Augmented Reality based - Decision Making (AR-DM) to support multi-criteria analysis in constructions

Valentino Sangiorgio[a*], Silvia Martiradonna[ab], Fabio Fatiguso[a], Ignacio Lombillo[b]

[a] *DICATECH, Polytechnic of Bari, Via Edoardo Orabona 4, Bari, Italy*

[b] *Structural Engineering & Mechanics Department, University of Cantabria, Av. de los Castros 44 Santander 39005, Spain*

ABSTRACT

Multi-Criteria Decision Analysis (MCDA) and in particular the Analytic Hierarchy Process (AHP) is widely used in construction thanks to its versatility and ability to involve qualitative and quantitative data in the analysis. On the other hand, many complex problems are difficult to be solved because of the large amount of information to be considered.

In this paper, an Augmented Reality based Decision Making (AR-DM) is proposed to get a novel MCDA following the hierarchical structure of the AHP. For the first time, the AR immersive environment is combined with the Simos-Roy-Figueira method to provide a large amount of visual information during the decision phase. The proposed approach is tested to support the selection of an experimental Precast Concrete Panel for RC Buildings retrofitting. Finally, a comparison with the classical approach and two other improved version of the AHP procedure is performed to validate and show the potential of the method.

KEYWORD

Augmented Reality; Analytic Hierarchy Process; Decision science; Multi-criteria decision methods; Simos-Roy-Figueira (SRF) method; Building Retrofitting; Precast Concrete Panels.

1 Introduction

Multicriteria decision making, and in particular the Analytic Hierarchy Process (AHP) is a wide used tool in different areas of construction [1]. These effective mathematical tools can support the subjective evaluation of performance criteria by decision-makers [2,3]. In particular, the AHP allows to decompose complex problems in its basic components in order to individually analyze every aspect on the base of different criteria. After each component is weighted and judged, all the problem parts can be reassembled to recompose the whole problem puzzle and give the resulting priority scale to the decision maker. One of the main advantages of these approaches regards the possibility to consider both qualitative and quantitative data in the analysis. These positives aspects allowed the wide use of this tool in different areas of constructions. The principal field of application of the AHP in construction can be classified as follows: i) *project or construction stage*; ii) *maintenance and intervention* and iii) *safety or risk analysis*

i) In the *project or construction stage*, Fong and Choi [4] and Jaskowski et al. [5] used AHP for the contractor-selection decision, and in a similar way, Plebankiewiczm and Kubek [6] and Kahraman et al. [7] identified the best material supplier choice. Wong and Li [8] analyzed the selection of the intelligent building systems by identifying key selection criteria using AHP methodology. In addition, different contributions provide adequate solutions by AHP for the systematic evaluation of many factors, which include efficiency, user comfort, safety, reliability, functionality, and maintainability, to characterize the design work [9] and the weighting of soft benefits in comparison with costs [10,11] and environmental impact [12] and to support the selection of construction systems according to their contribution to sustainability [13];

ii) AHP have a positive impact to support *maintenance and intervention*, by comparing many measures, such as multi-attribute, multivariate qualitative and quantitative data [14]. Such performance assessments are used to evaluate different aspects of construction, such as safety evaluation and management in construction sites [15,16,17], green building rating [18], energetic rehabilitation [19,20], construction management [21, 22];

iii) Several applications involve the use of AHP in *safety or risk analysis* to evaluate building safety performance level [23,24], hazardous phenomena such as marine aggressive environment [25], vulnerability by take qualitative data into account [26,27], large-scale structural vulnerability analysis [28, 29], and muti-risk analysis such as seismic and volcanic risk assessment [30, 31, 32].

Comparing a large number of criteria in the field of construction is often necessary. The trend is increasing the involved parameters to perform multi attribute analysis even more complex. Consequently, many problems are difficult to be solved by the “users” or Decision Makers (DMs) because a large amount of information that need to be considered in the weights’ evaluation phase. In addition, often the AHP analysis requires time consuming and the involvement of non-expert users in the decision-making process. Some recent research focuses on novel approaches in order to decrease

the necessary number of comparisons in AHP. For instance, Ishizaka [33] proposes a method based on clusters and pivots and Abastante et al. [34] validated a methodology to reduce and avoid the comparison between relevant objects and less relevant objects.
An effective tool that can support multi-criteria methods is the Augmented Reality (AR). There are few attempts to use the AR in support of decision-making process related literature [35] and exhaustive studies to synergistically include the AR technology in a multicriteria decision making approach is missing. Nevertheless, the potential of AR in the construction sector is amply demonstrated [36, 37]. Indeed, some authors investigated the use of distributed AR in collaborative design applications to support architecture and interior design [38]. In addition, such tool can be useful in improving construction, management, maintenance and renovation of structures [39]. Finally, the related literature also demonstrated the potential of some spatial AR helpful at the territorial scale applied to the urban design, geographic information system and large construction management [40].

In this paper, a novel Augmented Reality based Decision Making (AR-DM) is proposed to get a powerful multicriteria analysis approach. The AR-DM exploits the immersive virtual environment to visually provide a large amount of information during the decision process. The novel approach starts from the problem structuring in a flowchart (typical of the classical AHP), and proceeds with new phases inspired from the SRF method. The AR-DM steps are listed as following: 1) structuring of the problem; 2) setting of the AR environment; 3) local weights evaluation; 4) synthesis of priorities.
In particular, the structuring of the problem and the synthesis of priorities (steps 1 and 4) follow the classical AHP procedure. In this way, the proposed approach can exploit the decomposition of the problem into independent criteria to transform a multidimensional scaling problem into many one-dimensional scaling problems. This process is very useful to study each criterion individually and identify the best 3D models that can be used in AR to support the analysis. The synthesis of priorities of the AHP is strictly related to the structuring of the problem and consequently considered in the proposed approach. Moreover, steps 2 and 3 exploit the AR technology and an adapted version of the Simos-Roy-Figueira (SRF) method [41] for an effective weight evaluation. The SRF was developed for the ELECTRE method in order to provide a simple and visual approach for the local weight evaluation. Such approach is very effective to be adapted and used in combination with the AR. Indeed, thanks to this combination, the user can perform the weighting of complex decision by exploiting useful information displayed in the AR environment.

The novelties of the proposed method are listed in the following items:

i) Compared to AHP, in the AR-DM the decision maker can make the comparison of the involved parameters exploiting the SRF procedure in a useful AR environment. In this way, even non-expert users of the specific problem can successfully carry out the procedure thanks to the useful information displayed in the virtual 3D models.

ii) Compared to SRF procedure, the proposed weights evaluation procedure is applied several times to obtain all the weights defined in the hierarchical structuring of the problem according with the AHP. In addition, the algorithm for weights evaluation is improved, based on the aggregation principles of local weights of the AHP.

iii) An adapted consistency tests can be used to assess the reliability of the local weights.

In this contribution, the proposed approach is used to select the best experimental Precast Concrete Panel (PCP), to be integrated with a novel technology for building retrofitting [42] and applied in a case study located in the southern Italy.

Finally, a validation is obtained by comparing the novel approach with three methods (the classical AHP procedure and two other recent improved version of the AHP) by investigating the same decision problem.

The rest of the paper is structured as follows. Section 2 describes the AR-DM approach specifying the step-based procedure; Section 3 presents the case study and shows the application of the AR-DM approach. Section 4 shows a comparison with the classical AHP and other two improved AHP and discusses potential of the methods. Finally, Section 5 draws the conclusions.

2 The *AR-DM* methodology

This section proposes the novel procedure based on the synergic combination of AHP, AR and SRF. The AHP is the theoretical approach used to effectively structure de decision and achieve the final decision ranking. AR provides a large amount of visual information to support the DM (or "user") in the decision process. Furthermore, the SRF is the theoretical starting point that allowed to develop the novel approach to make the comparison and obtain the weighs evaluation.

2.1 Overview of the method: the four steps of the AR-DM

In this section the novel procedure of the *AR-DM* is described and the following *AR-DM* 4-steps Method are presented: 1) *Structuring the problem (AR-DM Step 1)*; 2) the *AR setting (AR-DM Step 2)*; 3) *local weights evaluation* in the AR environment *(AR-DM Step 3)*; and 4) *Synthesis of priorities (AR-DM Step 4)*.

In particular, *Step 1* follows the footstep of the AHP [43] and is devoted to decomposing and structuring the problem in a flowchart to obtain a complete overview of the involved *parameters* which are classified as macro-criteria, criteria and alternatives. Note that hereafter the term *parameters* is used to generically indicate macro-criteria, criteria or alternatives.

In the *Step 2*, the AR environment is set by following a specific procedure to create the virtual 3D models.

Step 3 regards the *parameters* evaluation by the DM by using the improved SRF-based approach. The evaluation is performed directly in AR exploiting the 3D models and according to the following three "*AR phases*":

- firstly (*AR phase 1*) the user orders the 3D models to perform a local preliminary ranking,
- secondly (*AR phase 2*) the user compares 3D models in pairs and achieve the local ranking,
- thirdly (*AR phase 3*) the *local weights evaluation* is performed by exploiting SRF theory and a *local consistency test* is used to verify the coherence of the results.

The *Step 3* is repeated until all *parameters* are weighted.

Finally, in *Step 4*, if all *parameters* are weighted, the synthesis of priorities is performed to obtain the *global weights*. Figure 1 shows an overview of the method illustrating the fundamental steps and phases in a flowchart.

The steps and phases of the procedure are described in detail in the following subsections.

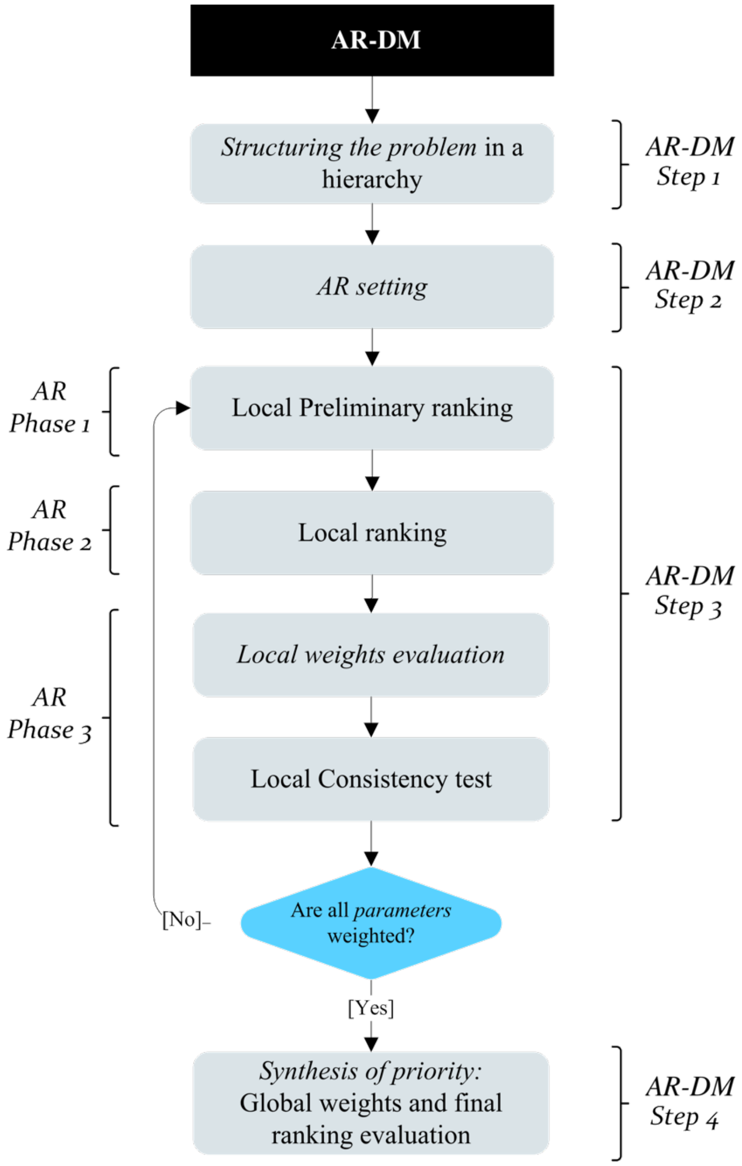

Fig.1. The flowchart of the AR-DM procedure.

2.2 AR-DM step 1: Definition of goal, criteria, and alternatives

The *AR-DM step 1* regards the identification of the *goal* and the structure of the problem according to a hierarchical flowchart composed by different levels [43]. This step provides a detailed, simple and systematic decomposition of the *parameters* of the problem into its basic components. This flowchart represents the goal of the analytical process, the macro-criteria, criteria and alternatives classified in different levels, to have a complete description of the considered phenomenon.

2.3 AR- DM step 2: AR and 3D models setting

The *AR-DM step 2* is essential for the procedure and in this phase AR environment and the virtual 3D models are set for the analysis.

The number of 3D models that are necessary depend on the number and typology of *parameters* to be analyzed and structured in the flowchart of *AR-DM Step 1*. In particular, a 3D model can be designed for every alternative and customized with respect to the criterion to be analyzed in order to show the most useful visual information connected to the criterion.

In particular, every 3D model could enclose the following information: i) the name of the *parameter*; ii) the representative 3D model or scheme; iii) an useful description or qualitative information connected to the *parameter*; iv) quantitative data, which can be typological, functional, characteristic or economic; v) advantages, vi) disadvantages or other information.

2.4 AR-DM step 3: local weights evaluation

After all the 3D models have been created, the DM can perform the *local weights evaluation* by analyse every single aspect of the decision problem in the AR environment.

In particular, the AR supported analysis is carried out in three phases named *AR Phase* 1, *AR Phase 2*, and *AR Phase 3*. These three *AR* phases are developed in accordance to the SRF theory and are explained as follows.

Let us assume that a set of 3D models is defined to evaluate a set of *parameters*.

In *AR Phase 1* the user is asked to rank the 3D models (representing a set of *parameters* in relation to a specific criterion) from the less important to the most important according with the decision theory of SRF [41]. So, the user orders the 3D models in an AR environment by assigning to them an ascending importance to obtain a preliminary local ranking: the 3D models positioned to the left correspond an assignment of low importance, on the contrary in the right part of the AR environment the user can position the most important 3D models. In addition, if the user decides that some 3D models have the same importance (i.e., the same weight), he can assign the same position to a subset of 3D models. Consequently, the output of *AR Phase 1* is a local preliminary ranking of the considered parameters. Figure 2 represent the local preliminary ranking of a generic set of 3D models from less important to most important.

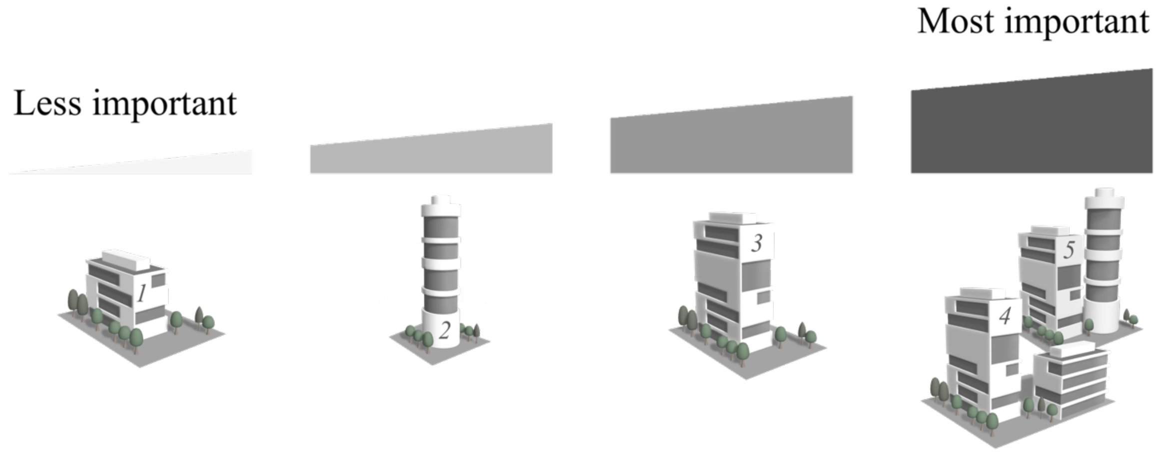

Fig.2. Example of *AR phase 1*: local preliminary ranking of a set of 3D models (representing parameters).

In *AR Phase 2*, the user can decide how large the differences of two successive 3D models (or subsets of 3D models) are. This operation is made by comparing in pairs adjacent 3D models. The users can introduce empty spaces (represented with white cubes) between two successive 3D models (or subsets of 3D models) in order to increase their differences in relation to the local preliminary ranking. The absence of empty spaces between two consecutive 3D models means small difference. The more empty spaces are introduced, the more the differences between the two 3D models are considered. The *AR Phase 2* finishes with the assignment of a rank (local ranking), both to the 3D models, empty spaces and subsets 3D models (Figure 3).

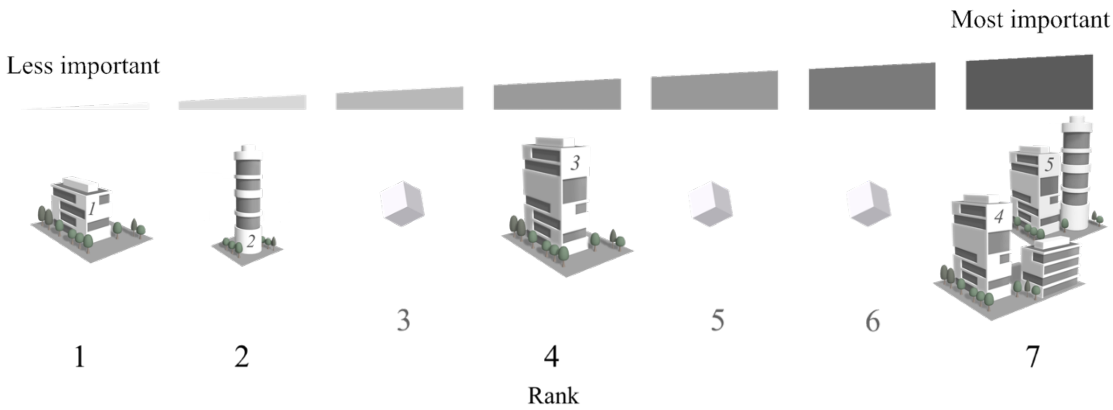

Fig.3. Example of *AR Phase 2*: local ranking obtained using 3D models and empty spaces (white cubes).

In the *AR Phase 3* it is possible to derive weights from the result of *AR Phase 2*. This procedure is proposed starting from the theory of SRF. Compared with the classical SRF method, the algorithm for weights evaluation is improved, based on the aggregation principles of local weights of the AHP in order to apply the weights evaluation procedure several times and weight all the considered parameters.

Now it is necessary to formalize a mathematical procedure to extract weights from the local ranking obtained by using 3D models and empty spaces. Let us assume that a set $N = \{p|p = 1, \dots, n\}$ of parameters (with $n \in \mathbb{N}$ where $\mathbb{N}$ is the set of natural numbers) are analyzed through the *AR phases* and let us denote $C = \{c_p|p = 1, \dots, n\}$ the set of 3D models c_p where c_p is associated to the p^{th} parameter for $p = 1, \dots, n$. In addition, we define the set $E = \{q|q = 0, \dots, m\}$ (with $m \in \mathbb{N}$) of empty spaces. A rank $r_p \in \{1, \dots, n+m\}$ is assigned to each 3D model $c_p \in C$ during *AR Phase 2*. The local weight $v_p \in \mathbb{R}^+$ associated to each 3D model $c_p \in C$ (and then to each parameter *p)* is computed by the following formula:

$$v_p = \frac{r_p}{\sum_{p=1}^{n} r_p} \qquad \text{for } p = 1, \dots, n, \qquad (1)$$

where $\mathbb{R}^+$ is the set of real positive numbers. Note that it holds $v_p \in [0,1]$ with $\sum_{p=1}^{n} v_p = 1$. We remark that equation (1) is defined in order to respect the principle of the weight extraction of the matrix of Saaty [41] where the weights are normalized to 1 by considering the perception of the DMs.

At this point, a suitable local consistency test is proposed in order to verify if the user is aware of the choices made in the *AR phases,* and to check the weighs coherence. The presented test is inspired by the theory of Saaty and SRF [41,43]. Indeed, analogously with the AHP and the matrices of Saaty, the proposed consistency test is based on additional and redundant judgements in order to verify the coherence. In addition, it is specified to be compatible with the proposed *AR phase 2*.

In particular, in the *AR* system the DM is asked to perform an additional 3D model comparison (between two 3D models randomly extracted from the set C) expressing numerically how much one parameter (associated to the 3D models) is more important than another. Let us assume that the user extracts the 3D models c_i and c_j (with i and $j = 1, \dots, n$) and assigns a value k to this pair comparison. This value k represents the difference between c_i and c_j according to the user's perception. Consequently, if the user has consistently applied the *AR Phase 2,* k should have a similar value to the ratio between the weights v_i and v_j associated to c_i and c_j respectively.

Consequently, the local consistency denoted $LC(i,j)$, is evaluated by the following formula:

$$LC(i,j) = \left|\frac{k-(v_i/v_j)}{v_i/v_j}\right| \quad \text{for each } c_i, c_j \in C \qquad \text{with } i \neq j. \qquad (2)$$

Formula (2) numerically specifies the difference between the additional comparison expressed by k and the obtained weights v_p.

On the basis of several empirical tests in agreement with Saaty [43], it is possible to assume that the values $LC(i,j) < 0.30$ are acceptable. It is worth noting that this first local consistency test does not ensure that the final result is reliable, but it indicates whether the user has a good perception of the importance of the analyzed parameters.

It should be note that analogously to AHP, the proposed AR-DM can include also quantitative parameters in the analysis. If the DM needs to evaluate a set of parameters N composed by numerical values of the same unit of measurement, the weights of this parameters can be directly obtained normalizing the numerical values of the parameters.

2.5 AR-DM step 4: synthesis of priorities

In the final *AR-DM step 4*, the *synthesis of priority* (or weights aggregation) is performed to determine the rankings and the global weights for each alternative by following existing approaches widely used in related literature for the MCDMs.

To this aim, the weights of criteria are combined with the weights of the alternatives in order to obtain the global weights. In the related literature there are many equations to perform the weights aggregation and the use of a specific equation depends on the investigated problem [24, 44]. This work uses the simplest and widespread weights aggregation method existing in literature of the weighted sum. In this approach, the global weights are obtained by multiplying each criteria weight by the alternative weight and totaling the results for each alternative [45].

3 AR-DM application to the case study

The proposed approach is applied to select the best cladding for the experimental Precast Concrete Panels (PCPs) devoted to energy retrofitting. The several involved criteria and alternatives are difficult to be compared because the DM shall simultaneously consider many information about the novel PCPs system to make a consistent decision.

The following subsections describe in detail the PCPs system, the case study, and the application of the AR-DM to face the complex decision problem.

3.1 The PCP system

The novel intelligent PCP system is devoted to satisfying thermal, structural needs and performance monitoring of the residential reinforced concrete buildings (built after 1950). It is composed by innovative precast concrete panels integrated with elements installed directly on the existing building structure / façade and equipped with a set of data acquisition devices (Figure 4) [46, 47].

One of the advantages in using the PCPs system is the possibility to integrate the external cladding already during the prefabrication process, avoiding the typical waste of time due to the building finishes after retrofitting [42]. Nevertheless, the choice of a coating material rather than another is of basic importance. In fact, it can affect the characteristics of the panel in terms of aesthetical effect, time and needs of production, installation, technical properties, and economic sustainability.

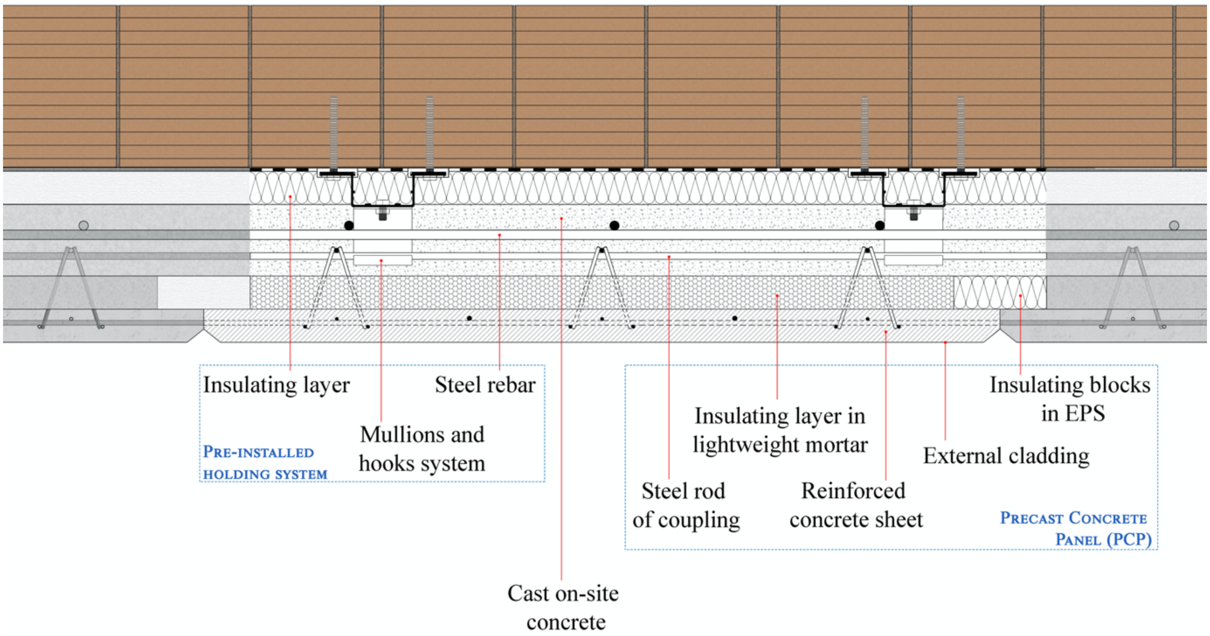

Fig. 4. Constructive detail of the innovative precast concrete panel system.

3.2 The case study

The choice of the best PCP depends on the case study considered for the retrofitting. Since the PCP is a novel and experimental technology, the decision is made complicated by the absence of previous applications both in practical and scientific scenarios. Hence, the DMs (or users) are represented by a group of practitioners (designer) operating in the construction field.

The considered case study regards a RC building of an economic-popular residential complex located in Trani, a city few kilometers far away from Bari (Italy). It was built between 1958 and 1963, consisting of a basement and two floors, four apartments and a regular footprint area of 258 m^2. It has two principal facades with lodges and balconies, a lateral blind façade and the last one shared with another building. The external wall thickness is 25 cm in the lodges and 40 cm in the rest of the building with a thermal transmittance value (U-Value) of 1.03 W/m^{2}K. The original envelope is realized in stone tiles in the basement and plastered in the upper part with no insulating layers included.

In the following subsection the AR-DM is used to select the best PCP cladding to be applied in the defined case study, considering the necessity of the building retrofitting and its integration in the local context.

3.3 Step 1: the problem structuring

The AR-DM step 1 consists in the *Structure of the Problem* to determine an effective choice regarding the best selection of the PCP cladding for the building envelope.

In particular, the goal is defined as the *Precast Concrete Panel Cladding Selection*. To this aim, six criteria *i* (with *i*=1,…,6) are defined to characterise the envelope by considering four *macro-criteria*: *aesthetics*, *production and executive needs*, *thermal behaviour* and *costs*.

In addition, a set of six different intelligent precast envelope solutions are proposed as *alternatives* *j* (with *j*=1,…,*6*) of the decision problem. The six *criteria*, and the six possible *alternatives* are structured in a hierarchical flowchart that is showed in Figure 5. It is worth noting that every alternative is related and then connected with all the defined criteria.

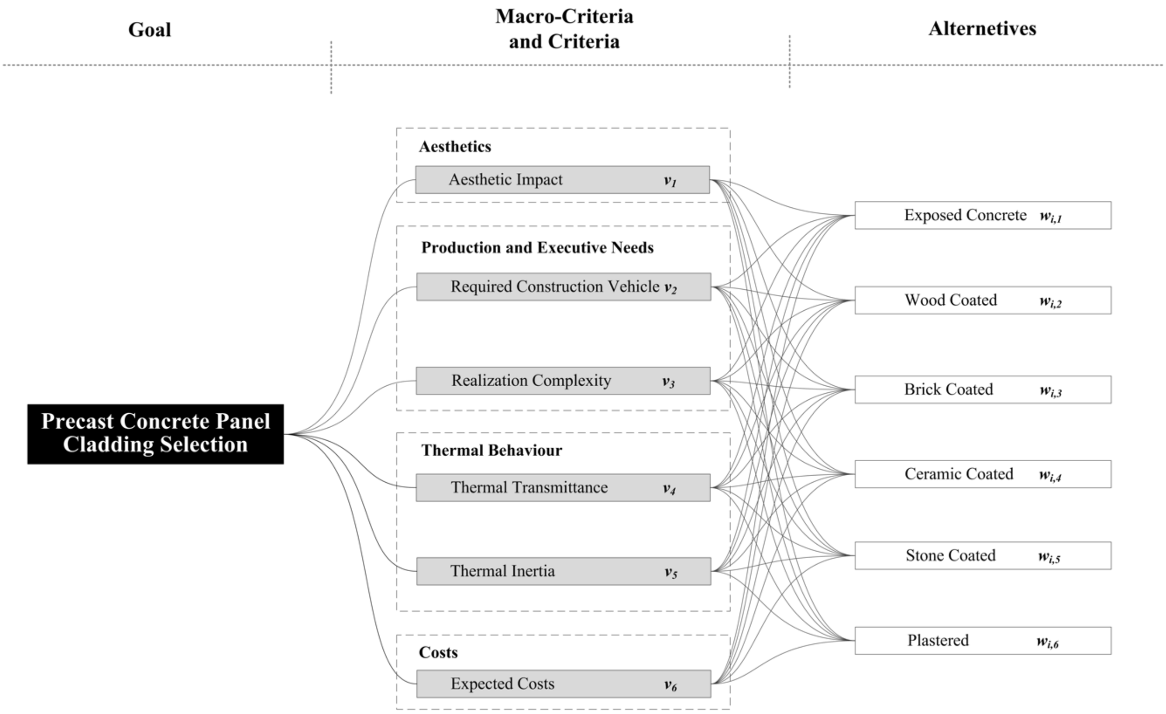

Fig. 5. *Structure of the Problem*: criteria and alternatives to determine the best intelligent precast envelop.

The rationality of the defined six criteria and alternatives is explained as follows.

The First *macro-criterion* and *criterion* regards the aesthetic aspects of the panel in relation to the case study:

1) *Aesthetic Impact* (*i*=1) is an important factor because may have a strong influence on the society. Indeed, since the PCPs system is born for the social houses retrofitting, a low aesthetic impact may have some negative effect i.e. marginalization and social discrimination. Instead, a high aesthetic impact may return dignity to the building, integrate tenants with the rest of the city and makes the building gain value [48].

The Second *macro-criterion* takes the *Production and Executive Needs* into account to evaluate the PCP cladding. It considers two qualitative *criteria,* one related to the vehicle required to transport the panels from the factory to the construction site and another to evaluate the realization complexity required during the prefabrication and installation process of the panels. To this aim, the second and third criteria are defined:

2) *Required construction vehicles* (*i*=2) is related to the typology of lorry employed to deliver the panels to the construction site. In general, the most used vehicles for precast modules (module up to 3 m) are the articulated lorry and the combined truck with tractor and trailer. The Italian road regulation lays down the size limits and the permissible weight of vehicle bodies.
   Indeed, articulated lorry shall not exceed 16.50 m in length and 2.50 m in width with bodies 12.50 m or 13.60 m long. In addition, the elements shall be placed in the body up to a height of 2.50 m and the maximum load they may transport shall be 300 kN.
   The combined truck can be 8 m long maximum, 2.50 m wide with a 6 m long trailer. The load is 150 kN and the goods can be placed up to a height of 2.50 m. If they enclose the crane to move and install the elements on the building façade, the deliverable load decreases of about the crane weight [49].
   The type of vehicle used and the number of trips depend on the arrangement and the maximum number of panels. In turn, they depend on the size and weight of the panels. In addition, the wooden beams to separate the rows of panels and protect their cladding shall be considered. They reduce the permissible load of the vehicle of about 2%.
3) *Realization Complexity* (*i*=3) is important to consider the different requisition and measures for the correct production and execution of the panels both in the factory and in the construction place (according to the rules of workers prevention and protection on the work). In particular, caution during the movement phases, scaffolds, props and stiffening of anchors are considered in this criterion. The necessity of retail labour and the time for fabrication and installation are also included.

Another significant *macro-criterion* is the *Thermal Behaviour* of the building which can be assessed through two important quantitative criteria:

4) *Thermal Transmittance* (*i*=4) is the coefficient of heat transmission between surfaces. The regulation UNI EN ISO 6946:2018 defines the thermal transmittance as “the heat flow through a unit surface subjected to a temperature difference of one degree”. It depends on the material characteristics and thickness of the building component [50]. The Italian regulation establishes the limit value of the existing building elements subjected to energy improvements. It is 0.36 W/m^2K for the walls. At lower values correspond a better thermal performance of the building component [51].
5) *Thermal Inertia* (*i*=5) is the capacity of a building component to mitigate the temperature fluctuations in the internal environment due to the variation of thermal loads throughout the day, to accumulate and release heat after several hours. According to the regulation UNI EN ISO

13786:2018, two dynamic parameters are considered in order to appreciate the wall thermal inertia: the periodic thermal transmittance and the periodic internal thermal capacity. The first parameter evaluates the heat shift for 24 hours, the second one is the effective thermal accumulation capacity of the wall. High performance of the wall is determined by a periodic thermal transmittance value lower than 0.10 W/m^2K (time shift coefficient greater than 12 hours and attenuation factor lower than 0.15), and a high value of periodic internal thermal capacity [52].

The final macro-criterion considers a preliminary evaluation of *Costs*. To this aim, the last quantitative *criterion* is defined as follows:

6) *Expected Cost* (i=6) is the economic parameter that considers the increasing of expenses to realize the PCP in function of the cladding material and its assemblage technology. It takes into account the costs of the labour in the factory and in the construction site, the increasing in production, installation, refinement times and the mere costs of the materials.

Supposed that the retrofitting technology of the PCPs System remains unvaried, six PCP *alternatives* may be defined at the cladding variation.

1) *Exposed Concrete* (j=1) is the base panel (PCP) of the experimental retrofitting system. The standard module is 1.2 m wide, 2 m long and 0.1 m thick. It consists in a precast sheet in reinforced concrete, an internal insulating layer in lightweight mortar and recycled EPS blocks [42]. Its external finish is smooth and shows the typical grey color of Portland cement concrete.
2) *Wood Coated* (j=2) is the PCP integrating the wooden planks used for external surfaces covering. According to the designer project, the planks are easily mounted in the construction site by a mullion-clip system embedded in the external concrete sheet of the panels. This technology permits hiding the junctions among the panels.
3) *Brick Coated* (j=3) is the base panel integrated with ceramic solid bricks during the prefabrication process in its visible part. The bricks, 25 cm long, 12 cm wide and 5.5 cm thick, are arranged in rows along the width and with offset vertical joints. In order to reduce the panel weight, the hypothesis to cut the bricks has been considered, obtaining pieces of 2.5 cm thick. Hence, the panels leave the factory already with the brick coat.
4) *Ceramic Coated* (j=4) is the standard PCP cladded with ceramic tiles already in the factory, before casting the concrete of the sheet. They can be arranged according to the architectural design and with various shape tiles. Those considered are 20x40 cm in brown shadows. Also in this case, the PCPs leave the factory integrated with the ceramic cladding.
5) *Stone Coated* (j=5) is the base panel cladded by “Trani’s stone” tiles. This stone type is widely used in Apulian region, in the southern Italy, for its characteristics and whitish aspect. In the factory, according to the designer drawing, the tiles are arranged as first layer of the PCP and

integrated in the slab by means the concrete casting. The stone coated PCP arrives to the construction site ready to be mounted on the building.

6) *Plastered* (*j*=6) is the base panel integrated with a set of layers composed by mortar, a plaster net, second layer of mortar and the colored tint. After installing the panels and adding the net in the junctions among the panels, the existing building façade is cladded in situ with the plaster, colored on the client request.

3.4 Step 2: the PCP selection in AR

Once the problem is defined, the AR-DM step 2 is applied and the 3D models c_j associated with alternatives *j* (for *j=1, … ,6*) are realized.

In particular, six 3D models are developed to show in AR the final effect of the different PCPs applied to the case study useful to compare the *Aesthetic Impact* of the final possible results. Moreover, other six 3D models are realized to represent the different PCP cladding variation in order to support the evaluation of *Realization Complexity*. Figure 6 shows the 3D model of the *Stone Coated* PCP in the left and the *Stone Coated* PCP applied to the case study in the right.

It is worth noting that the comparison regarding the remaining criteria of *Required construction vehicles, Thermal Transmittance, Thermal Inertia and Costs* can be carried out quantitatively as described in the last sentence of AR-DM step 3. To this aim, there is no need for specific 3D model to support these specific comparisons.

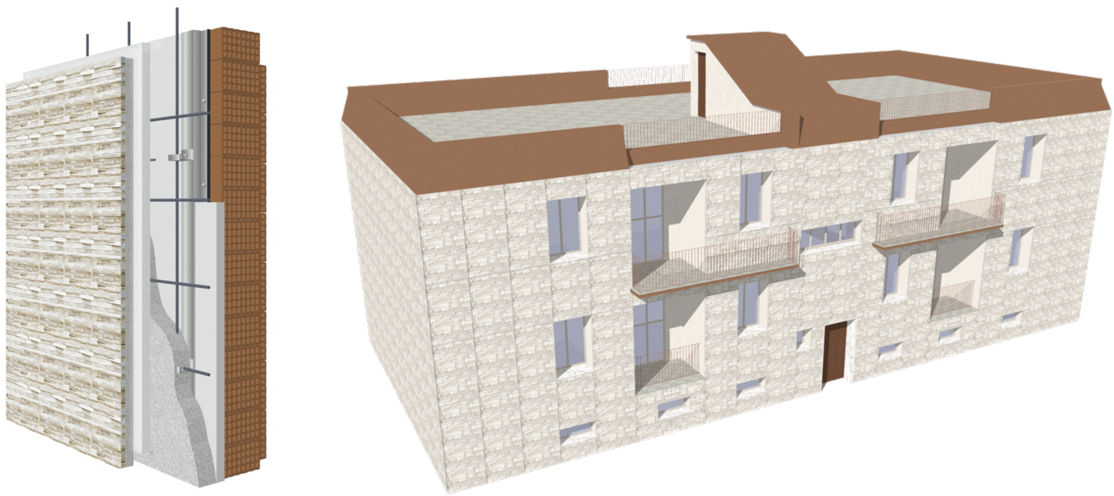

Fig. 6. *Stone Coated* PCP: 3D model of the panel and application to the case study.

3.5 Step 3-4: the evaluation of local and global weights

In AR-DM step 3, every criterion and alternative are analyzed in order to weight the involved parameters. Let us define the set of criteria $N_1 = \{i|i = 1, \dots, 6\}$ and the set of alternatives $N_2 = \{j|j = 1, \dots, 6\}$. The local weights of criteria and alternatives are defined as follows:

- v_i is the local weight associated with the *i-th* criterion $\forall i \in N_1$;
- $w_{i,j}$ is the local weight associated with the *j-th* alternative related to the *i*-th criterion, for $\forall i \in N_1, \forall j \in N_2$.

By involving the evaluation of the group of users operating in the construction field, the *AR-DM step 3* allows evaluating local weights: an evaluation is applied in order to identify the tabulated weights of criteria v_i and six ones are developed to evaluate the alternatives $w_{i,j}$.
In particular, the rank r_i is assigned to each criterion i during *AR Phase 2* and consequently the local weights v_i are computed on the basis of equation (1) by considering $p = i$.
In addition, six ranks r_{ij} are assigned to each alternative j with respect to each of the six criteria *i* during *AR Phase* 2. Subsequently, local weights $w_{i,j}$ are computed by reworking equation (1) as follows:

$$w_{i,j} = \frac{r_{ij}}{\sum_{j=1}^{6} r_{ij}}, \forall j \in N_2, \forall i \in N_1. \quad (3)$$

To provide an example, the users start from the evaluation of the *Aesthetic Impact* ($i = 1$) by considering the alternatives $j \in N_2$. In *AR phase 1* the users order the 3D model associated to alternatives j on the base of his qualitative judgement from the one that have the worst *Aesthetic Impact* to the one that has the greatest *Aesthetic Impact*. Subsequently, in accordance with *AR phase* 2 a set of empty spaces are used to increase the differences between two consecutive alternatives.
Figure 7 shows the *Aesthetic Impact* evaluation in AR environment useful to display and compare the final effect of the PCPs applied to the case study. In Figure 7 an “on desk” analysis is showed with virtual 3D models in scale. In this case the users consider *Ceramic Coated* PCP as the best aesthetical solution (positioned on the right in the AR environment).

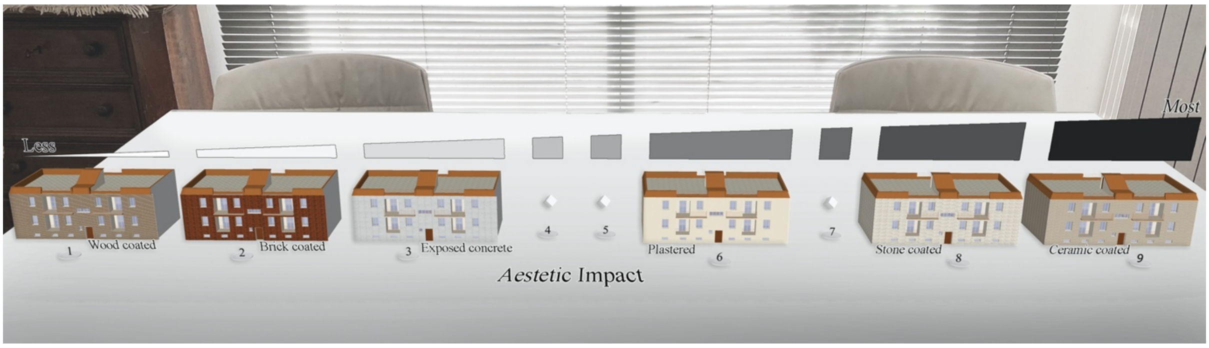

Fig. 7. Example of *AR phase 2* by considering *Aesthetic Impact* criterion.

The weights $w_{1,j}$ are determined by using equation (3) and exploiting the rank assigned and showed in Figure 7.

In addition, a Local Consistency check is performed and the users randomly extracted alternatives c_4 (*Ceramic Coted*) and c_2(*Wood Coted*) according to *AR phase* 3. The users assign a value of $k_{4,2} = 9.5$ to the pair comparison between c_4 and c_2. This value *k* represents the differences between c_4 and c_2 according to the user's perception. In particular the users believe that c_4 has a weight 9.5 times greater than c_2. If the *AR Phase 2* has been consistently applied, *k* should have a similar value to the ratio between v_4 and v_2. To this aim, by reworking equation (2), it is possible to verify the Local Consistency as follows:

$$LC_{4,2} = \left|\frac{9.5-(w_{1,4}/w_{1,2})}{w_{1,4}/w_{1,2}}\right|. \quad (4)$$

The Local Consistency check is verified since it holds $LC_{4,2} = 0.056 \leq 0.3$, i.e., the DMs correctly carried out the procedure.

Analogously, the *AR* three *phases* are performed for all the criteria and alternatives. In this way, all values of v_i and $w_{i,j}$ $\forall j \in N_2, \forall i \in N_1$ are determined.

To provide another example and show the potential of the AR environment in support of the decision making, Figure 8 and Figure 9 show the local weights evaluation of the alternatives in relation with the criterion *Realization Complexity* performed directly on site. Figure 8 shows how every 3D model can be rotated and displayed at the real scale in AR environment, in order to comprehend many aspects of the PCP, including the element of which are composed, the installation methods, the used materials, the stratigraphy and the final result. More in details, Figure 8 shows how the the *Wood Coted* PCP is applied to the existing façade allowing the visualization of all the components.

In addition, the ranking evaluation of all the 3D models related to the criterion realization complexity is showed in Figure 9. In the left part of the figure, the PCPs with less *Realization Complexity* are positioned (the *Exposed Concrete* PCP), while on the right the more complex ones are located (the *Brick Coated* PCP). Also, in this case equation (3) is used to obtain the local weights. After obtaining all the local weights of the problem the tabulated weights related to the considered *Structure of the Problem* are achieved (Table 1).

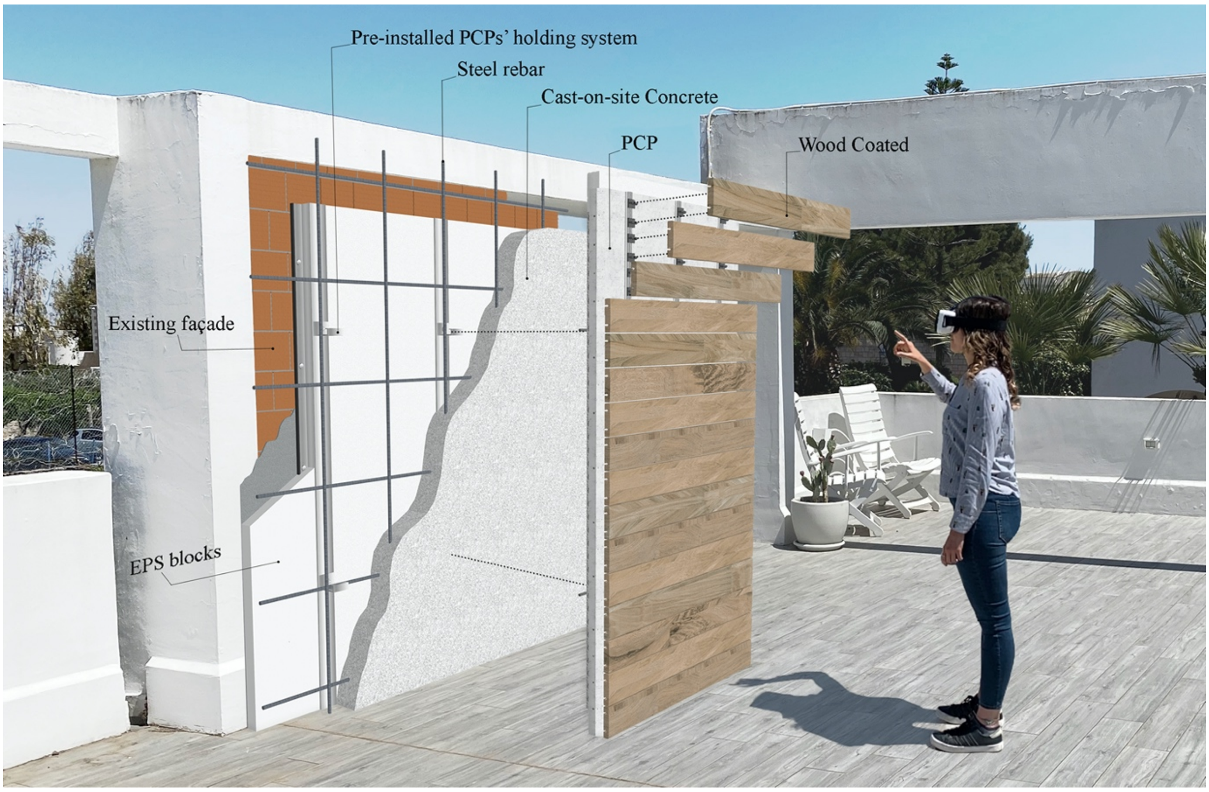

Fig. 8. *Wood Coted* PCP: virtual application on site during the building retrofit displayed in AR.

Fig. 9. Ranking of 3D models related to the *Realization Complexity* criterion performed on site.

Table 1 Tabulated weights obtained with the AR-DM

Criterion	v_i	*Alternative*	w_{ij}
Aesthetic Impact	*0.18*	*Exposed Concrete*	0.10
		Wood Coated	0.03
		Brick Coated	0.07
		Ceramic Coated	0.31
		Stone Coated	0.28
		Plastered	0.21
Required Construction Vehicle	*0.03*	*Exposed Concrete*	0.18
		Wood Coated	0.15
		Brick Coated	0.15
		Ceramic Coated	0.18
		Stone Coated	0.14
		Plastered	0.18
Realization Complexity	*0.09*	*Exposed Concrete*	0.30
		Wood Coated	0.13
		Brick Coated	0.03
		Ceramic Coated	0.27
		Stone Coated	0.07
		Plastered	0.20
Thermal Transmittance	*0.24*	*Exposed Concrete*	0.16
		Wood Coated	0.17
		Brick Coated	0.17
		Ceramic Coated	0.17
		Stone Coated	0.17
		Plastered	0.17
Thermal Inertia	*0.26*	*Exposed Concrete*	0.19
		Wood Coated	0.02
		Brick Coated	0.20
		Ceramic Coated	0.19
		Stone Coated	0.20
		Plastered	0.20
Expected Costs	*0.21*	*Exposed Concrete*	0.19
		Wood Coated	0.14
		Brick Coated	0.16
		Ceramic Coated	0.18
		Stone Coated	0.17
		Plastered	0.17

Then, it is possible to calculate the global weights w_j' (AR-DM step 4) representing the effective preferences of the group of users with respect to the best PCPs selection for the considered case study. In particular, the following equation is used to obtain the synthesis of the priority according to the classical formula of Saaty [43]:

$$w'_{\mathrm{j}} = \sum_{i=1}^{6} v_{\mathrm{i}} \times w_{\mathrm{i,j}}\, , \forall j \in N_2. \tag{5}$$

The obtained global weights are showed in Table 2.

Table 2 Global weights obtained with the AR-DM

Alternative	w'_i
Exposed Concrete	0.18
Wood Coated	0.10
Brick Coated	0.15
Ceramic Coated	0.21
Stone Coated	0.18
Plastered	0.19

4 Comparison among AR-DM, AHP and two improved AHP

A comparison with the classical AHP and two improved versions of the AHP is performed and discussed in this subsection, in order to validate the AR-DM and emphasize the potential of the method. In particular, the same decision problem is faced by the same user group by using the following three approaches: i) the well-known classical AHP based on the three steps of Saaty [43]; ii) an improved parsimonious AHP methodology including five additional steps developed by Abastante et al. [34] hereafter named A-AHP; iii) an improved AHP method based on clusters and pivots developed by Ishizaka [33] hereafter named I-AHP.

The three AHP approaches are applied to the presented case study and are described in detail in the Supplementary Methodology.

4.1 Comparison of results

The results obtained with the four approaches are very similar and only few differences in the importance of some parameters appear. In particular, the same preferences and final ranking are obtained by using all the compared approaches (AR-DM, AHP, A-AHP and I-AHP) for the PCP selection. Indeed, the group of users individuate the following global weights: i) *Ceramic Coated* is the most efficient PCP (according to all methods) thanks to good performing characteristics in all the criteria and the related global weight expressed in percentage and ranging from 21% to 23%; ii) *Stone Coated*, *Exposed concrete* and *Plastered* PCPs have a similar global weight ranging between 17% and 19%; iii) finally, *Brick Coated* and *Wood Coated* PCPs are the worst panels for the considered case study with a weight ranging from 13-15% and 9-11%, respectively.

Figure 10 shows the global weights (expressed in percentage) obtained with the four approaches (AR-DM, AHP, A-AHP and I-AHP) representing the final preferences of the best PCP selection for an economic-popular residential complex located in Trani.

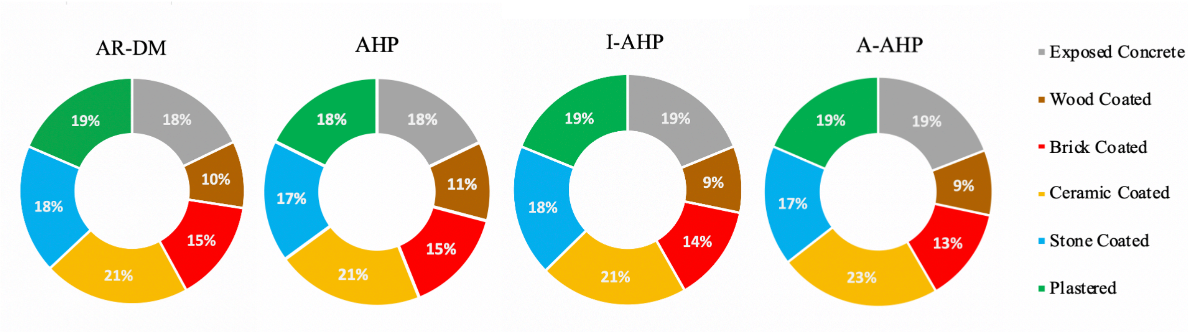

Fig. 10. Global weights obtained with the AR-DM and the classical AHP approach.

4.2 Application differences between the compared approaches

Even if the results of the four approaches are equivalent, users have faced a different difficulty in the application of the methods. The main differences have been identified in three fundamental features (Table 3): i) the length of the decision-making, ii) the complexity of the approach and iii) the consistency of evaluation.

i) The length of the decision-making in terms of time is the first important difference. The proposed AR-DM is the faster approach and needs on average 15 minutes to evaluate seven rankings. On the contrary, the AHP requires a time that can vary from 50 to 80 minutes to evaluate seven matrices of AHP. The A-AHP and I-AHP are able to reduce the number of paired comparisons, consequently these improved approaches can be performed on average in 50 and 38 minutes, respectively.

ii) The complexity of the approach is the second important difference. The AR-DM is entirely based on a visual, fast and intuitive procedure exploiting an immersive virtual environment to support the analysis. The AR environment becomes fundamental to simplify the evaluation process of the DM in particular for weighting related to *Aesthetic Impact* or *Realization Complexity*. Furthermore, this case study has shown how users become rapidly familiar with the AR-DM method.

On the other hand, the classical AHP required in total 105 comparison pairs to get the final result. In addition, in the AHP, the support by an expert in the field is required in all procedure phases.

Also in this case, the A-AHP and I-AHP are able to simplify the approach by reducing the number of comparison. In the proposed case study, the A-AHP and I-AHP respectively required 42 and 63 comparison pairs to achieve all the local weights. Therefore, users are able to focus on fewer comparisons and keep high concentration throughout the decision process. Such improved version is easier than the classical AHP.

iii) In conclusion, the consistency of the judgments is a typical problem of the AHP methodology. Indeed, in AHP applied to the case study, consistency is not immediately reached in over 50% of cases. Consequently, a trial and error procedure is used to reach consistency: such procedure can divert decision maker concentration from the decision and compromise the result [21]. On the other hand, in the AR-DM, A-AHP and I-AHP the consistency is almost always immediately reached. All approaches reached the consistency at the first attempt for the 85% of the evaluation. In particular, in the AR-DM approach the AR environment and the speed of the procedure allow users to maintain high concentration throughout the decision-making process and pass the consistency check. In the A-AHP and I-AHP the reduced size of the comparison matrices makes it easy to achieve consistency.

To sum up, the four approaches are all effective in terms of achieved result, but the AR-DM uses a more intuitive AR supported procedure that is able to achieve the same result of the classical AHP in a faster and more consistent way. For the qualitative parameters that require visual information, the DM founds in the AR environment an exceptional support.

The A-AHP and I-AHP has very strong points such as the simplicity in the achieving consistency. The AR-DM compared with the improved AHP methods has similar performance, but it is faster and more useful for decision problems that require a deep visual investigation of criteria and alternatives, as in the proposed case study.

Table 3 Application comparison of AR-DM, AHP, A-AHP and I-AHP through the proposed case study.

Approach	*Average Length (Time)*	*Complexity of the approach*	*Consistency Requirement*
AR-DM	*15 minutes*	*7 ranking*	*86% at the first attempt*
AHP	*65 minutes*	*Rquired in total 105 pairs comparison*	*50% at the first attempt*
A-AHP	*50 minutes*	*7 ranking and 42 pairs comparison*	*92% at the first attempt*
I-AHP	*38 minutes*	*63 pairs comparison*	*89% at the first attempt*

4.3 Methodological differences between the compared approaches

The last comparison of the four approaches concerns the methodological differences in terms of improvement over the classical AHP.

The AR-DM follows the footstep of the SRF method for the comparison. To this aim the method provides a graphical support for the DM and avoids direct comparison between the more relevant and less relevant objects. In addition, the proposed approach is able to avoid rank reversal problems and it has no limits in the comparison scale (in the AHP, the comparison is limited by the verbal scale related to values ranging from 1 to 9).

In a similar way, the A-AHP and I-AHP are able to avoid direct comparison between relevant and irrelevant objects and both the methods can enlarge the comparison scale. In addition, the A-AHP is able to avoid rank reversal problems as specified in [34]. On the other hand, the I-AHP is able to reduce only the possibility of the ranking contradiction. Indeed, Ishizaka indicates in [33] that the rank reversal problem is not completely addressed by his method. Table 4 sum up and schematize the methodological comparison.

Table 4 Methodological comparison of AR-DM, AHP, A-AHP and I-AHP.

Approach	*Graphical support for the DM*	*Avoid direct comparison between relevant and irrelevant objects*	*Avoid rank reversal problems*	*Enlarge the comparison scale*
AR-DM	×	×	×	×
A-AHP		×	×	×
I-AHP		×		×
AHP				

5 Concluding Remarks

This paper proposes for the first time a Multi-Criteria Decision Method (MCDM) supported by the Augmented Reality (AR), one of the enabling technologies of the industry 4.0, named AR-DM. The novel approach is based on the structuring of the problem in a hierarchy typical of the Analytic Hierarchy Process (AHP) and exploiting a visual-based comparison of parameters inspired by the Simos-Roy-Figueira (SRF) method [41].

This ambitious research project is carried out in four phases: i) the definition of the novel AR-DM 4-steps; ii) the involvement of an improved version of the SRF method to evaluate the weight in synergy with AR and the AHP; iii) a case study application of the AR-DM to support the selection of the best solution among six Precast Concrete Panel systems (PCPs) for the building envelope intervention; iv) a comparison with the classical AHP, and two recent improved version of the AHP in order to validate the approach and show the potential of the novel method.

The research shows that the posed method exploits the AR to obtain a great support in the decision in addition to the positive aspects of the AHP and SRF combination. The structure of the problem and the equation regarding the global weight evaluation are taken from the classical AHP procedure of which the effectiveness is widely demonstrated in the literature [43]. In addition, the comparison of the parameters of the decision problem is performed as suggested by the SRF method [41] but readapted and supported by modern AR tools.

As a result, the decision maker is able to carry out the comparison of the involved parameters thanks to a very simple procedure developed in AR allowing to determine numerical values for weights. The comparison is supported by specific 3D models designed to be helpful in the understanding of the parameters involved in the problem. In this way, even non-expert users of the considered problem can successfully carry out the procedure. In addition, the method is provided with consistency tests in accordance with the AHP theory that allows verifying the coherence of the local weights

The peculiarities of the AR-DM method allow overcoming some of the drawbacks of the most common MCDM:

1) the difficulty for the user to quickly understand and correctly apply the decision method thanks to the simplicity of the decision analysis in a user-friendly AR environment;
2) the difficulty of applying a MCDM even by users who do not have a complete knowledge of the problem. This drawback is overcome thanks to the possibility of including useful information in the 3D model in order to provide a fast and effective understanding of the parameters to be compared;
3) the difficulty of carrying out the complete method in a short time to allow a high concentration of the user in all the steps. Also in this case, the AR tool in combination with the SRF makes the proposed method fast and effective in the same time as demonstrated by the comparison with the classical AHP, A-AHP and I-AHP;
4) the direct comparison between relevant and irrelevant objects is avoided;

5) the rank reversal problems typical of the eigenvalue method is avoided;
6) the comparison scale is enlarged if compared with the AHP.

In conclusion, this method opens up new possibilities for applying MCDM in a simpler, faster and more accessible way in order to being able to carry out analyzes also by non-expert users.

The method, thanks to the use of the 3D models in AR, is particularly effective in the field of construction where technical drawing, axonometry representation and three-dimensional models have been used for centuries for their ability to visually transmit a useful information to the decision maker. Indeed, engineers, architects and practitioners can use this approach in any multi-criteria decision that requires a visual support in many field (energy, structural, realization process, management). Beyond this, the approach can be used to investigate the needs and perception of non-expert DMs which can be represented by building users, customers, workers, suppliers etc. To provide some example, the aesthetic impact (important for users and customers), or the realization complexity of a product (required for the workers) can be effectively investigated by using the proposed approach.

Future research will focus on a complete analysis of the possibility of applying the method also in different application fields. In addition, in order to increase the applicability and encourage the use of the proposed approach, the AR-DM will be implemented in Decision Support Systems (DSS) and smart devices in order to obtain an even fast and customized tool applicable on a large scale.

References

[1] A. Schöttle, P. Arroyo, The impact of the decision-making method in the tendering procedure to select the project team, IGLC 2016 - 24th Annual Conference of the International Group for Lean Construction, 2016, pp. 23–32.

[2] A. Mardani, A. Jusoh, K.M.D. Nor, Z. Khalifah, N. Zakwan, A. Valipour, Multiple criteria decision-making techniques and their applications - A review of the literature from 2000 to 2014, Econ. Res. Istraz. 28 (2015) 516–571. https://doi.org/10.1080/1331677X.2015.1075139

[3] K. Govindan, M.B. Jepsen, ELECTRE: A comprehensive literature review on methodologies and applications, European Journal of Operational Research. 250 (2016) 1-29. https://doi.org/10.1016/j.ejor.2015.07.019

[4] P.S.W. Fong, S.K.Y. Choi, Final contractor selection using the analytical hierarchy process, Constr. Manage. Econ. 18 (2000) 547–557. https://doi.org/10.1080/014461900407356

[5] P. Jaskowski, S. Biruk, R. Bucon, Assessing contractor selection criteria weights with fuzzy AHP method application in group decision environment, Autom. Constr. 19(2) (2010) 120-126. https://doi.org/10.1016/j.autcon.2009.12.014

[6] E. Plebankiewicz, and D. Kubek, Multicriteria selection of the building material supplier using AHP and fuzzy AHP, J. Constr. Eng. Manage. 142 (2016) 04015057. https://doi.org/10.1061/(ASCE)CO.1943-7862.0001033

[7] C. Kahraman, U. Cbeci, and Z. Ulukan, Multi-criteria supplier selection using fuzzy AHP, Logist. Inf. Manage. 16 (2003) 382–394. https://doi.org/10.1108/09576050310503367
[8] J.K.W. Wong, H. Li, Application of the analytic hierarchy process (AHP) in multi-criteria analysis of the selection of intelligent building systems, Build. Environ. 43 (2008) 108–125. https://doi.org/10.1016/j.buildenv.2006.11.019
[9] K. Nassar, W. Thabet, Y. Beliveau, A procedure for multi-criteria selection of building assemblies, Automation in Construction. 12 (2003) 543-560. https://doi.org/10.1016/S0926-5805(03)00007-4
[10] S. Kwon, G. Lee, D. Ahn, H.S. Park, A modified-AHP method of productivity analysis for deployment of innovative construction tools on construction site, J. Constr. Eng. Project Manage. 4 (2014) 45–50. https://doi.org/10.6106/jcepm.2014.4.1.045
[11] A. Shapira, M. Goldenberg, AHP-based equipment selection model for construction projects, J. Constr. Eng. Manage. 131 (2005) 1263-1273. https://doi.org/10.1061/(ASCE)0733-9364(2005)131:12(1263)
[12] N. Bobylev, Comparative analysis of environmental impacts of selected underground construction technologies using the analytic network process, Autom. Constr. 20 (2011) 1030-1040. https://doi.org/10.1016/j.autcon.2011.04.004
[13] S. Guzmán-Sánchez, D. Jato-Espino, I. Lombillo, J.M. Diaz-Sarachaga, Assessment of the contributions of different flat roof types to achieving sustainable development, Building and Environment. 141 (2018) 182-192. https://doi.org/10.1016/j.buildenv.2018.05.063
[14] S. Das, M.Y. Chew, K.L. Poh, Multi-criteria decision analysis in building maintainability using analytical hierarchy process, Constr. Manage. Econ. 28(10) (2010) 1043–1056. https://doi.org/10.1080/01446193.2010.501806
[15] E.A.L. Teo, F.Y.Y. Ling, Developing a model to measure the effectiveness of safety management systems of construction sites, Build. Environ. 41 (2006) 1584–1592. https://doi.org/10.1016/j.buildenv.2005.06.005
[16] M. Dağdeviren, I. Yüksel, Developing a fuzzy analytic hierarchy process (AHP) model for behavior-based safety management, Inf. Sci. 178 (2008) 1717–1733. https://doi.org/10.1016/j.ins.2007.10.016
[17] F. Li, K.K. Phoon, X. Du, M. Zhang, Improved AHP method and its application in risk identification, J. Constr. Eng. Manage. 139 (2013) 312-320. https://doi.org/10.1061/(ASCE)CO.1943-7862.0000605
[18] H.H. Ali, S.F. Al Nsairat, Developing a green building assessment tool for developing countries - Case of Jordan, Build. Environ. 44 (2009) 1053-1064. https://doi.org/10.1016/j.buildenv.2008.07.015

[19] E. Gigliarelli, L. Cessari, A. Cerqua, Application of the Analytic Hierarchy Process (Ahp) for Energetic Rehabilitation of Historical Buildings, Proceedings of the International Symposium on the Analytic Hierarchy Process, 2011.
[20] E. Wang, Z. Shen, J. Neal, J. Shi, C. Berryman, A. Schwer, An AHP-weighted aggregated data quality indicator (AWADQI) approach for estimating embodied energy of building materials, Int. J. Life Cycle Assess. 17 (2012) 764–773. https://doi.org/10.1007/s11367-012-0417-8
[21] V. Sangiorgio, G. Uva, F. Fatiguso, Optimized AHP to overcome limits in weight calculation: Building performance application, Journal of Construction Engineering and Management. 144 (2017) 04017101. https://doi.org/10.1061/(ASCE)CO.1943-7862.0001418
[22] S. Wu, A. Lee, J.H.M. Tah, G. Aouad, The use of a multi-attribute tool for evaluating accessibility in buildings: The AHP approach, Facilities. 25 (2007) 375–389. https://doi.org/10.1108/02632770710772478
[23] V. Sangiorgio, S. Martiradonna, G. Uva, F. Fatiguso, An information system for masonry building monitoring, Proceedings of 2017 IEEE Int. Conf. Serv. Oper. Logist. Informatics, IEEE, 2017, pp. 230–235. https://doi.org/10.1109/SOLI.2017.8120999
[24] V. Sangiorgio, G. Uva, F. Fatiguso, User reporting–based semeiotic assessment of existing building stock at the regional scale, Journal of Performance of Constructed Facilities. 32 (2018) 04018079. https://doi.org/10.1061/(ASCE)CF.1943-5509.0001227
[25] V. Sangiorgio, G. Uva, F. Fatiguso, J. M. Adam, A new index to evaluate exposure and potential damage to RC building structures in coastal areas, Engineering Failure Analysis. 100 (2019) 439-455. https://doi.org/10.1016/j.engfailanal.2019.02.052
[26] G. Uva, V. Sangiorgio, S. Ruggieri, F. Fatiguso, Structural vulnerability assessment of masonry churches supported by user-reported data and modern Internet of Things (IoT), Measurement. 131 (2019) 183-192. https://doi.org/10.1016/j.measurement.2018.08.014
[27] V. Sangiorgio, G. Uva, J. M. Adam, Integrated Seismic Vulnerability Assessment of Historical Masonry Churches Including Architectural and Artistic Assets Based on Macro-element Approach, International Journal of Architectural Heritage. (2020) 1-14. https://doi.org/10.1080/15583058.2019.1709916
[28] M. Panahi, F. Rezaie, S. A. Meshkani, Seismic vulnerability assessment of school buildings in Tehran city based on AHP and GIS, Nat. Hazards Earth Syst. Sci. 14 (2014) 969–979. https://doi.org/10.5194/nhess-14-969-2014
[29] R. Aghataher, M.R. Delavar, M.H. Nami, N. Samnay, A fuzzy-AHP decision support system for evaluation of cities vulnerability against earthquakes, World Appl. Sci. J. 3 (2008) 66–72.
[30] V. Sangiorgio, G. Uva, M.A. Aiello, A multi-criteria-based procedure for the robust definition of algorithms aimed at fast seismic risk assessment of existing RC buildings, Structures. 24 (2020) 766–782. https://doi.org/10.1016/j.istruc.2020.01.048.

[31] H.P. Tserng, S.Y.L. Yin, R.J. Dzeng, B. Wou, M.D. Tsai, W.Y. Chen, A study of ontology-based risk management framework of construction projects through project life cycle, Autom. Constr. 18 (2009) 994–1008. https://doi.org/10.1016/j.autcon.2009.05.005
[32] Formisano, F.M. Mazzolani, On the selection by MCDM methods of the optimal system for seismic retrofitting and vertical addition of existing buildings, Comput. Struct. 159 (2015) 1–13. https://doi.org/10.1016/j.compstruc.2015.06.016.
[33] A. Ishizaka, Clusters and pivots for evaluating a large number of alternatives in AHP. Pesquisa Operacional, 32 (2012) 87-102. https://doi.org/10.1590/S0101-74382012005000002
[34] F. Abastante, S. Corrente, S. Greco, A. Ishizaka, I.M. Lami, A new parsimonious AHP methodology: assigning priorities to many objects by comparing pairwise few reference objects. Expert Systems with Applications. 127 (2019) 109-120. https://doi.org/10.1016/j.eswa.2019.02.036
[35] E. Pantano, A. Rese, D. Baier, Enhancing the online decision-making process by using augmented reality: A two country comparison of youth markets, Journal of Retailing and Consumer Services. 38 (2017) 81-95. https://doi.org/10.1016/j.jretconser.2017.05.011
[36] H.L. Chi, S.C. Kang, X. Wang, Research trends and opportunities of augmented reality applications in architecture, engineering, and construction, Autom. Constr. 33 (2013) 116–122. https://doi.org/10.1016/j.autcon.2012.12.017
[37] X. Wang, M.J. Kim, P.E.D. Love, S.C. Kang, Augmented reality in built environment: Classification and implications for future research, Autom. Constr. 32 (2013) 1–13. https://doi.org/10.1016/j.autcon.2012.11.021
[38] Y. Shen, S.K. Ong, A.Y.C. Nee, Augmented reality for collaborative product design and development, Des. Stud. 31 (2010) 118–145. https://doi.org/10.1016/j.destud.2009.11.001
[39] D. Yu, J.S. Jin, S. Luo, W. Lai, Q. Huang, A Useful Visualization Technique: A Literature Review for Augmented Reality and its Application, limitation & future direction, in: Vis. Inf. Commun., Springer US, 2009, pp. 311–337. https://doi.org/10.1007/978-1-4419-0312-9_21
[40] Z. Feng, V.A. González, R. Amor, M. Spearpoint, J. Thomas, R. Sacks, et al., An Immersive Virtual Reality Serious Game to Enhance Earthquake Behavioral Responses and Post-earthquake Evacuation Preparedness in Buildings. arXiv:1905.11082 [Preprint]. 2019 [posted 2019 May 27; cited 2020 May 7]: [32 p.]. Available from: http://arxiv.org/abs/1905.11082
[41] J. Figueira, B. Roy, Determining the weights of criteria in the ELECTRE type methods with a revised Simos' procedure, Eur. J. Oper. Res. 139 (2002) 317–326. https://doi.org/10.1016/S0377-2217(01)00370-8
[42] S. Martiradonna, F. Fatiguso, I. Lombillo, Precast concrete module for structural and energy rehabilitation of reinforced concrete buildings, Proceedings of REHABEND 2020: Euro-American Congress: Construction pathology, rehabilitation technology and heritage management, 2020, pp. 1618-1626.

[43] T.L. Saaty, Decision making with the analytic hierarchy process, Int. J. Serv. Sci. 1 (2008) 83. https://doi.org/10.1504/IJSSCI.2008.017590

[44] V. Sangiorgio, J.C. Pantoja, H. Varum, G. Uva, F. Fatiguso, Structural Degradation Assessment of RC Buildings: Calibration and Comparison of Semeiotic-Based Methodology for Decision Support System, J. Perform. Constr. Facil. 33 (2019) 04018109. https://doi.org/10.1061/(ASCE)CF.1943-5509.0001249

[45] P. T. Harker, L.G. Vargas, The theory of ratio scale estimation: Saaty's analytic hierarchy process, Management science. 33 (1987) 1383-1403. https://doi.org/10.1287/mnsc.33.11.1383

[46] S. Martiradonna, I. Lombillo, F. Fatiguso, Performance monitoring of refurbished buildings through innovative precast concrete modules, Proceedings of IEEE Int. Conf. Syst. Man Cybern., 2019, pp. 953–957. https://doi.org/10.1109/SMC.2019.8914472

[47] S. Martiradonna, F. Fatiguso, I. Lombillo, Thermal improvements of existing reinforced concrete buildings by an Innovative Precast Concrete Panel system, in: Colloqui.AT.e 2020, New Horizons for Sustainable Architecture, Italy. Forthcoming 2020.

[48] G. Masera, F. Pittau, L. Malighetti, G. Iannaccone, Prefabrication as Large-scale Efficient Strategy for the Energy Retrofit of the Housing Stock: An Italian Case Study, Procedia Eng. 180 (2017) 1160–1169. https://doi.org/10.1016/j.proeng.2017.04.276

[49] Regolamento di esecuzione e di attuazione del nuovo codice della strada, D.P.R. No. 495 (December 28, 1992).

[50] Building components and building elements – Thermal resistance and thermal transmittance – Calculation methods, UNI EN ISO 6946:2018 (March 1, 2018).

[51] Adeguamento linee guida nazionali per la certificazione energetica degli edifici, D.M. No. 192 (June 26, 2015).

[52] Thermal performance of building components – Dynamic thermal characteristics – Calculation methods, UNI EN ISO 13786:2018 (March 1, 2018).