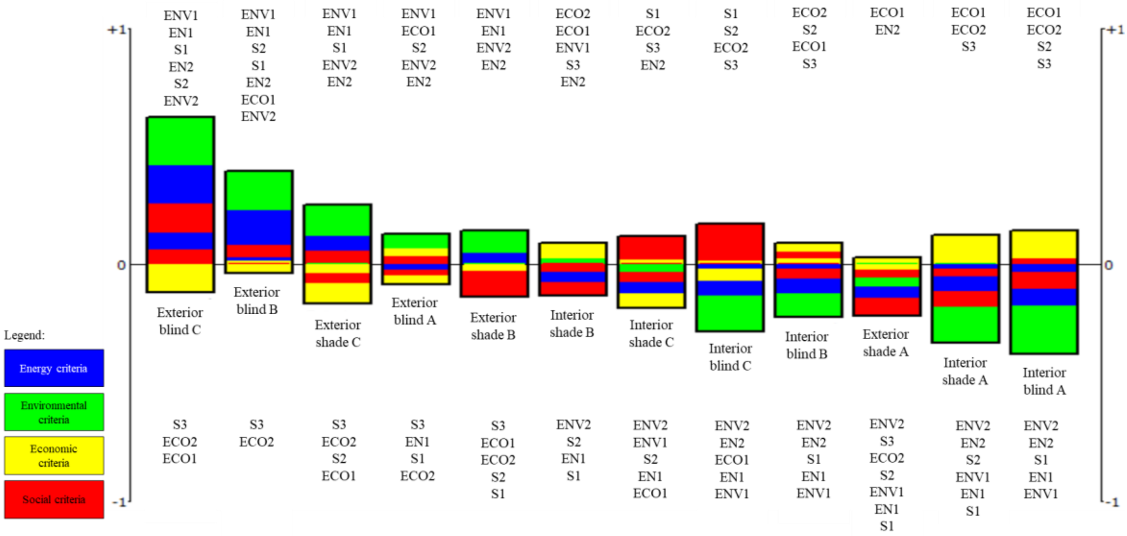

Fig. 8. *PROMETHEE Rainbow output, with respect to the energy expert's weightings.*

Furthermore, Visual PROMETHEE allows to build the so-called Geometrical Analysis for Interactive Aid (GAIA), which is a visualisation method that shows the relationships between the defined alternatives and the considered scenarios (Mareschal, 2011). The GAIA plane representation is exploited to evaluate the multi-scenario analysis and permits to observe the possible divergences between the experts' standpoints (**Errore. L'origine riferimento non è stata trovata.**). On the multi-scenario plane, each expert's view is represented by an axis drawn from the center of the plane, while the points in the GAIA plane represent the considered alternatives. On the graph it is possible to visualize the preference ranking of the alternatives, which decreases from right to left, well highlighting the most preferred option for all scenarios (i.e., the exterior blind with control C), located on the extreme right side of the plane. The red axis indicates the decision PROMETHEE stick, which is characterized by the same orientation of all the other scenarios axes. In detail, **Fig. 9** clearly shows how the energy expert' scenario is divergent especially compared to the economy expert's one, pointing in different directions (i.e., bottom vs. top of the plane); however, the red decision axis is oriented to the right as all other axes, thus highlighting a moderate conflict among scenarios.

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Fig. 9. Outputs from the GAIA plane with respect to the experts' scenarios (GAIA-scenario).

5.1 Sensitivity analyses

To investigate the stability of the results, proper sensitivity analyses must be conducted, allowing to determine how the ranking might change in accordance with the variation of the importance of the involved criteria. Specifically, in this paper, an equal scenario (i.e., equal weights for all criteria) and four extreme scenarios (i.e., weighting coefficients are changed by exaggerating the criteria belonging to a domain family at once) are developed, to study their effect on the alternatives ranking. The weighting coefficients used for the equal and the extreme scenarios are reported in **Fig. 10**.

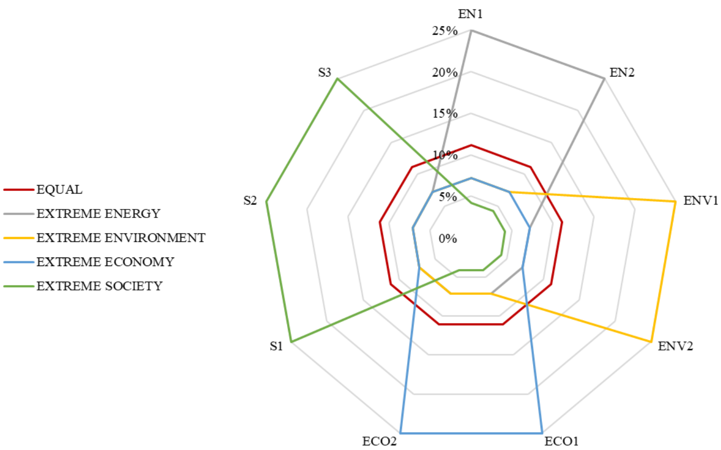

Fig. 10. Criteria weightings for equal and extreme scenarios.

The development of new scenarios according to the weighting coefficients reported in **Fig. 10** leads to the definition of new alternatives rankings, as shown in **Fig. 11**, to be compared with the previous rankings (reported in **Fig. 7**).

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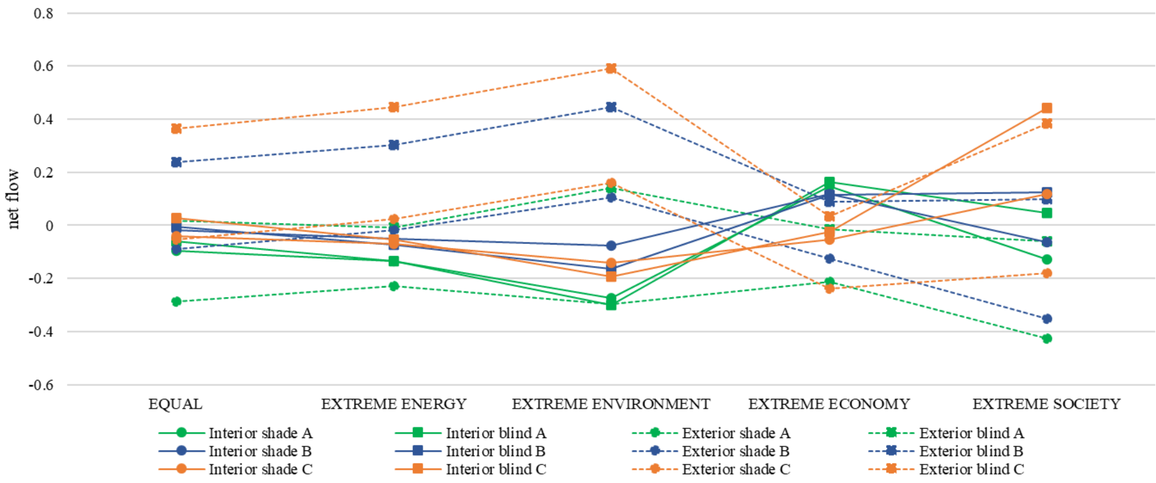

Fig. 11. *Ranking of the alternatives resulting from the application of PROMETHEE II method on the equal and extreme scenarios.*

In all five sensitivity analyses, the final rankings present significant changes, mostly in the intermediate position. The equal, the extreme energy and the extreme environment scenarios present the same first two positions in the final ranking, while the situation is completely different for the extreme economy and extreme society. Indeed, for these two cases, the exterior blind with the control strategy C is not the best performing option, as in all other scenarios. Starting from the extreme economy scenario, the most impacting result is the first position of the cheapest alternative (i.e., interior blind coupled with control strategy A, represented with the green continuous line with squared indicator), which instead reaches the last position for the energy expert (see **Fig. 7**). In the extreme economy scenario, the ranking is profoundly influenced by economic criteria and, thus, the interior shading devices are rewarded, specifically if associated with the control strategy A (i.e., manual operation performed by occupants). Moving to the extreme society scenario, the best alternatives are identified as the interior blind with control strategy C (orange continuous line with squared indicator) and the exterior blind with the same control mechanism (orange dotted line with squared indicator); indeed, this scenario advantages the solutions that better guarantee high thermal and visual comfort conditions and with a lower visual impact. For almost all sensitivity scenarios, the alternative considering the combination of exterior shades with control strategy A (green dotted line with circular indicator) represents the worst solution, similarly to what obtained for the experts' scenarios previously analysed.

Finally, the visual stability tool available on the software (Mareschal, 2011) is used to explore the stability of the results when varying one weight at once, for each scenario. The visual stability intervals show how the net flows may change as a function of the variation of each criterion weight; specifically, the visualization tool allows to identify, per each criterion and each scenario, which is the range of the associated weighting coefficient according to which the final ranking of the alternatives remains unaltered, as well as how the positions in the final ranking would change out of this range of stability. For the sake of exemplification, **Fig. 12** presents the visual stability of the energy criterion related to cooling needs reduction (EN1) and the economic criterion for investment costs (ECO1) according to the energy expert's scenario. In each graph, the weight is reported on the x-axis, while the net flow ranking is shown on the y-axis; the colored lines represent the net flow trends of each alternative, associated to the possible weight variation of the considered criterion from 0% to 100%. The green/red vertical line shows the weighting coefficient used in the analyzed scenario, while the blue dotted vertical lines identify the stability range (i.e., the range of weights that the specific criterion could have to maintain the final ranking unaltered). Comparing, for the same scenario, the EN1 and ECO1 criteria, it is possible to note that the energy scenario seems to be more stable for what concerns EN1, with a stability interval ranging from 11.31% to 28.45%, and more sensible to changes on the economic criterion (for which the stability interval is narrower). Indeed, if the variation of the EN1 weighting coefficient will in any case confirm the first positions (i.e., exterior blind C and exterior blind B) and the last one (i.e., interior blind A), a different result is obtained for the variation of the ECO1 weight; specifically, according to this scenario, after the 25% weight it is possible to visualize a complete change of the ranking, in favor of less expensive solutions (e.g., exterior blind A or interior blind A), while disadvantaging

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more energy efficient solutions; in this sense, it is interesting to note, for instance, how with a high weight for ECO1 the exterior blind C would reach the second last position.

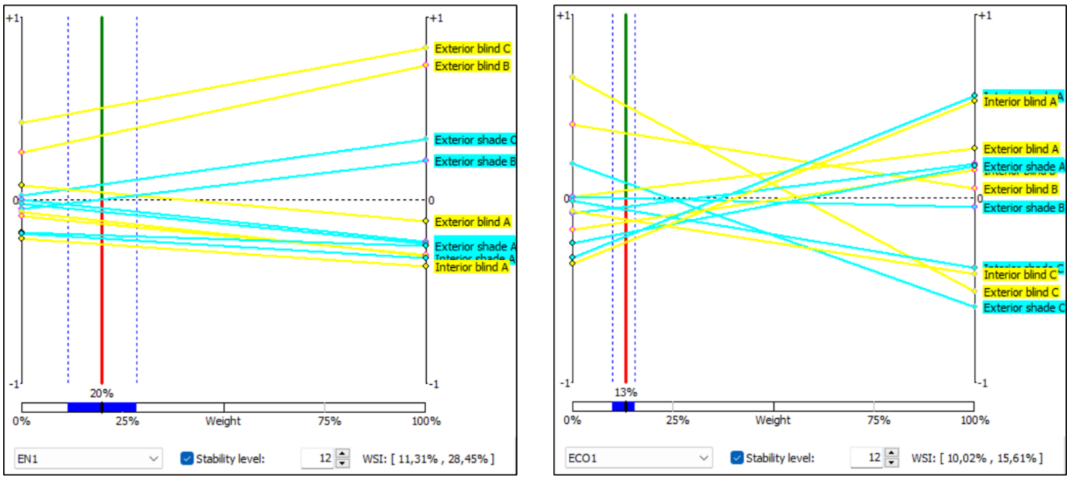

Fig. 12. *Visual stability intervals for EN1 (left) and ECO1 (right), according to the energy expert's scenario.*

6. Conclusions and future perspectives

Solar shading devices and their effective management and control can have a strategic role in improving buildings performance and achieving the advocated smart building revolution. The selection of the best combination of shading system and control strategy is by definition a multi-criteria challenge, since the investment decision-making process is influenced by several and often conflicting factors. For this reason, there is the need to develop proper multi-disciplinary methodological approaches, capable of identifying and deepening the potential contradictions between economic, social, environmental, architectural and energy aspects associated to shading devices installations, also considering the perspectives of the potential actors involved in and influenced by the decision. In line with this, the work proposes a multi-step methodological approach to support the investment decision-making process regarding the selection of the most adequate solar shading device and associated control strategy for an office building coupling methods and tools from diverse disciplines. To include in the evaluation approach the estimation of the energy performances of the shading systems and their impact on energy consumptions and occupants’ comfort, the approach combines EnergyPlus-based energy dynamic simulations with the PROMETHEE II multi-criteria decision analysis; the evaluation is based on the comparison of a set of alternative solutions of shading devices combined with diverse strategies of automation and control mechanisms, based on a set of multi-domain quantitative and qualitative criteria. The multi-step methodological approach was tested for the Energy Center building, a newly constructed office building located in the North-West of Italy, well representative of its building category. Diverse experts were involved, to include their opinions in the evaluation procedure, allowing to perform a multi-scenario analysis; all experts have confirmed the solution combining the exterior shades with the control strategy C (i.e., the most automated) as the best alternative among the ones at disposal, giving importance to its capacity of significantly reducing energy needs and environmental impacts, without impacting on occupants’ comfort and satisfaction. Despite other solutions have lower investment and maintenance costs, its higher energy, social and environmental performances have rendered it the best solution for all interviewed experts.

The work allows to highlight how the integration of energy dynamic simulations with the PROMETHEE II method can represent a promising solution for supporting energy investment decision-making processes, giving different perspectives on the performances of the alternatives at disposal. This consideration is valid for different smart features in buildings, making the methodological approach potentially applicable also for the assessment of other smart devices. Future work will be devoted to applying different multi-criteria techniques in combination with energy dynamic simulations, as well as to testing the proposed methodological approach for different case studies of interests. Furthermore, future analysis could be devoted to refining and tailoring the set of criteria included in the methodological proposal, in order to extend the study also to other building typologies.

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