AN APPLICATION OF MULTICRITERIA DECISION METHODOLOGY TO RELIGIOUS HERITAGE CONSERVATION THE CASE OF THE CATHEDRAL OF JEREZ DE LA FRONTERA (CADIZ)

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Abstract

In this study a new methodology for the evaluation of conservation treatments is presented. With the multicriteria decision methodology (MCDM), each conservation treatment is evaluated considering different assessment factors previously ordered according to an importance-based hierarchy. The total value of each alternative based on these weights is calculated and the rating of each alternative is calculated using a distance-based MCDM method. This technique is based on a positive ideal solution, which is determined with respect to the distance of each alternative to the best-performing one.

The paper is structured as follows: firstly the designed methodology is summarized and the conservation treatments evaluation framework is presented. Secondly, we present a real case and the best alternative for the Conservation of the Cathedral of Jerez de la Frontera is selected using the MCDM-based method.

Keywords: MCDM, built heritage, consolidant treatments, water repellent, treatments

1. Introduction

Researchers have achieved a great deal of knowledge and experience in the study of the factors and mechanisms affecting the deterioration of built heritage. In addition, they have wide-ranging information on the application of different products and treatment techniques. Consequently, undertaking conservation work without extensive previous information-gathering on what is happening in the building and the anticipated effects of the use of any treatments is no longer acceptable.

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An intervention project should include all the planned actions, which must be supported by data obtained in the previous study phase, the first stage of which is diagnostic. During the diagnosis, weathering factors must be researched as these agents cause changes in stone properties that appears as alteration indicators. The second part focuses on proposed corrective actions, studying the effects of treatments both immediately after application and long term under the influence of the weathering factors that will continue to affect the building.

The evaluation of treatment products and techniques, prior to their application in the building, aims to determine the behaviour of the treated material and its response to weathering factors with the ultimate purpose of selecting the most suitable for use in the restoration process. It can be done in two ways: by making controlled applications in small areas of the monument and determining the effects produced, or by applying treatments to samples of the stone materials and measuring different characteristics to determine their effectiveness and weathering resistance.

In order to apply this second alternative, we developed a methodology [1] performing several tests for measuring the properties and characteristics of the treated stone. This procedure concluded with a qualitative assessment of the results for each treatment, having a global vision that allows the best 'average' behaviour to be chosen. In this work, a different last step is proposed. The last step is a decision matrix that makes the methodology clear and systematic. The decision step employs numerical tools that provide a global quantitative result evaluating the effect of each treatment.

Taking into account that the treatment selection can be considered a complex multi-criteria decision problem, the main objective of this study is to propose a mechanism to decide the most suitable conservation treatment for a given type of stone employing numerical tools that provide a global quantitative result evaluating the effect of each treatment.

The Multi Criteria Decision Matrix (MCDM) is a powerful tool widely used for evaluating and ranking problems containing multiple criteria [2]. The MCDM techniques generally enable a problem to be clearly and systematically structured. The MCDM attempts to find the best option from all of the feasible alternatives in the presence of multiple decision criteria.

According to the analysis of Dutta and Husain [3], there are two main groups of MCDM methods. One is based on a preference index to rank alternatives by taking into account the importance of each attribute (weight) and the value of each alternative on each attribute (decision matrix) [4]. The other type is based on value functions and utility theory [5, 6], with several variants, such as multi-Attribute Utility Theory (extremely complex [7], costly and time consuming), linear Additive Evaluation Model (applicable if criteria are independent of each other and if uncertainty is not built formally into the model [8, 9]) or 'fuzzy MCDM methods' [10-12], that choose the alternative that minimizes the distance between the fuzzy ideal-positive solution and the fuzzy ideal-negative solution.

Many authors have applied various MCDM methods in different research fields but, to the best of our knowledge, none have been applied in heritage conservation except the above-mentioned paper of Dutta and Husain related to the indexing of built heritage in Calcutta for renovation and maintenance purposes [13-15].

In this paper we apply this method to the Cathedral of Jerez de la Frontera (Cadiz, Spain). Jerez Cathedral is a seventeenth century building; in particular, its construction was developed between 1695 and 1778. The cathedral was built originally as a Collegiate Church, raised over the original Great Mosque of Jerez and the ancient Church of the Saviour, whose origin dates from 1264 [16].

In the late seventeenth century, the old Collegiate Church of Jerez was ruined so the City College and the City Council decided to demolish to build a new one. This work began on 1695 under the direction of Diego Moreno Meléndez [16]. After several interruptions, on 1778 the inauguration of the new church was celebrated, although works continued until 1849. The construction works of the temple lasted over more than eighty years. This long duration causes that three architectural styles can be found on the Cathedral: neoclassical, Baroque and Gothic.

This work includes, as the main objective, the evaluation of possible conservation treatments and the selection of the better one. The work was done as follows:

- The diagnosis of alteration of the materials from the Cathedral, the characterization of stone materials and the identification of visual deterioration indicators. Results previously published [17].
- Determination of the effectiveness of conservation treatments (consolidants and water repellents) on the stone by means of laboratory tests with stone samples. Results previously published [17].
- Evaluation of the conservation treatments and selection of the best alternative for the Conservation of the Cathedral of Jerez de la Frontera is carried out using the MCDM-based method.

2. Materials and methods

2.1. Stone types

The stone of Puerto de Santa María (PSM) is an ivory colored bioesparithic calcarenite, with an open porosity of 35% [17]. It is a soft, crumbly rock, to the point that the grains can be detached by simple friction. Macroporosity is predominant, while the microporosity is practically inexistent and medium-sized pores scarce. Through various chemical methods, Rodriguez [17] obtained the main elements of lithotype, presented in the Table 1.

Table 1. Main elements of the PSM lithotype.

	LOI	SiO_2	CaO	Al_2O_3	Fe_2O_3	MgO	SO_3	Na_2O	K_2O
PSM	26.30	39.41	33.09	0.28	0.27	0.15	0.39	0.18	0.28

2.2. Weathering factors and indicators

In the case of the stone of the Cathedral, the main weathering factors that affect it are: wind, thermo-hygrometric oscillations, soluble salts and biological agents.

The presence of salts causes the following weathering indicators: efflorescence, crusts, chromatic alteration, concretion, striction, pitting, crater formation, corrosion, alveolar erosion, swelling, blistering, contour scaling, peeling, chipping and film separation.

Within the biological agents, from microorganisms to plants and animals, the most common indicators produced by living organisms are deposits, spotting, disaggregation and pitting.

Although there are evidences of materials deterioration all over the temple, the facades that present the most important signs of alteration are the main (N-NW) and western ones while the southern has suffered lack of attention. The dome and the upper terrace sculptures are in good condition, probably due to the application of conservation treatments in the past.

A visual inspection of the church was carried out. The magnitude of the main weathering indicators in the temple is shown on Table 2. A qualitative evaluation of the main deterioration factors was performed taking into account the extension of the alteration and the importance of them.

Table 2. Qualitative magnitude of weathering indicators of the building.

Weathering Indicators	Importance
Chromatic Alterations	++
Material losses	+++
Cracking	+++
Incrustations	+
Plants	++

Legend: + Low, ++ Medium, +++ High

Table 3. Treatments characteristics.

Product	Manuf.	Properties	Dilution	Composition
Estel1000	CTS S.r.l.	Consolidant	75% on white spirit	Tetra ethyl silicate
Estel 1100	CTS S.r.l.	Consolidant + Water repellent	75% on white spirit	Tetra ethyl silicate + Oligomeric polisiloxane
Silo 111	CTS S.r.l.	Water repellent	10% on white spirit	Oligomeric organosiloxane

2.3. Conservation treatment

The next step in studying the behavior of stone has been to apply conservation treatments to PSM, the most abundant stone in the building. Cubic samples of 5cm have been prepared from blocks taken from the original quarry (in Puerto de Santa María), and from ashlar fragments from the cathedral. After cutting, the samples have been cleaned, dried to the air till constant weight. In this way, the stone has got and hygroscopic water content in equilibrium with ambient.

The treatments characteristics are summarized on Table 3. Estel 1000 is a consolidant product, Estel 1100 is consolidant and also water repellent and Silo 111 is a water repellent.

To get an impregnation as uniform as possible, the samples have been treated by immersion in the products during ten minutes, time enough, due to the high porosity of stone, to get a complete impregnation. The treatments drying process has been followed by weighing the samples daily until constant weight.

2.4. Evaluation of treatments

Consolidant and/or water repellents treatments were evaluated according to three aspects [18]:

A. Compatibility of the treatment with the material, measured by compatibility indicators (CI) because it is fundamental to know how the treatment modifies certain characteristics of the material, including porosity and pore size distribution, water vapour permeability, water desorption rate, and color. If changes in the above-mentioned characteristics are very high, the treatment could be discarded.
B. Treatment effectiveness, measured by effectiveness indicators (EI) because treatments are applied with the object of achieving an improvement in certain characteristics. This category can be divided into two different sub-criteria:
   i. In the case of water-repellent products, a decrease in water entry into the stone. This can be measured through the absorption of water by capillarity and immersion, drop angle or drop absorption time.
   ii. For consolidant products, the increase in material cohesion. This criterion can be measured by mechanical properties such as superficial hardness or compressive strength or indirectly through ultrasonic velocity.
C. Resistance of the treated stone to weathering, measured by resistance indicators (RI). The last step in treatment evaluation consists in submitting the samples to conditions that simulate the alteration mechanisms in the building, but in an accelerated timeline. Freeze-thaw cycles and salt crystallization are two of the usual accelerated weathering tests.

In order to evaluate the effectiveness and to select the most appropriate conservation product, several characteristics on the stone have been measured (Table 4). Before and after the treatment, the mass and the total open porosity

[19] of all the samples have been measured. Capillarity absorption has been determined on all the samples, following the test proposed by Ontiveros (1998), adapted from UNI-EN-1925. Water desorption for all samples was measured (NORMAL 29/88). The cohesion of the stone has been determined indirectly through the ultrasonic rate [20]. It has been measured in the three perpendicular directions, and average values were calculated. The colour of samples before and after treatments application was measured using a Colorimeter Minolta CR-210 and using templates for diameter reduction according to Arroyo et al [21]. Salt crystallization test carried out is that proposed by Villegas [22], adapted from UNI-EN-12370. The response of the treated samples to the weathering factors that act over the Cathedral of Jerez has been determined by means of an accelerated weathering test (salt crystallization). A 10% sodium sulphate solution is used and it is formed by 20 cycles as follows: 24 hours of immersion in the solution, +22 hours of drying at 65ºC, +2 hours for cooling and weighing.

Table 4. Criteria hierarchy for both objectives.

	Positive/negative Sign criteria	Kind of evaluation of the property	Consolidation hierarchy	Water repellent hierarchy
Porosity variation	Treatments decrease stone porosity and this effect is negative	CI	5	4
CWC	Treatments usually increase the CWC in desorption tests and this effect is negative	EI	3	5
Colour changes	Any change in material colour is negative	CI	2	2
Capillarity absorption	Treatments decrease the CWA and this effect is positive	EI	4	8
Water desorption	A higher water desorption rate is positive	EI	1	6
Hardness	Treatments increase stone hardness and this effect is positive	EI	6	1
US rate	Treatments increase stone cohesion and this effect is positive	EI	8	2
Accelerated weathering	A higher number of cycles before crushing is positive	RI	7	7

3. Results

3.1. MCDM applied to the Cathedral of Jerez de la Frontera

We propose a simplified MCDM-based approach. We have adapted the methodology to make it suitable for heritage conservation characteristics. The evaluation procedure of this study consists of six main steps.

3.1.1. Step 1 - identifying evaluation criteria

The first step of this method is the selection of indicators (evaluation criteria) to ensure the adequate evaluation of treatment performance. The evaluation criteria were listed (Table 4). Based on our experience, we have defined a limited number of indicators that best fit the characteristics of treated stone.

3.1.2. Step 2 - evaluating conservation treatments (performance matrix)

Material characteristics before and after treatment application have to be measured to analyse the performance of a particular conservation product. An performance matrix was computed, representing the values of each treatment with respect to each criterion (material property) (Table 5). Table 5 was designed listing in the 8 columns the 8 properties of the stone materials selected in Step 1 and in the 4 + 2 rows the 4 studied treatments, the blank group, and the ideal group. The ideal group is not a real group, but the combination of the best possible results in the evaluation of characteristics. In the matrix, the blank and the best measurements were included for comparison reasons.

3.1.3. Step 3 - computing the evaluation criteria matrix

Values of experimental results for each property (Step 2) after application of the different conservation treatments were normalized for calculations. First, the increases in the values of each property after the application of conservation treatments were calculated compared with the blank (Table 6: incremental matrix).

Table 5. Performance matrix.

	P	**CWC**	**C**	**CWA**	**WDR**	**H**	**USV**	**SCC**
Blank	32.5	0,53	0	1.08	595.7	61	1879.0	10
E1000+S111	24.9	1.26	7.6	0.20	287.3	61	2140.9	15
S111	25.2	0.555	7.3	0.03	379.7	60.3	1726.3	20
E1000	30.5	0.72	2.0	0.66	154.6	65.1	2203.1	13
E1100	28.8	1.15	3.7	0.31	530.1	66.5	2183.9	13
BEst	32.5	0	0	0.03	595.7	66.5	2203.1	20

P = Porosity (%); CWC = critical water content (%); C = Changes in Colour (CIELab); CWA = capillary water absorption (mg/cm^{2}s); WDR: water desorption rate (mg/min); H: Brinell Hardness (HB); USV = Ultrasonic velocity (m/s); SCC = salt crystallization cycles before crush (number of cycles)

Table 6. Incremental matrix.

	P	**CWC**	**C**	**CWA**	**WDR**	**H**	**USV**	**SCC**
Blank	0	0	0	0	0	0	0	0
E1000+S111	7.6	0.73	7.6	0.88	2.6	0	261.9	5
S111	7.3	0.02	7.3	1.06	1.8	0.7	-152.6	10
E1000	2.0	0.19	2.0	0.42	0.4	4.1	324.2	3
E1100	3.7	0.62	3.7	0.77	2.6	5.5	304.9	3
IDEAL	0	-0.53	0	1.06	0	5.5	324.2	10

For each property (each column in the performance matrix), the maximum increment (Δ_{jmax}) was established, and normalized evaluation terms (Table 7) were calculated using equation 1:

$$\text{Normalized evaluation criteria term for Ti} = \frac{\Delta_{ij}}{\Delta_{jmax}} \quad (1)$$

According to that codification, normalized evaluation terms vary from 0 to 1, 0 being the values of the blank group properties and 1 the values of the properties that differ most with respect to the blank group (Table 6). Normalized evaluation terms are calculated as the proportion of each increment with respect to the maximum increment, as mentioned in equation 1.

Table 7. Normalized evaluation criteria matrix.

	P	CWC	C	CWA	DR	H	USV	SCC
Blank	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
E1000+S111	1.00	1.00	0	0.82	0.70	0.00	0.81	0.50
S111	0.95	0.03	0.95	0.97	0.49	0.00	0.15	1.00
E1000	0.26	0.26	0.26	0.39	1.00	0.75	1.00	0.30
E1100	0.48	0.85	0.48	0.71	0.15	1.00	0.94	0.30
IDEAL	0.00	-0.73	0.00	1.00	0.00	1.00	1.00	1.00
Hierarchy 1	5	3	2	4	1	6	8	7
Hierarchy 2	2	5	2	8	6	1	2	7
Sign	-	-	-	+	+	+	+	+

Hierarchy 1: Criteria weights for consolidants; Hierarchy 2: Criteria weights for water repellents

3.1.4. Step 4 - determination of criteria hierarchy

Following the process and the analysis phases, the weighted indicators are computed. The evaluation criteria used in Step 1 are ordered according to their importance.

The objective of the application of conservation treatments is to change or improve one or several material characteristics. However, not all the material characteristics can be considered equally important for conservation purposes. Instead, they are more or less relevant depending on the intervention goal (consolidation, water repellence, or both).

In this method, a number between 1 to 8 has been assigned to each criterion (or material characteristics), that is, they have to be ordered depending on their importance for the conservation purpose (Table 4). The grading is different for consolidant or water repellent uses, so two different rankings have to be defined for each group — consolidant or water repellent. This order represents the best knowledge of decision-makers. The criteria for treatment effects on material characteristics (positive or negative) are also shown in Table 4.

3.1.5. Step 5 - decision matrix computing

Defining the best conservation product consists in taking the best values of alternatives. The normalized performance values (normalized evaluation criteria matrix) were multiplied with the criteria weights and corrected using a + or – sign. The criteria weights were determined in Step 4. The sign was allocated in accordance with the following rule: when one material characteristic treated with treatment I, is better than the same characteristic in the blank group, the value of the term is positive, and when the characteristic is worse than in the blank group, then it is negative.

3.1.6. Step 6 - results and discussion

The last step consists in adding all the terms of the decision matrix in each row. After representing the decision matrix and adding the terms of each row, the final valuation can be calculated and a vector with the final score of each conservation treatment can be obtained (Tables 8 and 9).

For each treatment, the sum of each normalized term has to be computed and the final value can be calculated (Tables 8 and 9).

$$\text{Final value} = \Sigma_i = \sum_j \frac{\Delta ij}{\Delta jmax} \cdot I_j \tag{2}$$

In the last column, the relative values have been calculated for each treatment with respect to the ideal case (considered to be 100%). The blank, which is the one most distant from the ideal case in this study, has also been included.

Table 8. Decision matrix-Consolidation.

	P	**CWC**	**C**	**CWA**	**DR**	**H**	**USV**	**SCC**	**SUM**
E1000+S111	-5.00	-3.00	-2.00	3.27	0.70	0.02	6.45	3.50	5.96
S111	-4.77	-0.082.91	-1.91	3.90	0.49	0.01	1.17	7.00	5.83
E1000	-1.32	-0.78	-0.53	1.55	1.00	4.50	7.98	2.10	14.56
E1100	-2.39	-2.54	-0.96	2.85	0.15	6.00	7.51	2.10	12.70
IDEAL	0.00	2.18	0.00	4.00	0.00	6.00	8.00	7.00	27.18

Table 9. Decision matrix-Water repellent.

	P	**CWC**	**C**	**CWA**	**DR**	**H**	**USV**	**SCC**	**SUM**
E1000+S111	-2.00	-5.00	-2.00	6.53	4.19	0.00	1.61	3.50	8.88
S111	-1.91	-0.14	-1.91	7.79	2.94	0.00	0.29	7.00	14.06
E1000	-0.53	-1.30	-0.53	3.11	6.00	0.75	2.00	2.10	11.63
E1100	-0.96	-4.24	-0.96	5.70	0.89	1.00	1.88	2.10	5.39
IDEAL	0.00	-3.63	0.00	8.00	0.00	1.00	2.00	7.00	21.63

4. Conclusions

The MCDM-based system is of considerable use to conservation researchers. It provides them with a strong basis for determining the best conservation treatment for a specific monument according to objective results obtained in the laboratory. The final result is a grading of the treatments with the relative value of the 'ideal case'.

Concretely, the proposed methodology allows the direct, objective determination of the best treatments for a specific stone, and the comparison of different treatments with the same scale.

In addition, this method is extremely versatile as the properties studied can be changed or new ones added depending on the considerations desired by technicians. The hierarchy vector can also be defined taking into account the personal criteria of the decision-makers, adapted to each specific study. So, it can be easily adapted to the needs and data available. Each researcher can vary the evaluation criteria and the treatments.

It should be noted that the results provided by this method are relative, that is, they are the best treatment among those studied, for a specific stone and for the weathering factors considered.

Specifically for the building studied in this work, the numerical results show clearly the best consolidant, E1000, and also prove that the addition of the water repellent, S111, after the consolidation worsen its behavior. For water repellency this treatment gets he best result.

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