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Proposal of a multi-step methodological approach for evaluating the performances of solar shading devices in office buildings

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ABSTRACT

In the framework of the building sector transition, which is a key priority to achieve the decarbonization targets, a smart building revolution has started, pushing for the adoption of advanced control strategies and smart management systems to increase buildings energy efficiency, while improving occupants' comfort and satisfaction. For the design and management of smart buildings, solar shading devices and related control systems for their effective usage need to be strategically assessed. There exist several factors that can influence the choice of shading systems, due to the potential conflicts from economic, environmental, social and energy standpoints. For this reason, proper methodological approaches are needed to couple the energy and environmental assessment of the performances of the different systems when installed in a specific building and the social and economic impacts that these solutions can have on building occupants, facility managers and decision-makers. In line with this, the work aims to propose a multi-step methodological framework to support decision-makers in selecting an adequate solar shading device and relative control strategy for an office building, integrating energy dynamic simulations with multi-criteria decision analysis techniques.

Keywords: smart buildings, solar shading devices, building management, control strategies, multi-criteria analysis, PROMETHEE method.

1. INTRODUCTION

Among the European priorities, a strong effort is asked to the building sector for reducing its environmental impact and improving its energy efficiency, to become a key enabler of the energy transition process [1]. When dealing with the building sector transition, it is fundamental to consider how climate change consequences and new occupants' habits are affecting energy needs in buildings; in particular, due to the recent temperature growth, air conditioning demands are increasing, asking building to be efficiently designed to reduce solar gains in summer and to be equipped with proper cooling systems. In this context, the use of solar shading has become particularly interesting, especially considering its impact on space cooling demands. The term solar shading is used to indicate all devices able to dynamically respond to external solar stresses. There exist different shading devices, varying from interior to exterior systems, with diverse shading properties and characterized by several design variables that influence their performances [2]. However, generally, the installation of solar shading systems allows maximizing thermal gains during the winter season and reducing loads during summer. Their efficient design can contribute to achieve significant energy savings in buildings, especially when effectively combined with proper management and control strategies [3]. Moreover, besides energy-related benefits, the use of solar shading systems can help improving occupants' visual and thermal comfort. In this regard, 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 operate the opening or closing of the different shading systems according to the values of specific variables (e.g., internal temperature, external temperature, external solar radiation on window, etc.). In line with this, smart buildings are in the spotlight, thanks to their capability of optimizing the use of energy resources and systems, among which also solar shading devices, with the help of automation and control strategies [3].

There exist several factors that can influence the choice of shading devices, due to the potential conflicts from economic, environmental, social, energy, architectural, and daylighting standpoints. Proper methodological approaches are needed to support the decision-making process, in the attempt to identify the solutions of shading system and associated management and control strategy representing the best trade-offs between the conflicting criteria, with the final goal of maximizing occupants' thermal and visual comfort, while reducing costs and energy and environmental impacts. Indeed, even though energy simulation tools are powerful instruments to estimate and compare the energy, environmental and comfort performances of different shading and control strategies, they usually support the selection of the systems in relation to a single criterion, rather than according to the trade-off between different multi-domain criteria [2]. In this context, the coupling of energy simulation software with multi-criteria decision analysis (MCDA) can be beneficial, allowing to identify the best compromises between the different compared alternative strategies, also according to decision-makers' preferences and judgements [2].

In line with this, the work aims to propose a decision-making framework based on a multi-step methodological approach, capable of coupling multi-criteria decision analysis with energy modelling and simulation, aiming to evaluate the performances of different shading device options according to a set of energy, environmental, economic and social criteria [4,5]. Attention is primarily devoted to recent constructions, and mainly to office buildings, which are usually equipped with large window areas; for this building typology, an efficient shading design and management is fundamental to guarantee adequate comfort conditions to workers, also to increase their productivity.

The paper is organized as follows: after this brief introduction, the following section will be devoted to the description of the developed methodological proposal for selecting the most appropriate solar shading device and related automation and control strategy for an office building; then, the main results are summarized in the "results and discussion" section, identifying a proper set of multi-domain criteria to be used for the multi-criteria analysis; finally, the main conclusive remarks and future development of the work will be reported in the last section.

2. METHODOLOGICAL PROPOSAL

Aiming to choose an adequate solar shading device and relative control strategy for an office building, a multi-step methodological approach is defined, coupling the energy-related analyses of the performances of the different considered devices with multi-criteria techniques. The methodological proposal is represented in Fig. 1, showing the progressive steps needed to assess and compare different alternatives, simultaneously considering all the different criteria potentially affecting the decision-making process.

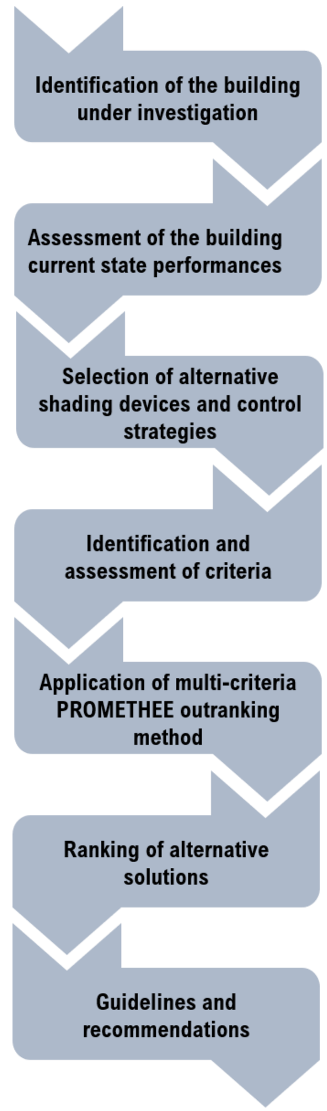

Fig. 1. Multi-step methodological approach.

Once identified the building under investigation for the installation of solar shading devices, the methodological approach involves a first assessment of the building energy and environmental performances in its current state, evaluated through energy dynamic simulations, using EnergyPlus software [6]. Then, different combinations of shading devices and automation and control strategies are defined, while a set of multi-domain criteria are properly identified and assessed, to evaluate the options performances according to energy, environmental, economic, and social aspects. The PROMETHEE II (Preference Ranking Organization Method for Enrichment Evaluations) multi-criteria method [7] is used to rank the identified alternative options.

The PROMETHEE II is an outranking method, based on the comparison of the different alternatives $A = \{a_i \dots a_n\}$ for a set of criteria $F = \{g_1 \dots g_q\}$ by means of preference functions (usual, U-shape, V-shape, level criterion, linear, and Gaussian) defined for each criterion by the decision-maker. Depending on the shape of the preference function, indifference (q) and preference (p) thresholds have to be defined. To quantify the global preference of the alternative a_i over a_j, the notion of preference index $\pi(a_i, a_j)$ has been outlined. It allows to aggregate all the unicriterion preferences $P_k(a_i, a_j)$ by considering the weight ω_k associated to each criterion. To define criteria weights, the methodology includes personal interviews with experts, based on SRF approach [8]. The last step relies on the calculation of the outranking flow scores of each alternative $a \in A$. To compare the outranking flows and to define the complete ranking of the alternatives, PROMETHEE II provides a complete ranking of the alternatives by calculating the net flow Φ:

$$\Phi(a) = \Phi^+(a) - \Phi^-(a)$$

Finally, proper sensitivity analyses can be developed to test the stability of the results, aiming to use the methodological approach to provide specific guidelines and recommendations to decision-makers.

3. RESULTS AND DISCUSSION

In order to apply the multi-criteria approach to compare and rank different alternative combinations of solar shading devices and automation and control strategies to be installed, a set of multi-domain criteria was selected for the analysis, as reported in Table 1. All criteria are expressed through quantitative indicators, with the sole exception of the visual impact, which was measured through a level scale, varying its value from 1 to 5.

Table 1. Considered multi-domain criteria.

Domain	*Criterion*	*Unit*
Energy	Cooling needs savings (EN1)	%
	Primary energy for heating and cooling (EN2)	kWh/m^2
Environmental	CO_2 emissions for heating and cooling (ENV1)	kg/m^2
	PM emissions for heating and cooling (ENV2)	g/m^2
Social	Percentage of occupied hours in thermal comfort (S1)	%
	Percentage of occupied hours in visual comfort (S2)	%
	Visual impact (S3)	Qualitative scale 1-5
Economic	Investment cost (EC1)	€/m^2
	Maintenance cost (EC2)	€/m^2

Energy and environmental criteria are assessed simulating the shading systems and their relative control strategies with the EnergyPlus software. Specifically, due to the significant impact that effective solar shading devices can have on space cooling needs, a specific criterium of cooling needs savings (EN1) is considered, to directly assess the effect that different combinations of solar shading and automation strategies can have on buildings cooling performances. Specifically, the cooling needs savings indicator is calculated comparing the performances of the alternative options with the current state conditions of the building (with no shading devices installed). EN2, ENV1, and ENV2 criteria are calculated starting from the energy consumptions of the building under study, using appropriate conversion factors from existing regulations.

Besides energy and environmental aspects, attention is also devoted to the impact that shading devices can have on occupants, in terms of thermal and visual comfort. With this objective in mind, among the social criteria, quantitative indicators are selected for evaluating these aspects, both computed based on the hourly simulations of the alternative options through EnergyPlus software. Specifically, thermal comfort is assessed in terms of the Predicted Percentage of Dissatisfied (PPD) index, defined by Fanger [9] and representing the percentage of occupants not satisfied by the thermal characteristics of the indoor spaces [10]. The PPD computation is related to the assessment of the Predicted Mean Vote (PMV) index, expressing the average vote of thermal sensation expressed by a large group of people, on a scale from +3 (hot) to -3 (cold) [9]. Specifically, according to Fanger [9], the thermal comfort condition in characterized by a PMV value ranging between -0.5 and +0.5, which in turn corresponds to a PPD lower than 10%. Therefore, obtaining the hourly

PMV and PPD values from the energy simulations, it was possible to calculate S1 as the percentage of occupied hours in which PPD is lower than 10%. Similarly, S2 criterion evaluates visual comfort 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 [6], S2 is calculated as the percentage of occupied hours in which the glare index is lower than 22.

Furthermore, within the social domain, the qualitative criterion of visual impact (S3) is included, expressed according to a 1-to-5 scale, where 1 corresponds to a low impact and 5 to a high impact. Associated to the aesthetics of the alternative strategies and to the impact of their installation on the external urban environment; the visual impact criterion allows to take into account the increasingly crucial need of integrating the single building within the urban environment, without compromising the specific characteristics and specificities of the external environment in which the considered building is located.

Finally, among the economic criteria, the alternative strategies are assessed in terms of investment (EC1) and maintenance (EC2) cost. The former considers the total costs necessary for the systems installation, including the shading systems and the related accessories for automation and control, when required; this indicator is usually defined using standardized national or regional price lists or market prices. The maintenance cost (both ordinary and extraordinary) is computed for the different options considering the entire life cycle of the systems.

As defined in Section 2, MCDA requires criteria weighing, as they do not all have the same importance. To take this into account, different actors can be involved to weight the criteria according to their knowledge and background. In the energy sector, it has become increasingly important to consider the different aspects of economic, environmental, and social sustainability. In this sense, involving experts in these fields can be reasonable and useful to support decision-making processes from an overall sustainability perspective. To do this, the SRF method can be used to give an appropriate value to the weights of criteria.

4. CONCLUSIONS AND FUTURE DEVELOPMENT

To achieve the smart building revolution and an effective improvement of buildings performance, solar shading devices and relative control strategies play a strategic role, in the attempt to improve both the energy performance of buildings and the comfort of their occupants. Being influenced by several factors, the choice of the adequate solar device and its smart management is by definition a multi-criteria problem, which requires a proper methodological approach able to identify and deepen the potential conflicts among the associated economic, social, environmental and technological aspects. The presented work aimed to describe a multi-step methodological approach to support decision-makers in selecting the most adequate shading device and associated control strategy for an office building. Specifically, the methodological framework integrates energy dynamic simulations of the performances of the alternative options to be compared with multi-criteria decision analysis techniques, in the form of the PROMETHEE II method. Once described the methodological proposal, the work also identified a set of multi-domain indicators to be used for the development of the multi-criteria decision analysis, commenting the calculation method and the main assumptions for their computation.

To conclude, the work represents the basis for further development, with the scope of applying the developed multi-step methodological approach to different case studies of interest, in order to test this multi-criteria decision analysis framework and assess the best performing solar shading device and relative control strategy for office buildings.

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