Heritage Evaluation: restoration plan through HBIM and MCDA

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Abstract. This study is prompted by the activity carried out within a EU funded project (WARMEST)[1] whose goal is to analyze monuments’ degradation due to factors such as climate change and growing number of tourists, create a model to describe and anticipate the phenomena, and put in place a user-friendly Decision Support System that will help in setting preventive maintenance plans. As part of the project, we had the chance to study in depth the degradation at the Patio de Los Leones, the core of the world-famous site of the Alhambra and Generalife, which attracts to Granada in Spain where they are located over 2 million tourists per year. The paper aims to define a new methodology to assess the level of urgency to restore the 124 columns of the Patio de Los Leones (Alhambra). It is not easy to identify all the factors affecting the columns’ deterioration and to establish which should be restored first. Our approach is to collect all the data regarding the decay factor and use multi criteria decision aid methods such as the Analytic Hierarchy Process in order to create a hierarchy among all columns according to their decay. We also will create an HBIM model of the Patio del Los Leones in order to optimize the management and maintenance of the columns. HBIM model can also optimize the data management and enable to compare results (in this case data about columns decay) over time.

1. Introduction

1.1. Cultural Heritage Evaluation
Cultural heritage can be considered as a dynamic category in constant evolution as its definition has changed through the years. According to the World Heritage Convention, the term cultural heritage refers to single monuments, such as architectural works, to works of monumental sculpture and painting, as well as to groups of buildings and sites, such as areas where archaeological sites are located [2]. This initial definition has been enlarged and nowadays the term cultural heritage may refer also to territorial systems, landscapes, itineraries and intangible heritage. Following this description, it is clear that the environment where in cultural goods are ideally defined can be represented by the following elements. Firstly, cultural heritage is a multidimensional issue, because it belongs to the economic categories of public and mixed goods. Secondly, cultural heritage is a multi-attribute problem considering that
A heterogeneous flow of services and functions characterizes cultural markets. Thirdly, cultural heritage is a multi-value problem because it concerns a wide spectrum of personal and inter-personal value benefits. According to the scientific literature, the economic and cultural value of cultural heritage must be addressed through the Total Economic Value paradigm, which allows the overall value to be decomposed in two macro-categories: the use value and the non-use value [3]. The use value, linked to the benefits the consumer receives directly from the cultural asset itself, is the utility that the historic artefact offers the consumer from the very moment he comes into contact with it; the non-use value, which refers to the utility that the consumers perceive from the conservation of the cultural assets for themselves and for the future generation. Moreover, speaking about cultural heritage evaluation, it is worth pointing out that a strong link exists between the cultural goods available in a given area and the active production of material culture [4]. This link ascribes a particular importance to economic development and it suggests to separate two fundamental moments concerning:

- the estimation of the values of the site;
- the creation of value by means of economic activities.

It has been generally agreed that these two moments represent the basis of the historical identity of the site and of the vitality of the culture expressed by the site. In this sense, the evaluation must consider not only the historical and emblematic aspects of the site, but also the opportunities provided by the site to the overall community.

Considering this study as a contribution to WARMEST European Project we tried to create a model which could help the evaluation process of the cultural site (Patio de los leones). In order to fulfill this task we used two methods: 1) the multi criteria decision aid in order to create a hierarchy among the 124 columns according to the need for restoration; 2) Creation of HBIM model optimizing maintenance procedures and collecting all data about columns decay over time.

2. Materials

2.1. BIM for Heritage Buildings

Nowadays, BIM has significantly spread also in the field of the management and documentation of infrastructure and cultural heritage [5]. Considering the latter field of application, BIM can be useful to represent in a virtual environment the actual conservation state of the analyzed buildings [6]. However, the virtual reconstruction procedure of historical-cultural heritage is not an easy task, because the objects to model consist of components whose heterogeneous, complex, and irregular characteristics and morphologies are not represented in the BIM software libraries [7]. Therefore, it is essential to introduce the historical and technical approaches into the BIM environment, as well as the point clouds, to model the different virtual parametric components and achieve a “BIM as-is model” of the architectural heritage analyzed [8].

The parametric design of the building elements from the point cloud is a time-consuming and error-prone manual process, because there are currently no automation or software processes that can ensure a direct change from point cloud to full BIM models [9]. Therefore, once the 3D virtual models have been created, the libraries of the parametric elements should be generated under the concept of H-BIM. The H-BIM concept was first used in the work of Murphy et al., 2009 from the Dublin Institute of Technology. According to Murphy et al., 2011 and Dore et al., 2012 H-BIM pursues the modeling and documentation of architectural elements, according to artistic, historical, and constructive typologies. In addition, H-BIM is considered to be a special library of BIM parametric objects that was specifically designed to preserve and manage cultural heritage within the general framework of “smart heritage”. Generally, the H-BIM library is built using the manuscripts and historical architectural documentation, laser scanning, photogrammetric techniques, and other data obtained from the physical analysis of the building in question. In addition, thanks to H-BIM it is possible to understand the materials and construction techniques, as well as help conservation efforts, management, restoration, or reconstruction of heritage buildings that no longer exist or that are not documented [10].
2.2. Multi criteria decision aid for cultural heritage

Decision-making processes in the context of cultural heritage projects are affected by several characteristics. They can be described as complex decision problem with many dimensions to be included in the analysis, taking into consideration historical and artistic value, economic con-strains, environmental impacts and so on [11]. Secondly, multiple actors with different and conflicting objectives have a role in the decision arena, such as public government representatives, architects, architectural historians, developers and owners. Thirdly, it is possible to mention the existence of factual information (for example, the degradation of an historical building) and value information to be incorporated in the process. Moreover, the evaluation must consider not only quantitative data, but also probabilistic variables and qualitative judgments, such as, for example, the landscape quality of a certain area. Finally, the evaluation tools must be able to guarantee the transparency of the decision process and to communicate in an easy way the results of the choices. It has been generally agreed that Multicriteria Decision Analysis (MCDA) can offer a formal methodology to deal with such decision problems, taking into account available technical information and stakeholders values. A formal methodology to deal with complex decision problem sis provided by multi-criteria decision-making (MCDM) analysis, consisting of a set of techniques that aims to comparatively assess alternative projects or heterogeneous measures [12]. The earliest references relating to MCDM trace back to Benjamin Franklin and to the mathematical contributions of Georg Cantor and Pareto, who firstly studied the aggregation of conflicting criteria into a single composite index. Since then, thanks to the contributions of Operational Research, multi-criteria analysis was employed in different areas, deriving techniques from other mathematical disciplines, such as mathematical modelling, statistical analysis and mathematical optimization. MCDM can be classified in two categories - multi-objectives decision analysis (MODA) and multi-attribute decision analysis (MADA)- in relation to the decision context and the complexity of the mathematical model [13]. The first type is commonly used to determine the optimal compromise solution with a probabilistic approach, which assumes continuous solution spaces. The second one utilizes a deterministic approach with a finite domain composed by a finite number of alternatives and requires multiple attributes to determine choices. MADA methods do not aim to compute an optimal solution; rather, they aim to determine a rank of decision alternatives that is optimal with respect to several criteria. The main difficulties in the application of MADA are related to the definition of the attributes starting from the construction of a sound knowledge framework. Recent studies examine scholarly literature pertaining to decision analysis and identify the most common MCDM methods, which are multi-attribute utility theory (MAUT), analytic hierarchy process (AHP), fuzzy set theory, analytic net-work process (ANP), case-based reasoning, data envelopment analysis, simple multi-attribute rating technique, goal programming, ELECTRE, PROMETHEE, weighted-averaged sum (WAS), the technique for order of preference by similarity to ideal solution (TOPSIS), and additive ratio assessment (ARAS)[14].

3. Methods

3.1. Analytic Hierarchy Process

The AHP is a useful and efficient decision aiding method for the formulation and analysis of decisions. Saaty, who introduced the AHP method, pointed out that the AHP is “a general theory of measurement”. It prioritizes and quantifies all possible alternatives by their evaluation and comparison among each other. In addition, AHP systematically includes, categorizes and orders all potential factors that can affect a specific process and offers a structured and straightforward solution for decision making[15]. The steps involved in the AHP method are schematically shown in Fig. 1, and may be summarized as follows:

Step 1: The problem is broken into a hierarchy of the following components:
- Goals: the objective to be achieved.
- Criteria: the elements based on which the alternatives are evaluated.
Alternatives: the possible set of actions, a good choice from which will depend on the extent to which the goal is achieved by fulfilling the different criteria.

Figure 1

Step 2: Data are collected from experts or stakeholders from the qualitative pairwise comparison based on the hierarchy described in Step 1. Experts can score the comparison with the categories listed as follows:
- Equal
- Marginally strong
- Strong
- Very strong
- Extremely strong

Step 3: “Pairwise comparison matrices” are created from the various criteria and alternatives. Matrices are developed based on $n (n – 1)$ judgements, where $n$ stands for the number of elements in each level. For every pairwise comparison, reciprocals are assigned to the conjugate pair. Thus, if criterion $i$ is judged to be twice as important as criterion $k$, then criterion $k$ is considered to be half as important as $i$. More formally, the matrix $A$ is formed based on the following rules:

$$a_{ik} = \begin{cases} 1 & \text{if } i = k \\ \frac{1}{a_{ki}} & \text{if } i \neq k \end{cases}$$

for all $i, k = 1, 2, ..., n$

In particular, the $n \times n$ pairwise comparison matrix can be described as:

$$A = \begin{pmatrix} 1 & a_{12} & \cdots & a_{1n} \\ \frac{1}{a_{12}} & 1 & \cdots & \frac{1}{a_{1n}} \\ \vdots & \vdots & \ddots & \vdots \\ \frac{1}{a_{1n}} & \frac{1}{a_{2n}} & \cdots & 1 \end{pmatrix}$$

Step 4: The overall priority or weight of the $i^{th}$ element ($w_i$) can be found from the normalized principal eigenvector $W$ by solving the following standard linear algebra equation:

$$AW = \lambda_{max} W$$
where $\lambda_{\text{max}}$ is the largest eigenvalue of $A$, and $W$ is normalized in the sense that the sum of all its components is equal to 1. The $n$ components of $W$ give the weights of the $n$ different criteria considered.

Step 5: The pairwise comparisons are said to be consistent if transitivity is preserved across all elements of $A$.

However, it is possible to accommodate certain amount of inconsistency in the ratings. The threshold is given by the constraint that consistency ratio (CR) should be less than or equal to 0.1. The consistency ratio is defined as $\text{CR} = \frac{\text{CI}}{\text{RI}}$ where the consistency index (CI) is computed as:

$$CI = \frac{\lambda_{\text{max}} - n}{n - 1}$$

Step 6: The final step of the AHP method consists of aggregating the local preferences $L_{P_k}(a_i)$ of each alternative $a_i$ based on the weights $w_k$ of the $k$th criteria $C_k$. This gives the composite weights $CW(a_i)$ of each alternative $a_i$ as:

$$CW(a_i) = \sum w_k L_{P_k}(a_i)$$

Following this procedure, we are going to obtain a hierarchy of the analysed columns according to the need for restoration.

3.2. Data collection methodology to assess columns decay factors

The data collection was characterized by two phases. The first one concerned a bibliographic data collection through research both in the archive of the Patronato de Alhambra y Generalife and in the library of the Faculty of Architecture of the University of Granada.

Through this research we collected historical photos, planimetry and section of the courtyard of the lions as well as a wide literature material about columns material and its property (physical, chemical and mechanical) and restoration activities carried out over time.

The second phase concerned the data collection in situ during our secondment in Granada.

We attended both the photogrammetry activity necessary for the construction of a 3d model of the patio and the thermographic photo session. The latter activity was useful to compare the temperature condition of the columns with the same thermographic photos took in 2004 for another study.

4. Results

4.1. Columns decay factors

Starting from the analysis of the collected data described in section 3.2 it was possible to identify the main causes of column decay. Those causes can be described as follow:

- Alterations due to climatic factors such as the sun exposure of the facade: the northern facade receives the highest level of exposure to the sun. Exposure time is up to 8 hours (columns 5 to 31 in summer) so the thermal gradient can reach 15°C. The east facade receives 3-4 hours of exposure in summer. The southern facade is hit by sunrays for a few days a year and for a short time which causes minor temperature gradients. The west facade is only affected by indirect radiation. The thermal gradient for this facade is 6.8°C in a day.

- Rising water due to capillary phenomena affects the bases of the columns. The northern zone is the most affected by the moisture. In particular, the salt contained in the water is the main cause of degradation. The marble floor also interferes with the conservation of the lower part of the columns because of the water splashing when it rains.

- Presence of salts: sulphates cause salt crystallization mechanisms which also contributes to the formation of plaques and sandblasting.

- Freezing phenomena: when water penetrates a marble fracture, it can condense due to the low temperature and increase in volume. Thus causing breakups and disruption.

- Biological agents: fungus, mosses cause moisture retention and encourage chemical reactions.

Another factor of deterioration are the pigeon excrements producing a corrosive effect on the marble since these contain nitric and phosphoric acids. This factor also creates aesthetic and hygienic problems.
Stone carving and installation: It were observed that all the columns of the patio are carved following the direction of the marble vein, while in most of the bases and capitals the direction of the vein is perpendicular to the longitudinal axis of these elements. This particular stone placement is responsible for several fractures.

Irregular load distribution: The placement of the columns allows the load transmitted by the building to cause tensions. Thus, generate fractures, fragmentation and loss of material.

Use of the monument (public visit): Tourist contributes to the creation of a black patina due to friction of their hands on the shafts. They can also be responsible for excoriations or loss of material due to sharp objects (such us metal separators) hitting the columns.

Earthquakes, vibrations, landslides causing building movements, fractures, fissures, fragmentations and collapses.

4.2. HBIM model

The creation of HBIM model helps the management of the sites. It is also a valid tool in order to create a library containing all the data about columns decay over time. The first step to create del BIM model was the photogrammetry process. For each column were taken almost 800 photos (Figure 2) in order to create a 3d model trough structure from motion (SFM) process (Figure 3). This model was exported from Autodesk 3ds Max software to Autodesk Revit software. Once the 3d model was imported into Revit the process to create a BIM model was quite complex. In fact, to date it is not possible to automatically transform a 3d model generated from SFM process into a 3d BIM model. For this reason, we had to make a manually reconstruction (Figure 4).

The second step after reconstructing the 3d bim model was to fulfill it with all the data collected. We linked to each columns a technical datasheet (Figure 5) containing information about:

- Geometrical data, such as dimensions and orientation;
- Architectural grammar, intended as architectural style;
- Material characterization;
- Evolution of columns degradation over time (from 1989 to 2019);
- Restoration process over time.
BIM models can be created with different levels of accuracy. During conversion between point cloud and geometrical model, several decisions can be made, in order to achieve different ranges of precision. LOD which means level of development has been created in order to classify that range [17]. Below we show a table of comparison between the level of development in 2017 (year the work started) until now.

| Standard     | 2017     | 2019     |
|--------------|----------|----------|
| USA Standard | LOD 200  | LOD 400  |
| Italian Standard | LOD B   | LOD D   |
| English Standard | Level 0 | Level 1  |
| Spanish Standard | LOD 200 | LOD 400  |

Table 1

As we can notice from table 1 it doesn’t exist a common language between the different Country standard. Generally speaking to date we reached a level of development where elements are modeled as specific assemblies, with complete fabrication, assembly, and detailing information. Once completed the HBIM model with all the data collected and organized into technical datasheet we will be able to set the Analytic Hierachy Process.

5. Conclusions
Considering these results we will continue to improve the research in order to give a further contribution to WARMEST project. For the next step of this research we will try to figure out which one among the factors described in section 4.1 affects columns' decay more strongly. In other words, we will give a weight to all the factors mentioned above collecting stakeholders’ opinion. In particular we will collect administrators' (from Patronato de Alhambra y Generalife) and restoration experts' thoughts in order to combine the needs of both. We will collect this opinion using online survey through social network. In fact, despite the widespread use of questionnaires as a method of data collection, many authors define it as an obsolete method [18], [19] and other ones defines it as a "static method" [20] that does not take into account the speed in which opinions and preferences change. Once collected and weighted all the factors we will add it into the AHP model in order to assess the level of urgency to restore the 124 columns of the Patio de Los Leones.

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