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MCDM for Maintenance of Plaster Coverings

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Abstract: Multi-criteria analysis can represent the point of connection for a total engineering of the building sector, which, in particular in relation to the phase of management of the built environment, still suffers from little acknowledgement on the implementation of different maintenance strategies. This is due, at the same degree, to the lack of solid knowledge on the modalities of performance decay, and to the lack of execution of in-depth analysis before the decision of a maintenance strategy.

In this paper, considering a component, plaster covering, for which the performance decay has been analyzed during a study on 100 buildings, some possibilities of application of multi-criteria decision methods (TOPSIS, WSM, WPM, VIKOR), together with their validation thanks to the partial similarities of the results, are presented.

Four different maintenance strategies are analyzed, and four different management scenarios are simulated as a function of the priority attributed to the criteria of evaluation.

Key words: maintenance, multi-criteria, TOPSIS, VIKOR

1. Introduction

More than 20 years after the birth of the maintenance plan, through the Italian framework legislation on Public Work, the new code in 2016 strongly highlights the necessity to refer to the life cycle, both in relation the programming of interventions (a technological aspect) and — incredible novelty — in relation to Life Cycle Cost (an economic aspect).

In particular, art. 96 discusses this important theme, and also details the evaluations that the contracting authorities have to execute, in order to assess the Life Cycle Cost according to what is indicated in the tenders' bids.

"The life cycle costs include all of the following costs, or parts of them, when relevant, related to the life cycle of a product, service or work:

a) costs sustained by the administration of the contracting authority or by other stakeholder, in detail:

1) costs related to the acquisition;

2) costs related to the usage, among which consumption of energy and other resources;

3) costs of maintenance;

4) costs related to life end, among which the costs of waste collection, disposal and recycling;

b) costs due to environmental externalities related to products, services and works during the life cycle, as long as their economic value can be determined and verified. These costs can include the emissions of greenhouse gas and other polluting substances, together with other costs related to the reduction of climatic changes".

As it can be noticed from the reported passage, indeed what is being highlighted is what the supporters of programmed maintenance have been advising for a long time, that is to say that the costs of a building, despite being traditionally identified with the costs of construction, are actually much higher during the phase of management, and that any economic evaluation has to be performed by considering the so-called *global cost*.

Moreover, it has to be adequately highlighted that the *global cost* has undergone significant evolutions, as

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the costs that are relatable to the concept of sustainability — to which the above-mentioned art. 96 clearly refers to, not only concerning the life end, waste collection, disposal and recycling of the building and its components but also when mentioning *environmental externalities* and *consumption of resources* — are now considered as a definitely not negligible share of it.

Certainly, the definition of life cycle that is reported in art. 3 is not less extensive, as it makes the concept much wider than the usual one, merely related to durability, defining it as: "*all the consequential and interconnected phases, including research and development that have to be performed, production, trades and their related conditions, transportation, use, maintenance, of the life of the product, the work or the service, from the acquisition of raw materials or the generations of resources to the disposal, the dismantlement and the end of the service or of the use*".

By enhancing the extent of this definition, it can be stated that the strategic evaluations on the management of the life cycle of a building component must not be performed by simply relating the cost of maintenance (intended as the cost needed to restore a performance to a degree that is close to the initial one) to the so-called Mean Time Between Failures, but rather hypothesizing, also in terms of sustainability, which will be the most appropriate choices. This does not mean, though many suggest so, just to employ natural materials instead of those which are less or not, but rather to take into account the number of interventions that will be performed during the life cycle of the component, the consumption of unrenewable energy, the regional factors, and any other issue related to the building-environment relationship.

The article suggests the employment of various multi-criteria analysis in order to lead designers, technicians in general and estate managers toward more sensible and conscious choices in terms of economic convenience, by evaluating the most appropriate ones with the support — indeed — of methodologies that allow to take into consideration various aspects at the same time.

It seemed particularly interesting to show an application on plaster coverings, as for them the modalities of decay management can lead to significantly different results from the point of view of cost.

2. Decay of Plaster Coverings

The performance decay of plaster coverings represents a classic example of a complexity of evaluation of the intermediate states, as this component is typically characterized by a functioning with no on-off pattern.

And even if the thermographic camera analysis can represent, at least, a help in the execution of non-subjective surveys, the detection of the state of failure is characterized by the same complexity. Plaster coverings, despite not being structural elements, can determine, at a certain point of their performance decay, a state of danger, and so it is important to determine a state of conservation (corresponding to a performance degree) to which the end of the life cycle can be associated.

Many researchers — even if in a small percentage, in the total number of studies on the durability of building components — have tried to assess the service life of plaster coverings with various methodological approaches.

Some of them have focused their attention on specific mortars (lime mortars [1, 2]) as they are typical of ancient constructions, with studies on their durability, mainly deriving from laboratory tests, while others have dedicated to other components, such as the type of sand [3].

Those who went beyond the laboratory tests, decided to follow the approach suggested by ISO 15686-7 code, through a significant operation of building sampling within a specific geographic context, evaluating the state of decay through visual inspections; establishing a numerical index of decay severity of stone claddings, in order to estimate a reference service life for this type of cladding [4].

Or, still starting from sampling and prolonged field observation, through:

- in-depth observation of the initial conditions at the beginning of the experimentation, in some cases by visual inspection, and in others with the support of a thermographic camera;
- documentation of the maintenance activities executed during the early years;
- observation of the evolution of the conditions of conservation in the following period, with inspections mainly carried out via thermographic camera.

The aim was that of evaluating the value of service life for plaster coverings, which was totally fulfilled, and the Nick Method for the evaluation of service life of plaster coverings, included in UNI 11156-3:2006, code is its result, published and presented also in other works [5-8].

This research continued, finalized to assess the life cycle of plaster covering by creating performance-time curves with an extension of 30 years for 53 of the initial 100 samples buildings, ultimately leading to the obtainment of the performance-time curve for the plaster covering as the envelopment of the single curves [9].

Alternatively, also applying the Factor Method for the prediction of service life through ex-post data, and also as an innovation by performing a multiple linear regression analysis in order to identify the most relevant sub-factors that explain the decay of stone cladding [10].

Eventually, some authors have tried exploring the possibility to use multi-criteria analysis for the specific problem of having a supporting tool for the decisions on maintenance of external envelopes [11, 12], or also making use of a probabilistic approach, proposing a methodology to model an predict the life-cycle performance of building façades based on Stochastic Petri Nets [13].

Actually, the evaluation of the service life of plaster coverings can be considered a topic of great interest especially as it is possible to associate to the knowledge of the law of performance decay, a criterion to individuate:

- the most appropriate interventions, depending on the time at which they are performed;
- the right times to perform them.

So, unavoidably the issue shifts to the possibility to draw a performance/time curve for the specific component as close to reality as possible, as it allows to enact strategies of predictive maintenance, which — when possible — constitute a definitely satisfying scenario, however substitutable, when necessary, by condition-based maintenance (Fig. 1).

An interesting model of prediction would indeed be one that joins the possibility to express hypothesis on the behavior of the component over time (that is to say, to evaluate the states of performance at different time steps) through a planning of controls that, given the preliminary individuation of a performance/time curve, allows to evaluate residual service life.

3. Material and Methods

During a field test, carried out in reference to ISO 15686-7 code, initially from 1988 to 2000, then until 2016, it was possible to obtain a number of trend curves

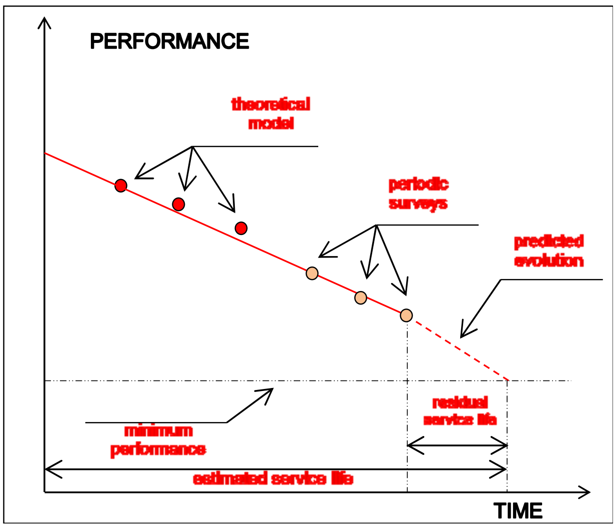

Fig. 1 Predictive maintenance as a combination of cyclic maintenance and condition-based maintenance.

of performance decay, for which the mean value can be considered reliable only for groups of sampled buildings with homogenous characteristics. In this sense, after choosing the significant sample (100 buildings in the city of Naples), it was possible to build an envelope curve with all the curves of the single buildings.

The experimentation was referred to a specifically determined typology of plaster covering, with the stratigraphy shown in Table 1.

For the evaluation of performances, after a preliminary individuation of the typology of interventions for the specific component (in the examined case, plaster + paint), the corresponding decay levels (in other words, the specific in-use conditions) have been identified, in reference to those suggested by ISO 15686-7 code to which, in turn, performance degrees are related.

The table of correspondences is reported in Table 2.

In order to compare different possibilities of management, to which different maintenance strategies correspond, the following ones have been considered:

- I — Consumption of the performance during its life cycle, with absence of maintenance interventions;
- II — Partial reconstructions and finishing works on the whole surface;
- III — Defense of plaster from atmospheric agents, by renovating the finishing layers with partial reconstructions;
- IV — Frequent removal of anomalies, with superficial interventions until the necessity of a partial reconstruction.

Table 1 Composition of the examined solution of plaster coverings.

Function	Material
Support	Tuff Masonry or Brick Cladding
Covering	Lime Plaster
Primer	Fine Common Mortar
Fixture	Siloxane Paint

Table 2 Table of correspondences between maintenance interventions, decay levels and performance degrees.

Maintenance intervention	Decay level (in-use condition for plaster coverings)	Performance degree (according to ISO 15686-7)
None	No performance decay	0. No symptoms
Partial grouting + painting (I_1)	Incipient exfoliations and air bubbles — evident chromatic alterations	1. Slight symptoms
Smoothing + painting (I_2)	Accentuated exfoliations and air bubbles — microcracks or incipient detachment extended to less than 30% of the surface	2. Medium
Partial makeover of the plaster + smoothing + painting (I_3)	Accentuated exfoliations and air bubbles — microcracks or incipient detachment extended to more than 30% of the surface	3. Strong symptoms
Total makeover of the plaster + smoothing + painting (I_4)	Partial/total collapse	4. Totally unacceptable, including collapse and malfunction

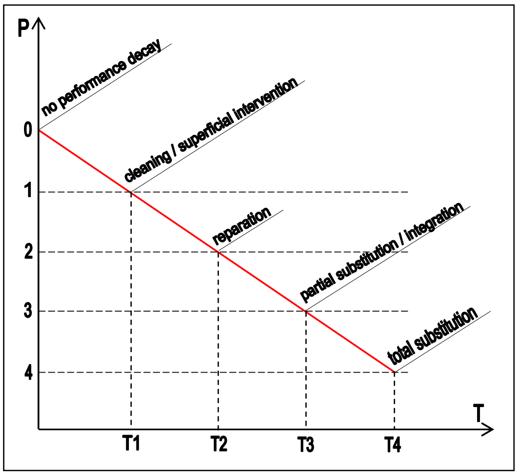

Fig. 2 Curve of performance decay, where interventions are associated with decay levels in correspondence of time thresholds.

From the point of view of planning, considering a period of 30 years (corresponding to the duration of the experimentation described above), the chronology in Table 3 was considered, derived from the on-site experience.

Compared to some approaches, which can still be considered interesting but are mainly qualitative, it was chosen, through several methodologies of multi-criteria analysis, to reach the quantification of the benefit/cost ratio of each strategy, in order to provide a decisional support which can lead toward the most opportune one, considering various criteria, which would otherwise be difficult to take into account.

Table 3 Detail of execution of maintenance interventions for the four strategies.

	5	10	15	20	25	30
Strategy I						
Strategy II			I_3			I_3
Strategy III				I_2		I_3
Strategy IV		I_1		I_1		I_3

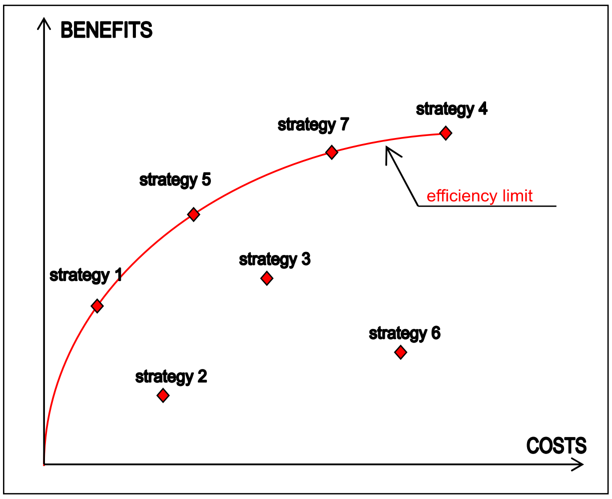

Fig. 4 Cost-benefit curve, in which the efficiency limit highlights the strategies to compare, in order to evaluate the optimal one.

4. State of the Art and Methodology of the Research

4.1 State of the Art

Multi-criteria decision analysis methods are a common tool to evaluate the optimal decision in various contexts, by giving to each alternative scores based on the criteria chosen, and then comparing them. Several methods have been developed in this field, and some of these have already been used in the field of the evaluation of optimal maintenance strategies.

The father of the idea behind this application was Triantaphyllou [14], who suggested the criteria to adopt to implement this evaluation, individuating them in cost, repairability, reliability and availability. He also showed an application of the use of AHP (Analytical Hierarchy Process) for this choice. Then, a lot of authors explored the use on this theme of combinations between different methods: among the others, Bevilacqua [15] implemented the AHP by integrating goal programming to determine the optimal maintenance policy in an oil refinery; Ilangkumaran [16] proposed a combination of fuzzy AHP with TOPSIS, in order to select the optimal maintenance policy for textile industry. Ghosh [17] introduced an integration of AHP, goal programming with fuzzy logic; Chen [18] tried using AHP, TOPSIS and grey relational analysis to evaluate the performance and decided the optimal maintenance policies that suited semiconductor company in a more effective and accurate manner.

Also, Vahdani [19] used VIKOR for the selection of a maintenance strategy, and later Ahmadi [20] used a combination of VIKOR, AHP and TOPSIS for the same purpose.

In this article, the methodologies of TOPSIS, WSM, WPM and VIKOR are carried out to evaluate the optimal maintenance strategy. Out of the four of them, two are relatively simpler (WPM and WSM), while TOPSIS is more articulate and, finally, VIKOR is much more complex.

There is, of course, a reason behind the inclusion of two simpler methods in the methodology. First, the convergence of the first three will be verified. Then, considering also that the fourth one, the VIKOR, actually depends on an aleatory parameter (individual regret), a deeper analysis will be provided on it, especially on:

- the best way to set such parameter, in order to obtain the result that has been proven to be correct by the other three;
- the possibility to use VIKOR method for the evaluation of the optimal maintenance strategy.

4.2 TOPSIS

The Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) is a multi-criteria decision analysis method, which was originally developed by Hwang and Yoon in 1981 with further developments by Yoon in 1987, and Hwang, Lai and Liu in 1993. TOPSIS is based on the concept that the chosen alternative should have the shortest geometric distance from the positive ideal solution and the longest geometric distance from the negative ideal solution. It is a method of compensatory aggregation that compares a set of alternatives by identifying weights for each criterion, normalising scores for each criterion and calculating the geometric distance between each alternative and the ideal alternative, which is the best score in each criterion. All the criteria have then to be monotonically increasing or decreasing.

In its application, the first step is to define the alternatives (A_i, $i = 1, 2, \ldots, m$) and the criteria (C_j, $j = 1, 2, \ldots, n$) according to which the alternatives will be evaluated. Then a weight (W_j, $j = 1, 2, \ldots, n$) has to be attributed to each of the criteria. In an original formal addition suggested here, the weight is positive if the criterion is beneficial, and negative if the criterion is not beneficial.

Once the scores for each alternative according to each of the criteria have been given, usually in the form of 1-10 scores assigned by a number of decision makers, the related D matrix, with n lines and m columns, can be created.

$$D = \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1n} \\ x_{21} & \ddots & \cdots & x_{2n} \\ \vdots & \cdots & \ddots & \vdots \\ x_{m1} & \cdots & \cdots & x_{mn} \end{bmatrix}$$

In the D matrix, called the fuzzy decision matrix, x_{ij} represents the score assigned to the i-th alternative according to the j-th criterion.

Then, the x_{ij} values in the matrix have to be normalized to r_{ij} values, by applying the equation:

$$r_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{m} x_{ij}^2}}, i = 1, 2, \ldots, m$$

The result is the normalized fuzzy decision matrix.

$$R = \begin{bmatrix} r_{11} & r_{12} & \cdots & r_{1n} \\ r_{21} & \ddots & \cdots & r_{2n} \\ \vdots & \cdots & \ddots & \vdots \\ r_{m1} & \cdots & \cdots & r_{mn} \end{bmatrix}$$

Then, the W_j weights that were established at the beginning for the criteria have to be applied to the matrix, by multiplying each of the r_{ij} values to the related w_j weight, obtained for each criterion through the equation:

$$w_j = \frac{W_j}{\sum_{j=1}^{n} |W_j|}$$

So, the t_{ij} values of the weighted normalized fuzzy decision matrix will be obtained as:

$$t_{ij} = r_{ij} \cdot |w_j|, i = 1, 2, \ldots, m; j = 1, 2, \ldots, n$$

The T matrix, made up by the t_{ij} values, can finally be realized.

$$T = \begin{bmatrix} t_{11} & t_{12} & \cdots & t_{1n} \\ t_{21} & \ddots & \cdots & t_{2n} \\ \vdots & \cdots & \ddots & \vdots \\ t_{m1} & \cdots & \cdots & t_{mn} \end{bmatrix}$$

At this point, in order to perform the evaluation, the worst alternative (A_w) and the best alternative (A_b) have to be determined as shown here:

$A_w = \{t_{wj} = \langle min(t_{ij} | i = 1, 2, \ldots, m | j: w_j >$ *0,maxtiji=1, 2, ..., mj:wj<0}*

$A_b = \{t_{bj} = \langle max(t_{ij} | i = 1, 2, \ldots, m | j: w_j >$ *0,mintiji=1, 2, ..., mj:wj<0}*

Then, for each of the alternatives, the distances from A_w and A_b can be calculated, in the form of d_{iw} and d_{ib}, respectively. Of course, the former is a positive parameter, while the latter is a negative one.

$$d_{iw} = \sqrt{\sum_{j=1}^{n} (t_{ij} - t_{wj})^2}, i = 1, 2, \ldots, m$$

$$d_{ib} = \sqrt{\sum_{j=1}^{n} (t_{ij} - t_{bj})^2}, i = 1, 2, \ldots, m$$

The discriminative parameter of the TOPSIS can finally be evaluated, in the form of the similarity to the best condition, s_{ib}. The decision with the highest value will be the best one among the m alternatives, or more in general the alternatives can be ranked according to this parameter in crescent order.

$$s_{ib} = \frac{d_{iw}}{d_{iw} + d_{ib}}$$

4.3 WSM

In decision theory, the Weighted Sum Model (WSM) is presumably the best known and simplest MCDM method to evaluate A_i (i = 1, 2, …, m) alternatives according to a C_j (j = 1, 2, …, n) criteria. The execution of this methodology consists in the sums of the products between the scores a_{ij} and the weight w_j of each criterion, for each of the alternatives. The weight is positive if the corresponding criterion is beneficial, or negative if it is not beneficial. This summation is named, for each A_i alternative, *weighted sum* or *weighted sum model score* ($A_i^{WSM\text{-}score}$). Its formula is then, of course:

$$A_i^{WSM-score} = \sum_{j=1}^{n} w_j a_{ij}$$

The best alternative is the one with the highest *weighted sum*. It can be noticed that, since non-beneficial criteria have a negative weight, their quota decreases the total of the *weighted sum*. Also, it has to be mentioned that, if the scores are not expressed in the same unit or in the same scale, a normalization is required for each of the criteria, before proceeding to the calculation of the *weighted sum*.

4.4 WPM

The Weighted Product Model (WPM) is similar to the WSM, but instead of summation it makes use of multiplication. Another major difference is that, instead of carrying out a single total evaluation for each alternative, it is executed by comparing all the possible sets of alternatives among the n: the best alternatives is the one that results to be better in all of the single comparisons.

Considering A_i (i = 1, 2, …, m) alternatives and c_j (j = 1, 2, …, n) criteria, the score for the i-th alternative according to the j-th criteria is a_{ij} and the formula to carry out the comparison between the k-th and the l-th alternative is:

$$P(A_K/A_L) = \prod_{j=1}^{m} (a_{Kj}/a_{Lj})^{w_j}$$

If the ratio $P(A_K/A_L)$ is greater than or equal to the value 1, then it indicates that alternative A_K is more desirable than alternative A_L. As long as there are no identical alternatives, only one k-th alternative is characterized by having a value that is higher than 1 in all of the comparisons. Of course, that alternative is the best one. In this method, no normalization is required before executing the pairwise comparisons, as the single ratios are between scores of the same criteria.

4.5 VIKOR

The VIKOR (*VIseKriterijumska Optimizacija I Kompromisno Resenje*, Serbian for Multicriteria Optimization and Compromise Solution) method was developed as a multi-criteria decision making method to solve a discrete decision problem with non-commensurable and conflicting criteria. This method focuses on ranking and selecting from a set of alternatives, and determines compromise solutions for a problem with conflicting criteria, which can help the decision makers to reach a final decision. Here, the compromise solution is a feasible solution which is the closest to the ideal, and a compromise means an agreement established by mutual concessions.

Assuming that each alternative is evaluated according to each criterion function, the compromise ranking could be performed by comparing the measure of closeness to the ideal alternative. For the alternative A_i (i = 1, 2, …, m), the rating of the aspect for the criterion c_j (j = 1, 2, …, n) is denoted by f_{ij}. For each criterion, the best and the worst score (highest and lowest if the criterion is beneficial, and vice versa if the criterion is not beneficial) are denoted with f^*_j and $f^\wedge_j$, respectively. Then, for each of the alternatives two characteristic values are calculated:

$$S_i = \sum_{j=1}^{n} w_j \frac{f_j^* - f_{ij}}{f_j^* - f_j^\wedge}$$

$$R_i = max_j \left(w_j \frac{f_j^* - f_{ij}}{f_j^* - f_j^\wedge} \right)$$

The alternative can be ranked according to both of the criteria, considering that the best result is the one with the lowest value.

A little explanation on these values is needed. In fact, S_i is higher for the alternatives which have good scores according to a higher number of criteria, while R_i is higher for alternatives which particularly excel according to at least one of the criteria. This means that, if there are differences in the ranking of the alternatives according to these two parameters, it means that:

- alternatives with a higher ranking according to S_i rather than R_i are more balanced alternatives, with good scores according to more criteria;
- alternatives with a higher ranking according to R_i than according to S_i are characterized by a very good score in a minor number of criteria, but worse scores in the others.

This point becomes very important in the following. In fact, the next step is to compute: $S^* = min_i(S_i)$, $S^\wedge = max_i(S_i)$, $R^* = min_i(R_i)$, $R^\wedge = max_i(R_i)$.

These values are needed when calculating the final value of the method, through:

$$Q_i = v\frac{S_i - S^*}{S^\wedge - S^*} + (1 - v)\frac{R_i - R^*}{R^\wedge - R^*}$$

In the formula, the only parameter that has not been described yet is v, which is named *individual regret* or *weight of the strategy of the majority of criteria*. Analytically, as v gets higher, the weight of S_i increases, while the weight of R_i decreases. In fact, considering what has been detailed before, if $v > 0.5$ the analysis is called *voting by majority*; an analysis where $v \approx 0.5$ is *by consensus* and finally, if $v < 0.5$, it is *with veto*. From the point of view of the decision maker, if the VIKOR is *with veto*, it means that a single criterion — presumably the one with the highest weight — is considered to be much more important than the others. If all of the criteria are somewhat important, then a *voting by majority* analysis should be performed.

Q_i ranks the alternatives according to the lowest value. Yet, the best alternative according to Q_i has to satisfy two conditions:

- C_1 or *acceptable advantage*, that is to say the difference between the second-to lowest value and the lowest value has to be higher than DQ, where $DQ = (m - 1)^{-1}$;
- C_2 or *acceptable stability*, according to which the best alternative must also have the lowest S_i and/or R_i value.

If one of the conditions is not satisfied, then rather than in a single solution, the result of the method consists in a set of compromise solutions. Assuming that $A^{(K)}$ is the alternative which is ranked k-th according to the Qi parameter:

- if C_1 is not satisfied, the alternatives $A^{(1)}$, $A^{(2)}$, …, $A^{(M)}$ stand as compromise solutions, where M is maximum value satisfying $Q(A^{(M)}) - Q(A^{(1)}) < DQ$
- if C_2 is not satisfied, the compromise solutions are $A^{(1)}$ and $A^{(2)}$.

5. Evaluation of Criteria

Through the methodologies listed above, the optimal maintenance strategy for plaster coverings will be unveiled. The maintenance strategies that will be submitted to the evaluations are those listed in the third paragraph as I, II, III and IV, from now on indicated respectively as A_1, A_2, A_3 and A_4, while the chosen criteria are the following:

- Cost (C_1);
- Safety (C_2);
- Availability (C_3);
- Sustainability (C_4).

In this section the evaluation of scores, for each of the criteria and for each of the alternatives, is presented.

5.1 Cost

Cost is probably the element that influences the most the choice of maintenance strategies, because of the hardly revisable budget in the availability of the commitment. The cost of each maintenance strategy of course depends on the cost of the single interventions. So, the total cost of a maintenance strategy is here calculated by multiplying the unitary cost of each intervention, found in the Price List of Campania Region of 2016, for a surface of 2000 m^2, which is a mean value for buildings like those sampled from 1988 to 2016. The costs are then capitalized to the 30th year according to the time schedule of the interventions.

Then, it has to be considered that different maintenance strategies result in different residual service life of the component. Values of residual service life at the end of the period of the maintenance strategy that are lower than the mean value of the service life of the component produce an economic loss, as some methods from the fields of estimation, such as the *depreciation cost approach*, point out. This economic loss can be evaluated as future expense related the cost of total reconstruction (I_4 from Table 2), which is needed to restore the original service life of the component after P_{min} is reached, discounted for a number of years equal to residual service life.

This value is finally summed to the capitalization of the costs of the single interventions of the strategy. Of course the assessment of residual service life, which depends not only on the number of years passed of the component, but also on the interventions that have been executed on it, is preliminary to the obtainment of this value.

Table 4 Detail of the calculation of cost for each maintenance strategy.

	Cost of single interventions	Capitalized cost	Estimated final residual life	Future expense	Total cost
A_1	0 €	0 €	0 years	141.880 €	141.880 €
A_2	113.880 € 113.880 €	258.370 €	15 years	105.420 €	363.800 €
A_3	85.920 € 113.880 €	211.650 €	12 years	114.540 €	326.180 €
A_4	77.120 € 77.120 € 113.880 €	314.000 €	16 years	98.610 €	412.610 €

5.2 Safety

Plaster coverings, being located on the external wall of the building, may represent one of the most dangerous elements of a building both for those who live in it, and for those who do not. This has been shown in events like the one occurred three years ago, when a 14-year-old boy lost his life, in the city of Naples, because of the fall of a big piece of plaster from the facade of a historical building, as important as poorly maintained. Though this kind of events is presumably avoided by executing interventions in the first 30th years of life, there is still a chance of failure, due to the probabilistic concept of service life.

Then of course safety, intended here as a value that is inversely proportional to the probability of failure over the period of duration of the maintenance strategies, deriving from the probabilistic nature of performance decay, is relevant as a criterion of choice. The probability of failure is evaluated by using the performance-time curves that have already been realized to assess residual service life. Considering that past experimentations have shown that, for plaster coverings, critical condition are present:

- after 15 years in the 9.4% if cases;
- after 20 years in the 47.1% of cases;
- after 22 years in the 52.8% of cases.

So, it seems correct to multiply these percentages of likeliness, to which the risk of failure is of course strictly related, for the value of the area between the curve and the horizontal line where $P = P_{min}$, calculated separately for each time interval defined by the years listed above. The final value, constituted by the sum of products between graph area and probability, is in a raw scale, but this issue is automatically solved by the normalization.

5.3 Availability

Availability is the capability of equipment functioning well during a definite period or even beyond it. Then, it is only necessary to calculate, for each strategy, the mean value of duration of the maintenance interventions (MTTR, Mean Time To Repair), and the mean time between interventions (MTBF, Mean Time Between Failures), in order to apply the well-known formula:

$$Availability = \frac{MTBF}{MTBF+MTTR}$$

The duration of interventions was obtained by multiplying the h/m^2 value reported in the Time List of Campania Region or, if not present, by extrapolating the work details from the Price List of Campania Region — 2016 Edition, for a surface of 2000 m^2, considered to be a mean value, as in the evaluation of costs.

The very high values of availability for all the strategies that appear in Table 6 surely stand as a proof of one of the main benefits of programmed maintenance, that is to say its possibility to reduce the frequency of interventions by executing in a single year as many interventions as possible.

Table 5 Evaluation of safety for each maintenance strategy.

	Graph area in 15-20 years	Graph area in 20-22 years	Graph area in 22-30 years	Safety assessment
A_1	17	5	6	7,13
A_2	53	15	29	27,4
A_3	17	20	36	30,1
A_4	33	28	60	48,0

Table 6 Evaluation of availability for each maintenance strategy.

	Periods between interventions	MTBF (years)	Duration of interventions	MTTR (years)	Availability
A_1	29.55 years	29.55	5.4 months	0.453	0.985
A_2	14.7 years 14.7 years	14.7	3.6 months 3.6 months	0.297	0.980
A_3	19.8 years 9.7 years	14.75	2.25 months 3.56 months	0.242	0.984
A_4	9.9 years 9.9 years 9.7 years	9.85	0.8 months 0.8 months 3.56 months	0.144	0.986

5.4 Sustainability

In the evaluation of sustainability, it would be redundant to take into account *economic sustainability*, as this theme already influences the cost parameter. Then, only environmental sustainability will be considered for the attribution of the scores according to this criterion.

Table 7 Evaluation of sustainability for each maintenance strategy according to the number of plaster reconstructions.

	Number of plaster reconstructions	Energy consumption	Sustainability
A_1	1	166.600 MJ	2
A_2	2	333.200 MJ	1
A_3	1,5	249.900 MJ	1,5
A_4	1,5	249.900 MJ	1,5

It is a common knowledge that buildings are one of the major causes of pollution, both in their construction, in the users' energetic needs when satisfied by non-renewable energy sources and in the activities of maintenance. Therefore, it seems significantly important to reduce the negative impact on environment of maintenance interventions.

The materials which production affects the most the environment is certainly the cement. Its environmental impact can be assessed in function of the energy that is released during its production, by considering that the ratio between the energy and the mass of cement is 4,882 MJ/kg [21] and by adopting a density value of 1.360 kg/m^3 for cement. The energy consumption caused by an intervention of total reconstruction on a surface of 2000 m^2 is then 166.600 MJ, while interventions of partial reconstruction, considered to occur on the 50% of the surface, dissipate 83.300 MJ. The value of sustainability is then evaluated as inversely proportional to the energy consumption.

6. Application of Methodologies

In the following, every methodology that has been detailed in the previous paragraph will be executed four times, considering different weights of the criteria in every application. This procedure has the purpose of simulating different external conditions and management scenarios, in which the priorities change according, for example, to the budget, or to issues related to the environment and safety.

Then, the scenarios are the following:

- *Scenario I*, balance scenario, with even weights (w_1 = -0.25; w_2 = 0.25; w_3 = 0.25; w_4 = 0.25);
- *Scenario II*, limited-budget scenario, with a higher weight of cost (w_1 = -0.4; w_2 = 0.2; w_3 = 0.2; w_4 = 0.2);
- *Scenario III*, risk prevention scenario, with a higher weight of safety (w_1 = -0.2; w_2 = 0.4; w_3 = 0.2; w_4 = 0.2);
- *Scenario IV*, environmental care scenario, with a higher weight of sustainability (w_1 = -0.2; w_2 = 0.2; w_3 = 0.2; w_4 = 0.4).

The matrix of the scores for the criteria and the normalised matrix, which are used in every methodology and for every scenario, are the following, referred to, as in the TOPSIS methodology, as *D* and *R*:

$$D = \begin{bmatrix} 141880 & 7{,}13 & 0{,}985 & 2 \\ 363800 & 27{,}4 & 0{,}980 & 1 \\ 326180 & 30{,}1 & 0{,}984 & 1{,}5 \\ 412610 & 48{,}1 & 0{,}986 & 1{,}5 \end{bmatrix}$$

$$R = \begin{bmatrix} 0{,}217 & 0{,}112 & 0{,}501 & 0{,}649 \\ 0{,}555 & 0{,}432 & 0{,}498 & 0{,}324 \\ 0{,}498 & 0{,}475 & 0{,}500 & 0{,}487 \\ 0{,}630 & 0{,}758 & 0{,}501 & 0{,}487 \end{bmatrix}$$

6.1 TOPSIS

The optimal strategy is individuated according to the highest value of s_{iw} in every scenario (in bold).

6.1.1 Scenario I

$$T = \begin{bmatrix} 0{,}054 & 0{,}028 & 0{,}125 & 0{,}162 \\ 0{,}139 & 0{,}108 & 0{,}124 & 0{,}081 \\ 0{,}124 & 0{,}119 & 0{,}125 & 0{,}122 \\ 0{,}157 & 0{,}190 & 0{,}125 & 0{,}122 \end{bmatrix}$$

PIS = (0.05; 0.19; 0.12; 0.16)
NIS = (0.16; 0.03; 0.12; 0.08)
d_{iw} = (0.13; 0.08; 0.10; 0.17)
d_{ib} = (0.16; 0.14; 0.11; 0.11)
s_{iw} = (0.45; 0.36; 0.49; **0.60**)

6.1.2 Scenario II

$$T = \begin{bmatrix} 0{,}087 & 0{,}022 & 0{,}100 & 0{,}130 \\ 0{,}222 & 0{,}086 & 0{,}100 & 0{,}065 \\ 0{,}199 & 0{,}949 & 0{,}100 & 0{,}097 \\ 0{,}251 & 0{,}152 & 0{,}100 & 0{,}097 \end{bmatrix}$$

PIS = (0.09; 0.15; 0.10; 0.13)
NIS = (0.25; 0.02; 0.10; 0.06)
d_{iw} = (0.18; 0.07; 0.09; 0.13)
d_{ib} = (0.13; 0.16; 0.13; 0.17)
s_{iw} = (**0.58**; 0.30; 0.42; 0.44)

6.1.3 Scenario III

$$T = \begin{bmatrix} 0{,}043 & 0{,}045 & 0{,}100 & 0{,}130 \\ 0{,}111 & 0{,}173 & 0{,}100 & 0{,}065 \\ 0{,}100 & 0{,}190 & 0{,}100 & 0{,}097 \\ 0{,}125 & 0{,}303 & 0{,}100 & 0{,}097 \end{bmatrix}$$

PIS = (0.04; 0.30; 0.10; 0.13)
NIS = (0.13; 0.04; 0.10; 0.06)
d_{iw} = (0.10; 0.13; 0.15; 0.26)
d_{ib} = (0.26; 0.16; 0.13; 0.10)
s_{iw} = (0.30; 0.44; 0.53; **0.75**)

6.1.4 Scenario IV

$$T = \begin{bmatrix} 0{,}043 & 0{,}022 & 0{,}100 & 0{,}261 \\ 0{,}111 & 0{,}086 & 0{,}100 & 0{,}130 \\ 0{,}100 & 0{,}095 & 0{,}100 & 0{,}195 \\ 0{,}125 & 0{,}152 & 0{,}100 & 0{,}195 \end{bmatrix}$$

PIS = (0.04; 0.15; 0.10; 0.26)

NIS = (0.13; 0.02; 0.10; 0.13)

d_{iw} = (0.15; 0.06; 0.10; 0.14)

d_{ib} = (0.13; 0.16; 0.10; 0.10)

s_{iw} = (0.54; 0.29; 0.49; **0.58**)

6.2 WSM

Here, due to the simplicity of the calculation, only the vector of $A_{Si}{}^{WSM\text{-}score}$ of the four strategies is shown for every S_i scenario. The highest value, corresponding to the optimal strategy, is always in bold.

$A_{S1}{}^{WSM\text{-}score}$ = (0.26; 0.18; 0.24; **0.28**)

$A_{S2}{}^{WSM\text{-}score}$ = (**0.17**; 0.03; 0.09; 0.10)

$A_{S3}{}^{WSM\text{-}score}$ = (0.23; 0.23; 0.29; **0.37**)

$A_{S4}{}^{WSM\text{-}score}$ = (0.32; 0.20; 0.29; **0.34**)

6.3 WPM

The vectors of product comparisons $P(A_i/A_j)$, $i, j = 1, 2, 3, 4, j \neq i$, are shown for every scenario and the optimal strategy, represented by the alternative for which all of the comparison are ≥ 1, is in bold.

6.3.1 Scenario I

$P(A_1/A_j)$ = (1.08; 0.92; 0.87), j = 2, 3, 4

$P(A_2/A_j)$ = (0.93; 0.86; 0.81), j = 1, 3, 4

$P(A_3/A_j)$ = (1.08; 1.17; 0.94), j = 1, 2, 4

$P(A_4/A_j)$ = (1.15; 1.24; 1.06), j = 1, 2, 3

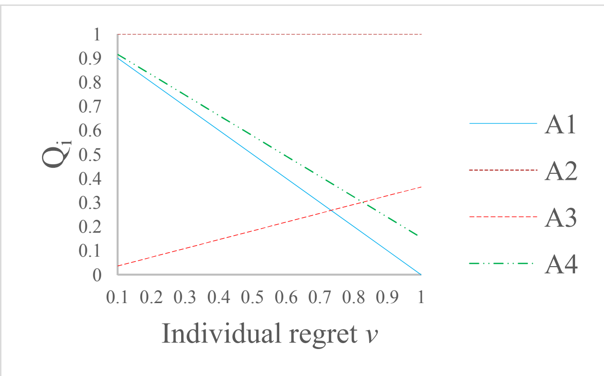

Fig. 4 Majority agreement-individual regret curves of the four strategies in Scenario I.

6.3.2 Scenario II

$P(A_1/A_j)$ = (1.28; 1.11; 1.11), j = 2, 3, 4

$P(A_2/A_j)$ = (0.78; 0.87; 0.87), j = 1, 3, 4

$P(A_3/A_j)$ = (0.90; 1.16; 1.00), j = 1, 2, 4

$P(A_4/A_j)$ = (0.90; 1.16; 1.00), j = 1, 2, 3

6.3.3 Scenario III

$P(A_1/A_j)$ = (0.81; 0.70; 0.61), j = 2, 3, 4

$P(A_2/A_j)$ = (1.23; 0.87; 0.75), j = 1, 3, 4

$P(A_3/A_j)$ = (1.42; 1.15; 0.87), j = 1, 2, 4

$P(A_4/A_j)$ = (1.64; 1.33; 1.15), j = 1, 2, 3

6.3.4 Scenario IV

$P(A_1/A_j)$ = (1.22; 0.99; 0.95), j = 2, 3, 4

$P(A_2/A_j)$ = (0.82; 0.82; 0.78), j = 1, 3, 4

$P(A_3/A_j)$ = (1.01; 1.23; 0.95), j = 1, 2, 4

$P(A_4/A_j)$ = (1.05; 1.28; 1.05), j = 1, 2, 3

6.4 VIKOR

Since in the VIKOR method there is an additional variable, represented by the v parameter, it was chosen

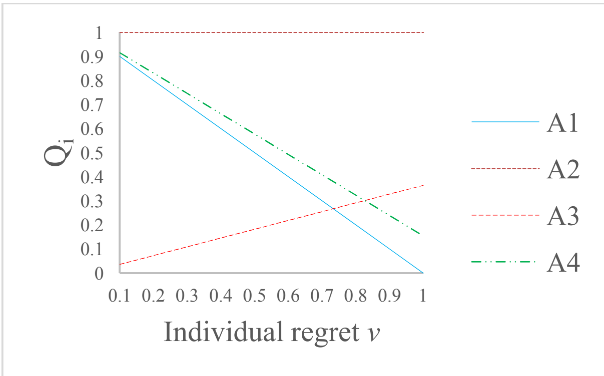

Fig. 5 Majority agreement-individual regret curves of the four strategies in Scenario II.

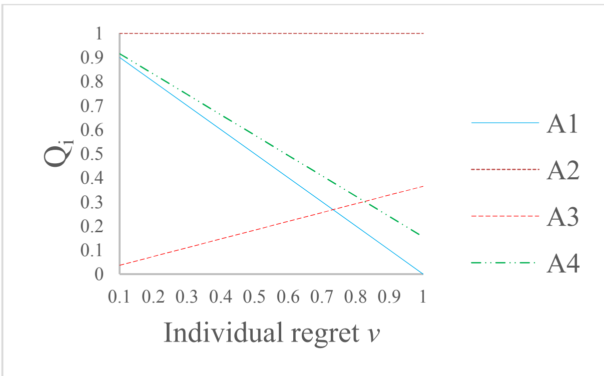

Fig. 6 Majority agreement-individual regret curves of the four strategies in Scenario III.

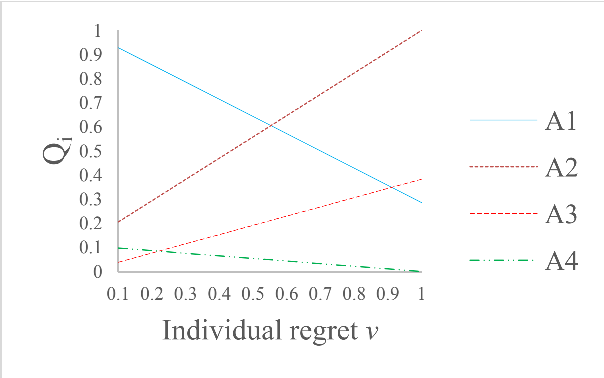

Fig. 7 Majority agreement-individual regret curves of the four strategies in Scenario IV.

to explore the possibilities of use offered by it. In fact, despite in other applications of this method in the field of the choice of maintenance strategies it was preferred to use a compromise value ($v = 0.5$) [22], it was mainly because such studies regarded maintenance in the industrial field, where the clash of interest between the stakeholders is certainly more absent than in the case of buildings, in which many more interests have to be taken into account.

That is why, the v parameter might be useful to balance disagreement within the stakeholders, and so it was chosen to evaluate, in every scenario, the optimal maintenance strategy according to different values of v, ranging from 0.1 to 1. In every scenario, a diagram shows the association of the majority agreement Q_i and v for every strategy.

The following vectors are the same in every scenario, as they do not depend on the weights; also, they are based on the D matrix, rather than on the R matrix, as the structure of VIKOR provides normalisation by itself.

$f^* = (141880; 48.1; 0.986; 2)$

$f^\wedge = (412610; 7.13; 0.98; 1)$

6.4.1 Scenario I

$S_i = (0.29; 0.83; 0.49; 0.37)$

$R_i = (0.25; 0.25; 0.17; 0.25)$

$S^* = 0.29$

$S^\wedge = 0.83$

$R^* = 0.17$

$R^\wedge = 0.25$

6.4.2 Scenario II

$S_i = (0.23; 0.83; 0.53; 0.5)$

$R_i = (0.2; 0.32; 0.27; 0.4)$

$S^* = 0.23$

$S^\wedge = 0.83$

$R^* = 0.2$

$R^\wedge = 0.4$

6.4.3 Scenario III

$S_i = (0.43; 0.77; 0.49; 0.3)$

$R_i = (0.4; 0.2; 0.18; 0.2)$

$S^* = 0.3$

$S^\wedge = 0.77$

$R^* = 0.18$

$R^\wedge = 0.4$

6.4.4 Scenario IV

$S_i = (0.23; 0.86; 0.49; 0.4)$

$R_i = (0.2; 0.4; 0.2; 0.2)$

$S^* = 0.23$

$S^\wedge = 0.86$

$R^* = 0.2$

$R^\wedge = 0.4$

6.5 Synthesis of the Multi-Criteria Analysis

The Table 7 shows a summary of the optimal maintenance strategies according to all the four methodologies adopted in the article: TOPSIS, WSM; WPM and VIKOR.

In S_1, according to VIKOR the optimal strategy is A_3 if $v < 0.7$ or A_1 if $v > 0.7$. In S_3, it is A_3 if $v < 0.2$ or A_4 if $v > 0.2$. In the other scenarios, the result is the same regardless of v.

Table 7 Synthesis of the results of the multi-criteria analysis.

<table>
<tr><th></th><th colspan="2">S_1</th><th>S_2</th><th colspan="2">S_3</th><th>S_4</th></tr>
<tr><td>TOPSIS</td><td colspan="2">A_4</td><td>A_1</td><td colspan="2">A_4</td><td>A_4</td></tr>
<tr><td>WSM</td><td colspan="2">A_4</td><td>A_1</td><td colspan="2">A_4</td><td>A_4</td></tr>
<tr><td>WPM</td><td colspan="2">A_4</td><td>A_1</td><td colspan="2">A_4</td><td>A_4</td></tr>
<tr><td>VIKOR</td><td>A_3</td><td>A_1</td><td>A_1</td><td>A_3</td><td>A_4</td><td>A_1</td></tr>
</table>

7. Results and Discussion

After the execution of the four multi-criteria decision methods, it resulted that, for all the scenarios, 3 methods out of 4 showed the same results, and this convergence demonstrates of course the validity of the results.

Moreover, in 3 scenarios out of 4, that is to say in all the cases where the economic expense was not considered much more important than any other issue, the fourth strategy, the one with the higher number of interventions, resulted to be the optimal one.

This result perfectly epitomizes the premise of the article: despite being the one with the higher cost, the majority of the methods state it constitutes the optimal strategy because the other three overlook at least one aspect of the life cycle of the component. In fact, strategies related to the absence of maintenance interventions hide the non-negligible risk of an unpredicted collapse; strategies that intervene directly on the plaster itself rather than on the finishing layers are much less sustainable, due to the energy consumed in the production of cement. And of course, this second choice is strongly influenced by the difficulty in evaluating the contribution of the good state of the finishing layers to the service life of the plaster.

So, the result actually shows that lowering the cost of maintenance tends to cause consequences that are less convenient than the reduction of the expense, as the economic difference between the fourth strategy and the other ones is ‘spent’ in a higher degree of safety and in a lower environmental impact. Unless, of course, lowering the net expense of maintenance is seen as the top priority, which is the meaning behind the second scenario.

This analysis, performed considering different cases and possibilities, can be considered to have provided a reliable result in terms of global convenience, available for use in practical cases, rather than a simple exemplar application.

Yet, the differences of results in VIKOR cannot be overlooked. One major explanation behind them is the characteristic of the method to enlarge little numerical differences. This was crucial for the criterion of availability, for which the results were almost identical for the strategies, but despite that the method attributed a much higher benefit to strategies which had a slightly higher value than the other ones. In addition to this, another problem is related to its characteristic of calculating the parameters of evaluations by ranking the scores, rather than by considering their actual entity. In other, the lack of safety of A_1 compared to A_4 has almost the same negative weight as the higher cost of A_4 compared to A_1, even though the former is much higher than the latter.

These two issues lead to the conclusion that the VIKOR method can be successfully used when the difference in the scores is more balanced, that is to say, nor too big nor too small. This aspect has of course to be taken into account in future applications. In any case, this constitutes a proof that operating with more MCDMs at the same time is necessary to acknowledge the flaws that exist in each method.

Finally, the interesting results of this experimentation certainly encourage further research in the field of durability, as the performance-time curve for plaster coverings was the only starting point for the numerical evaluation of the criteria. This means that the creation of reliable performance-time curves for other building components can offer the possibility to realize templates for multi-criteria analysis like this one on them as well.

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