Multi-criteria Analysis for Sustainable Buildings

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Abstract. Currently climate and housing standards in parallel with the energy savings govern the performance required to buildings. Consequently, innovative multi-functional components try to satisfy both the requirements of structural safety and thermal performance, but the choice of the designer is difficult due to the complexity of this new market. In this paper, the Multi-Criteria Decision Making (MCDM) analysis is proposed as suitable methodology that can provide adequate support for choosing the best building components between different alternatives. As case study, TOPSIS method (Technique for Order Preference by Similarity to Ideal Solution) has been applied for comparing four different types of floor. The criteria assumed in the case study are referred to different fields as well as thermal, acoustic, air quality building science, structural performances, economic and human impacts. The case study allows to point out that the optimal solution depends on the importance (weight) that the decision maker assigns to each considered criterion.

Keywords: Multi-criteria problem · Structural performance · Sustainability TOPSIS · Weight assignment · R.C. floor

1 Introduction

In the field of buildings construction the target of energy saving has led to a convulsive evolution of the market for the components of the "building envelope" that is focused only on this aspect, even though further performance has to be assured especially for the structural safety. The availability of multi-functional products with interdisciplinary performances makes necessary the adoption of quantitative models to assist designers in decision making, comparing solutions in term of cost, safety, durability, energy efficiency and so on. The main challenge for the involved decision makers includes the need to consider multiple objectives with different tradeoffs values, therefore a reliable approach to decision analysis is necessary. The wide variety of available solutions for the building envelope, suggests the use of non-dominated optimization to identify a set of feasible design solutions that represent a real compromise between the criteria. This approach, referred to as Pareto optimization, has been extensively applied in the literature concerned with multi-criteria design (Grierson 2008). In the context of building design, Multiple Criteria Decision Making (MCDM) methods provide a valuable tool for supporting the choice of the preferred Pareto optimum. Some examples of MCDA application are available in various engineering fields. In their paper Mardani et al.

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(2015) have documented the exponentially grown interest in the MCDM techniques and they have provided a state-of-the-art of the literature regarding applications and methodologies. They have established a list of around 400 articles categorized into 15 fields: energy, environment and sustainability, supply chain management, material, quality management, GIS, construction and project management, safety and risk management, manufacturing systems, technology management, operation research and soft computing, strategic and knowledge management, production management, tourism management and other fields. Kabir et al. (2013) in a recent paper have pointed out that approximately 300 works concern the application of multicriteria decision techniques in the field of infrastructure management. Considering building sector, most of the studies that apply the multicriteria approach are focused separately on energy, environmental or structural engineering criteria. More in detail, several papers discuss how high performance buildings require an integrated approach focusing on architecture conception (Fontanelle and Bastos 2014, Songa et al. 2015), on building envelope solution (Gagliano et al. 2015, Yang et al. 2016), on choice of HVAC system designs (Avgelis and Papadopoulos 2009) and integration of renewable energy and storage technologies (Wimmler et al. 2015, Ascione et al. 2015). As summarized above, the application of MCDA is not new, but, it is generally not related to multidisciplinary problems. In this paper, the potentialities of MCDA application are evidenced for the selection of building envelope components; in particular the application of the procedure is developed for a reinforced concrete (RC) floor; several traditional and innovative solutions are analyzed, considering both the energy efficiency as well as the primary structural performance.

2 A Multicriteria Approach for Roof Slab Technology

The choice of the alternatives to be considered to finalize a MCDA procedure is a key issue that can surely influence the result. Indeed, although the evaluation model is accurate and reliable, it can lead to a poor choice if the alternatives under consideration are weak (Brown 2005). There are several tools that may be employed in the definition of decision alternatives, such as brainstorming techniques (Osborn 1957), cognitive mapping (Eden 1988), dialog maps (Conklin 2006), among others.

More in detail, it has been shown that tools where decision alternatives are created considering the decision-makers' objectives (Keeney 1992) or stakeholders' values (Gregory and Keeney 1994) are the most useful. For example, the analyst can ask to decision makers to propose options that could perform adequately a single objective. In this study, the types of floor have been selected in order to compare two traditional types of reinforce concrete (RC) floors (one casted in situ and the other precast) and two new types of RC floors in which innovative materials are used to improve the energy efficiency.

The first type is a traditional brick-concrete floor, that is a RC floor lightened with hollow clay bricks (named type A1 in the following analysis); other three types of RC floor:

- A2: hollow-core floor;
- A3: expanded polystyrene lightened floor;

- A4: wood-cement lightened floor (Fig. 1).

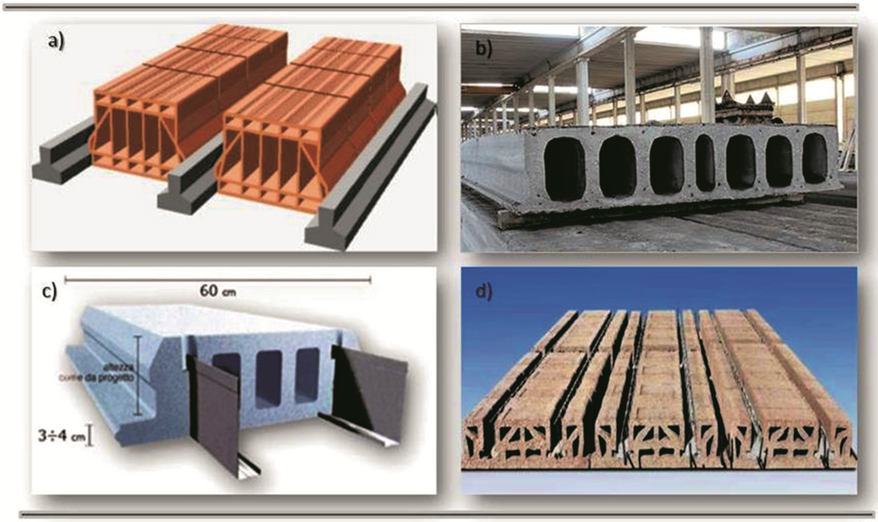


Fig. 1. Types of floor: (a) A1-Brick-concrete floor; (b) A2-Hollow-core floor; (c) A3-Expanded polystyrene lightened floor; (d) A4-Wood-cement lightened floor.

The brick-concrete floor is the most diffuse technology in Europe, but usually, it satisfies only the structural performance. It is completely cast in situ or realized with precast joists; the bricks are spaced to allow the concrete casting of the joists. The description of the properties of the roof layers is shown in Table 1; here, "s" is the thickness, "λ" the thermal conductivity, "c_p" the specific heat and "ρ" the density.

Table 1. Brick-concrete floor

	s [m]	λ [W/mK]	c_p [J/kgK]	ρ [kg/m3]
Interior plaster	0.02	0.700	1000	1800
Ribs and brick	0.20	0.916	878	1008
Slab	0.05	1.600	1000	2500
Screed	0.05	1.060	1000	1800
Waterproofing membrane	0.01	0.170	1000	900
Flooring	0.03	0.700	1000	1000

Instead, the hollow core floor have been created to address the need to reduce the commissioning work time. For this reason, often, it doesn't attempt other functional performance. The element A2 (Table 2) is a precast pre-stressed concrete slab that is completed in-situ with a concrete layer with thickness not less than 4 cm.

Table 2. Hollow-core floor

	s [m]	λ [W/mK]	c_p [J/kgK]	ρ [kg/m3]
Interior plaster	0.02	0.700	1000	1800
Hollow-core floor	0.20	1.120	1000	2400
Slab	0.05	1.600	1000	2500
Screed	0.05	1.060	1000	1800
Waterproofing membrane	0.01	0.170	1000	900
Flooring	0.03	0.700	1000	1000

The EPS-based solution could optimize the energy and environmental performance by operating, at the same time, an increment of the thermal insulation and a reduction of the structural weight.

In particular the third solution, A3, consists of a panel in Expanded Polystyrene (EPS) and a steel 'L' shaped profile embedded inside having a load-carrying function during the casting (generally the self-supporting capacity is guaranteed on a span of 2.50 m for a height floor equal to about 240 mm); two adjacent EPS panel are used as formwork for the casting of the concrete ribs. Therefore, the system is completed by a concrete casting on the top to realize a RC slab. The lower winglet (height ranging from 4 to 8 cm) ensures the continuity of the polystyrene even below the rafters, conferring a low transmittance to the floor and reducing the thermal bridges effect. Table 3 describes the properties of each layer of floor.

Table 3. Expanded polystyrene lightened floor

	s [m]	λ [W/mK]	c_p [J/kgK]	ρ [kg/m3]
Interior plaster	0.02	0.700	1000	1800
Insulating fin	0.04	0.036	1000	35
Ribs and panel	0.20	0.300	1400	413
Slab	0.05	1.600	1000	2300
Screed	0.05	1.060	1000	2000
Waterproofing membrane	0.01	0.170	1000	900
Flooring	0.03	0.700	1000	1000

The element A4, wood-cement lightened floor, consists of pre-assembled panels, of dimensions 100 cm × (20-25-30-39), length up to 6.5–7 m, with horizontal and vertical milling to eliminate thermal bridges and to improve acoustic performance. The floor must be completed on site with supplementary welded steel mesh and finishing casting of the slab. Table 4 shows the characteristic of layers selected for the case study.

Table 4. Wood-cement lightened floor

	s [m]	λ [W/mK]	c_p [J/kgK]	ρ [kg/m3]
Interior plaster	0.02	0.700	1000	1800
Fin insulating wood	0.05	0.103	2200	512
Wood-concrete block	0.20	1.120	1400	2400
Slab	0.05	1.600	1000	2500
Screed	0.05	1.060	1000	1800
Waterproofing membrane	0.01	0.170	1000	900
Flooring	0.03	0.700	1000	1000

3 Parameters for Multi-criteria Analysis

National and international policies devote increasing attention to the reduction of energy consumption and environmental impacts; however in any evaluation process also the economic investment has to be considered. In this section, a general discussion about the selectable criteria for comparing the floor technology is presented. Then, the evaluation system used in the case study is pointed out.

3.1 Structural Properties

The floor is a structural element with significant influence on the realization and behaviour of a building. The floor has the primary structural function of supporting vertical loads but in case of seismic actions it has the further function of distribution of horizontal actions. The design of a floor has to be developed according to the technical codes (in Italy DM 2008 or Eurocode 2). The major issues consist of the fulfilment of the resisting capacity (ultimate limit state) and functional performance (serviceability limit state a deformability limitation). Therefore parameters such as the structural weight, the reduction of the time for the transportation and the mounting operation can to be considered.

3.2 Properties Related to Indoor Comfort and Consumption Issues

Each construction component contributes to thermal and acoustic comfort inside the building, daylight conditions, energy efficiency and sustainability, as evidenced by da Silva and de Almeida (2010). There are a lot of factors that influence the behavior of building components as described below.

Thermal transmittance (UNI EN ISO 6946 2008) is a measure of insulation level of building components; usually, lower value of the thermal transmittance means lower energy consumption for heating. Briefly, according to code approach (Ministerial Decree 2015), this parameter defines the reference building; it is related to the evaluation of global performance index both for refurbished as well as for new design buildings.

In the summer period, thermal performance should be evaluated in dynamic regime; many indicator parameters can be used such as the time lag, the decrement factor, the thermal heat capacity and the periodic thermal transmittance (Y_{IE}) as defined by UNI EN ISO 13786 (2007). Briefly, periodic thermal transmittance represents the heat flow rate through the internal surface of the component when the ambient temperature varies as sinusoidal function. It is evident that a low value of Y_{IE} corresponds to better summer thermal performance of the building component.

Also the spectral properties of finishing layer should be considered. Indeed solar reflectance and thermal emittance significantly affect the temperature of the building components, and these can contribute to reduce the summer energy demand or building overheating as well as the heat island effect. A surface of roof highly reflective and highly emissive allows to minimize the amount of light converted into heat and to maximize the amount of heat that is radiated away. In climatic zones characterized by high energy requirements for cooling, often, this is a suitable technological solution; however also the problem due to reduction of heat gain during the winter period should be evaluated.

Sound insulation is the ability of building elements to reduce sound transmission. It is measured at different frequencies, normally 100–3150 Hz. The airborne sound insulation is expressed by a single value: Weighted Standardized Level Difference ($D_{n,t,w}$), Weighted Sound Reduction Index (R_w) and Weighted Apparent Sound Reduction Index (R'_w). Impact sound insulation can be expressed by a single value between Normalized Impact Sound Pressure Level ($L'_{n,w}$), $L_{nT,w}$ that is the Weighted Standardized Impact Sound Pressure Level and the $L'_{nT,w}$ that is the Weighted Standardized Impact Sound Pressure Level. These are calculated according to the standard EN 12354-1 (2000); EN 12354-2 (2000). In Italy, passive acoustic requirements of buildings are reported by the D.P.C.M. (1997). Moisture in envelope assemblies can cause numerous problems affecting the indoor air quality of a building and the longevity of building components. Moreover moisture can cause corrosion of components and dissolve water soluble constituents damaging structures; the induced degradation could reduce thermal resistance and the strength and/or stiffness of materials.

Vapor permeability is the ability of a material to allow water vapor to pass through it. This is a material property and it is not dependent on size, thickness or shape of the material. Vapor resistance is equivalent to the vapor permeability multiplied by the thickness (ISO 12572 2001). The total value of vapor resistance of building component influences the diffusion of water vapor current density.

3.3 Environmental Performance

Often the energy assessment is related to the need of reducing the environmental impact of building use as well as of construction industry. The sustainability of building sector should take into account the impact on the surrounding environment, human health, consumption of resources and on quality of the ecosystem. The most comprehensive methods to evaluate and reduce environmental impacts is the Life Cycle Assessment (LCA) methodology. According to International Standard ISO 14040 (2010), LCA is a "compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle." By taking into account the construction, assembly, processing and disposal of the component, LCA enables identification of the most significant impacts and stages during its life cycle that need to be targeted for maximum improvements.

3.4 Costs

The cost is surely one of the criteria to be considered in the analysis, since generally a prefixed budget is established in public and private investment, influencing the choice of the builders and buyers. The total cost to be sustained for the realization of each alternative includes: basic resources (manpower and materials), semi-worked (mortar, ready-mixed concrete, etc.) as well as transportation and freight (trucks, cranes, etc.). The works are intended performed in a workman like manner in accordance with applicable laws and regulations.

3.5 Case Study: Evaluation Area and Criteria

For the case study three areas of analysis have been considered:

- Structural Safety;
- Sustainability;
- Economic investment.

These evaluation areas have been structured in categories and evaluation criteria as shown in Fig. 2.

The evaluation area named *Sustainability* includes the *energy* and *indoor quality* categories. More in detail, among the parameters that define the thermal performance of floor thermal transmittance and the periodic thermal transmittance have been chosen. In the same category, the LCA criterion has been added with the aim to evaluate the environmental impact of floor supply chain. The indoor quality referred to building component has been studied in term of acoustic insulation and thus the weighted normalized impact sound pressure level ($L'_{n,w}$) has been considered as criterion. According to EN 12354-2 (2000-09), the limit value for residential kind of use is 63 dB, for tertiary building it varies between 55–58 dB. Finally, the moisture risk is evaluated with the global vapor resistance (R_v). The second evaluation area is named *Structural Safety* and it is divided into two categories: *technology* and *structural performance*. For these, two evaluation criteria have been considered; the commissioning work time (τ_c) and structural weight (S_w). More in detail, the analysed floors have been sized to meet regulatory requirements by adopting the simple supported beam scheme with a span of 6 m. The residential class use has been considered (Cat A), therefore a variable load of 2 kN/m^2 and a permanent load of 2.7 kN/m^2 in addition to the weight have been considered. For all alternatives a steel reinforcement area equivalent to 2Φ16 for each rafter has been imposed considering only the height as design parameter; the design heights obtained for the various types of floors are slightly different for the variation of the self-weight of each one. Finally the third evaluation area is *Investment;* it includes, at this stage of study, only the *cost of construction*.

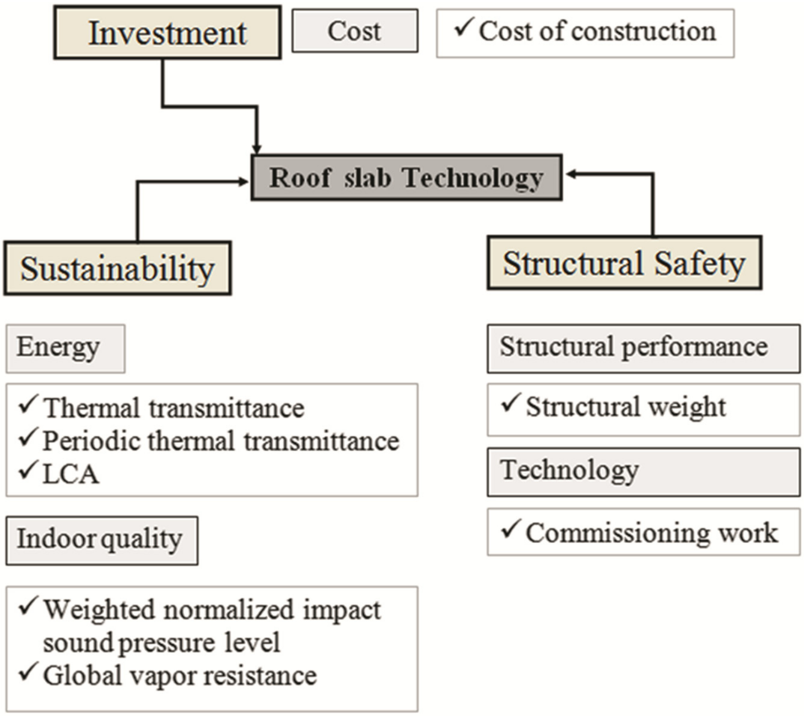


Fig. 2. Hierarchical structure of the evaluation process

The following table shows the values assumed by each criteria for every selected floor (Table 5).

Table 5. Multi-criteria analysis parameters

	U_f W/m^2K	Y_{IE} W/m^2K	LCA P_t	C_I $€/m^2$	$L'_{n,w}$ dB	R_v m^2sPa/kg	S_w kN/m^2	τ_c h/m^2
A1	1.76	0.49	10.12	46.31	51.83	$1200 \cdot 10^9$	3.21	0.42
A2	1.90	0.28	13.19	45.52	51.16	$1200 \cdot 10^9$	3.97	0.21
A3	0.48	0.01	13.25	66.76	56.01	$1440 \cdot 10^9$	2.39	0.36
A4	0.99	0.05	14.37	94.13	49.23	$1150 \cdot 10^9$	3.33	0.70

4 Weighing System Definition

The definition of a weighing system for every item involved in the analysis is another key issue of the MCDM approach. The weight assigned to the criteria, categories and areas of analysis, represents their importance compared to the immediately following level (partial weight) or with respect to the final objective (overall weight). Since there is no unique and standardized method for assigning weights, in this case study different evaluation scenarios are formulated and discussed. In fact the aim of the paper isn't to identify the best design solution of the case study, but to give a road map for developing the evaluation procedure knowing the consequences of the various decisions in a case of interdisciplinary problems. To this aim, 2 scenarios have been considered:

- *Scenario I: Higher weight to Structural Safety category*

In the first scenario, Structural Safety has been characterized by the greater importance. This scenario, therefore, could be representative of an evaluation process for a building construction in a high seismic zone. In seismic areas, indeed, the decision maker or designer attributes inherently greater importance to the structural performance rather than to Sustainability. In this case, a greater weight to the Structural Safety (0.6 in the case study) at the expense of the Sustainability (to which a weight of 0.2 is assigned) has been assigned. The residual weight of 0.2 is assigned to the Economic investment.

- *Scenario II: Higher weight to Sustainability category*

The second scenario is related to new energy efficiency threshold and thus the design of Nearly/Net zero energy buildings (Directive 2010/31/EU). A near-zero energy building is characterized by a very low primary energy needs, covered to a large amount from renewable sources. It is clear that a high performance building component affects the reduction of the final energy needs and therefore it plays a positive role in the global sustainability process. Consequently, greater importance is assigned to sustainability category, favoring the energy, environmental and indoor comfort criteria. Thus, the weight of 0.6 and 0.2 is assigned respectively to sustainability and structural safety area. A weight of 0.2 is assigned to the Investment area as in the previous case.

5 Methodology for Evaluating Criteria Performance

Multi-criteria decision-making (MCDM) methods are formal approaches to structure information and decision evaluation in problems with multiple, conflicting goals. In this paper, the selected solving methodology is TOPSIS based on distances from the ideal solution (Hwang and Yoon 1981). It can be considered a compensatory method because the better solution is the trade-offs between criteria, where a poor result in one criterion can be negated by a good result in another criterion. The best alternative should have the shortest distance from the positive ideal solution and highest distance from the negative ideal solution (also known as anti-ideal solutions). The distances are measured by the Euclidean metric and they are computed for normalized and weighted data. In the following lines, a short description of its application is reported; in particular, seven main steps can be identified.

Firstly, it is necessary to create the evaluation matrix (D) whose generic element a_{ij} expresses the performance of the generic alternative A_i (i = 1..n) compared to the generic criterion C_j (j = 1..m) and then the normalized matrix (R). Indeed, because the component properties and performance indices have different physical dimensions, the element of the matrix are normalized as:

$$r_{ij} = \frac{a_{ij}}{\sqrt{\sum_{k=1}^{n} a_{kj}^2}} \tag{1}$$

where r_{ij} is in the range of [0-1].

To prescribe the relative priority among the component properties and performance indices, a weight factor (w_{ij}) is given to each of them. This point will be deeply discussed in the next section. Thus, the third step consists in the calculation of the weighted normalized decision matrix (V), where the generic element v_{ij} is obtained as in Eq. (2):

$$v_{ij} = r_{ij} \cdot w_{ij} \tag{2}$$

As further step the ideal (A^-) and negative ideal (A^*) solution have to be calculated. In the matrix R whose elements are normalized and weighted according to Eqs. (1) and (2), the element with the most preferred value (i.e. the highest value in most except for costs) for the j-th component property or performance index is defined as the ideal v_{ij}^*, and the j element with the least preferred value is defined as the non-ideal v_{ij}^-. Hence, the matrices A^* and A^- which consist of v_{ij}^* and v_{ij}^-, respectively, are expressed by Eqs. (3) and (4):

$$\begin{aligned} A^* &= \left\{ \left(\max_i v_{ij} \middle| j \in J_b \right), \left(\min_i v_{ij} \middle| j \in J_c \right), \, i = 1, 2, \ldots n \right\} \\ &= \left\{ v_{1*}, v_{2*}, \ldots, v_{n*} \right\} \end{aligned} \tag{3}$$

$$\begin{aligned} A^- &= \left\{ \left(\min_i v_{ij} \middle| j \in J_b \right), \left(\max_i v_{ij} \middle| j \in J_c \right), \, i = 1, 2, \ldots n \right\} \\ &= \left\{ v_{1-}, v_{2-}, \ldots, v_{n-} \right\} \end{aligned} \tag{4}$$

where J_b is associated with the criteria or indices which are regarded as the best, and J_c is associated with the criteria having a negative impact or indices related to price that is, the less, the better. The selection of solution is made upon the distance between the best (S_i^*) and the worst (S_i^-) alternative calculated with the following equations:

$$S_i^* = \sqrt{\sum_{j=1}^{m} \left(v_{ij} - v_j^* \right)^2} \; per \; i = 1, 2, \ldots, n \tag{5}$$

$$S_i^- = \sqrt{\sum_{j=1}^{m} \left(v_{ij} - v_j^- \right)^2} \; per \; i = 1, 2, \ldots, n \tag{6}$$

Then the (C_i^*) of the alternative by S_i^* and S_i^- can be evaluated using the relationship:

$$C_i^* = \frac{S_i^-}{S_i^- + S_i^+} \tag{7}$$

With reference to the value of C_i^*, a preference ranking of alternatives can be made. It is evident that, if A_i coincides with the negative-ideal solution, C_i^* is zero, while for A_i coinciding with A*, the maximum value of C_i^* is 1. Although, it often happens that the best solution (the one characterized from the highest value of C_i^*) has at the same time the minimum distance and the maximum respectively by A* and A^-, in certain cases, this condition does not occur.

6 Case Study Results and Discussion

The 4 different RC floors previously introduced have been analysed by the MCDM method: A1-brick-concrete floor; A2- hollow-core floor; A3- expanded polystyrene lightened floor; A4- wood-cement lightened floor.

The 2 scenarios described in Sect. 4 have been identified:

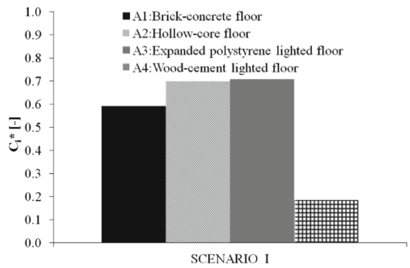
- ***Scenario I:*** Evaluation process in seismic zone, where the decision maker attributes inherently greater importance to the structural performance;
- ***Scenario II:*** Projects with energy and environmental performance requirements.

The values of C_i^* are presented in Fig. 3.

The graph of Fig. 3a shows that for scenario I the EPS lightened floor (A3) turns out to be the best alternative (maximum value of C_i^*) together with the precast floor (A2), when higher importance to the structural performance is given. In the first case the lowest self-weight prevails but in the second the success is due to low cost. Indeed the solution A4 (wood-cement floor) has low structural performance both in terms of structural weight and commissioning work; finally the traditional brick floor (A1) results with an intermediate condition.

Moving to analyse the scenario II (Fig. 3b), again the EPS lightened floor appears to be the best solution since it has the lowest value for the added parameters (U_f); the second choice could be the hollow-core floor meanwhile the worst performance competes to alternative A1 about equal to A4.

Finally, the results of proposed case study allow to remark that the adoption of several possible scenarios for definition of the weights can determine a different preference ranking for the alternatives. Thus, it is clear that decision makers can influence differently the final outcome. In the initial phase of decision problem, the final goal and the leading player of the builder process must be identified.



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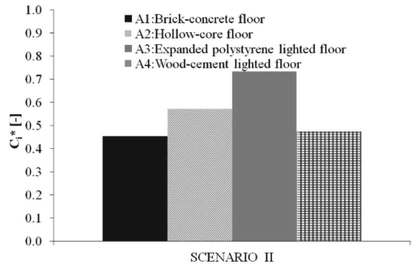

b)

Fig. 3. Results:(a) Scenario I; (b) Scenario II

7 Conclusions

The choice of the best solution for the building envelope components involves the examination of multiple conflicting criteria and objectives, as shown also by the case study of RC floor proposed in this paper. The application of a MCDM method requires at least three complex steps: the definitions of the alternatives and evaluation criteria, and then, the definition of a weighing system.

The application of the procedure to the case study allows to point out that the result changes with decision maker interest. We can conclude that it does not exist the absolute best solution for the building design, but there is a best solution in a particular design context; if the context is clear the MCDM is a useful decision tool.

The findings of the research represented in this paper are expected to be significant in further contributing to MCDM effectiveness in construction and private sectors. In the future, this research could be extended to compare further multifunction technologies as vertical components for the opaque and transparent building envelope, or to evaluate the entire building design configurations.

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