sustainability

Article

HBIM-Based Decision-Making Approach for Sustainable Diagnosis and Conservation of Historical Timber Structures

Silvia Santini *, Vittoria Borghese and Carlo Baggio

Department of Architecture, Roma Tre University, 00153 Rome, Italy
* Correspondence: silvia.santini@uniroma3.it

Abstract: Historical timber roofs play a significant role in architectural heritage, as listed in the World Heritage List protected by UNESCO. Despite their complexity, they are frequently lacking in maintenance, with the consequence that only a few original examples have been preserved until today, contradicting the principle of minimum intervention. In the paper, a decision-making approach has been proposed for the best and most sustainable solution, in which tradition and innovation meet to achieve the maximum quality with minimum intervention. With an emphasis on sustainability (environmental, economic, technological, historic, and social), analyses have been carried out in order to compare various intervention alternatives, modeled in a Heritage-Building Information Modeling (HBIM) environment, assessed using the Analytical Hierarchy Process (AHP), and implemented with the multi-criteria Modelo Integrado de cuantificacion de Valor para Edificacion Sostenibles (MIVES) methodology. The case study is the roof of the Michelangelo Cloister in the Diocletian Baths in Rome, which is a significant example of historical timber roofs. The results are given in terms of a quantitative sustainability index SI, which takes into account different alternatives of intervention, including the task of diagnosis.

Keywords: HBIM; MCDM; multi-criteria decision making; MIVES; AHP; timber; structure; heritage; NDT; diagnostic

check for updates

Citation: Santini, S.; Borghese, V.; Baggio, C. HBIM-Based Decision-Making Approach for Sustainable Diagnosis and Conservation of Historical Timber Structures. *Sustainability* **2023**, *15*, 3003. https://doi.org/10.3390/su15043003

Academic Editor: Asterios Bakolas

Received: 22 December 2022
Revised: 12 January 2023
Accepted: 4 February 2023
Published: 7 February 2023

1. Introduction

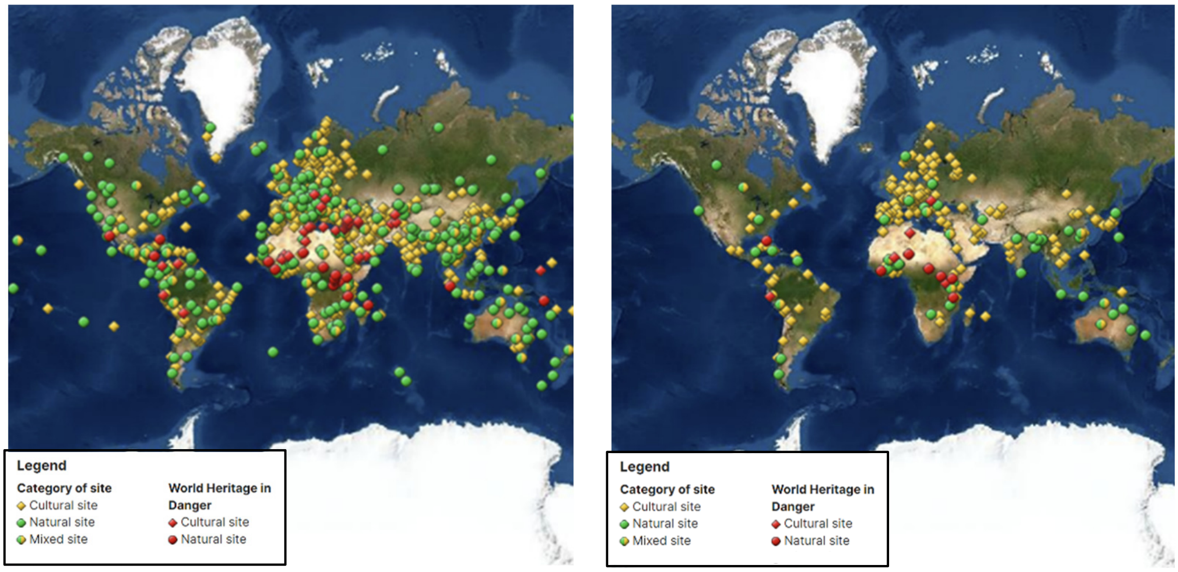
Even though there are many examples of wooden roofs with their complexity and magnificence all over the world, only a few of the original ones have been kept to the present day. Despite their relevance, they are often poorly monitored [1], with devastating effects caused by poor maintenance, fire, or earthquakes and with a total absence of diagnostic tests and provisions to reduce the deterioration with aging [2,3].

In Italy, 58 sites are currently protected by the United Nations Educational, Scientific, and Cultural Organization (UNESCO) in the World Heritage List, compared to 56 in China, 51 in Germany, 49 in France and Spain, making this country one of the nations with the greatest historical heritage in the world [4].

Although it is currently impossible to estimate the amount of wooden heritage, especially timber roof structures, that exists inside Italian boundaries, it is nevertheless conceivable to have an idea about wooden structures in general on a global scale. In Figure 1, a search of the UNESCO maps of protected sites can illustrate its worldwide relevance [5].

Concerning the overall architectural heritage, the only information available indicates that over 900,000 of the 3.16 million historic structures that must be preserved require structural repair, with around one-third of Italian buildings having been constructed before 1945 [6].

Only a small percentage of the original roofs in Italy have been kept. The majority of them have been partially or completely replaced because of the prevailing hypothesis of insufficient mechanical properties rather than performing an accurate assessment of the health state in force of the criteria for authenticity, as well as the concepts of minimal intervention and reversibility. This would require precise diagnostic procedures, including an examination of historical timber performance in situ using visual inspections (eventually assisted by drones) and non-destructive tests (NDT), such as hygrometric tests, ultrasonic investigations, penetrometric tests, and drilling resistance [7,8].



(**a**) (**b**)

Figure 1. (**a**) World Heritage Sites protected by UNESCO; (**b**) World timber heritage protected by UNESCO [5].

It is important to note that the performance standards for historical structures and the designing of new ones are the same according to ISO 2394 [9]. The Italian standards NTC 2018 in chapter 8.4 specifies that you are not forced to adapt but just to improve, in the case of historic buildings. For constructions of cultural interest in seismic areas, pursuant to the "Code of Cultural Heritage and Landscape" (Art. 29 of Legislative Decree 22 2004, n. 42), it is possible to limit the intervention by carrying out the relative safety assessment.

In some special cases (internationally speaking), exceptions, as explained in current legislation and studies, can be assessed based on economic and even sustainable or social factors [10–12].

In this paper, a methodology has been proposed to simultaneously evaluate various aspects during the entire life cycle of timber roof structures. The case study is the timber roof of the Michelangelo Cloister in Rome (Italy) with the evaluation of the interventions from the environmental, economic, structural, and social points of view. Four options that have been identified and used to restore the historic roof over the years have been examined and compared to assess sustainability while also considering the expenditure due to diagnostic activities.

The suggested methodology combines the Modelo Integrado de cuantificacion de Valor para Edificacion Sostenibles (MIVES), with the well-known multi-criteria analysis Analytical Hierarchy Process (AHP), developed by Thomas Saaty in the 1970s [13]. The goal of the integrated approach is to provide Sustainability Indices (SI) that can identify the best appropriate intervention in order to compare these indices and choose the best option [14].

The data required for the retrieval of information and the conduct of the analysis was obtained through modeling in the Heritage-Building Information Modeling (HBIM) environment. Through the creation of a Digital Twin, it is possible to have a single model that allows the authors to collect all the data acquired from surveys and investigations conducted.

Section 2 shows a mapping of the current state of the literature, and in Section 3, the sustainable interventions carried out in Italy on wooden roofs are discussed with the intention of illustrating remaining gaps and shortfalls. Then, the application and results for the case study of Michelangelo's Cloister are discussed with the aim to evaluate the helpfulness of the proposed procedure for the assessment of sustainability in the intervention on the wood historical heritage, useful to suggest maintenance and structural repair solutions for restoration.

2. Mapping of Literature on Historical Timber Roof Structures

The state-of-the-art analysis of the sustainability of intervention for a historical timber roof has been supported by bibliometric research software with the aim of extrapolating the key concepts and the most relevant authors in an efficient way. It allows us to carry out a bibliometric and scientometric investigation through the analysis and identification of the main authors, the keywords, and the amount of written publication to understand the most discussed issues, their correlation, and their development over time.

A visual deepening is therefore carried out through the mapping and the so-called hierarchical clustering, which is the grouping of the main objects and their hierarchical organization. This procedure makes it possible to better focus on selected information.

Over the years, various mapping modalities have been developed, the most widely used of which are those employing the combination of multidimensional scale (MDS) and hierarchical grouping [15]. The MDS is the most widely used mapping technique and has the objective of reorganizing the search, improving the approximation of internodal distances. The hierarchical grouping allows us to detect hierarchy among objects.

In this paper, the VOS mapping technique that combines both modalities and is based on the least square optimization method has been used [16–18]. The software collects the main data in nodes, graphed as spheres whose magnitude is proportional to the amount of data contained within, linked together through connection lines, the distance of which is a measure of similarity in terms of authors, keywords, papers, or citations in common.

The relative closeness between nodes s_{ij} is calculated according to Equation (1), considering a set of n nodes that must be grouped according to the number of links c_{ij} (authors, keywords, papers, and citations) between node I and node j:

$$s_{ij} = \frac{2mc_{ij}}{c_i c_j} \tag{1}$$

where m is the total number of links; c is the number of links between two nodes with c_{ij} equal to c_{ji} (always greater than or equal to zero), where i and j are different nodes.

The purpose of mapping is to identify a vector that, for each node, can find the correct position of the node itself in an n-dimensional map as shown in Equation (2) (that of VOS Viewer n = 2).

$$V(x_1, x_2, \ldots, x_n) = \sum_{i<j} s_{ij} d_{ij}{}^2 - \sum_{i<j} d_{ij} \tag{2}$$

The distance between nodes i and j is indicated by d_{ij} and identified in the mapping by Equation (3):

$$d_{ij} = ||x_i - x_j|| = \sqrt{\sum_{k=1}^{n} \left(x_{ik} - x_{jk}\right)^2} \tag{3}$$

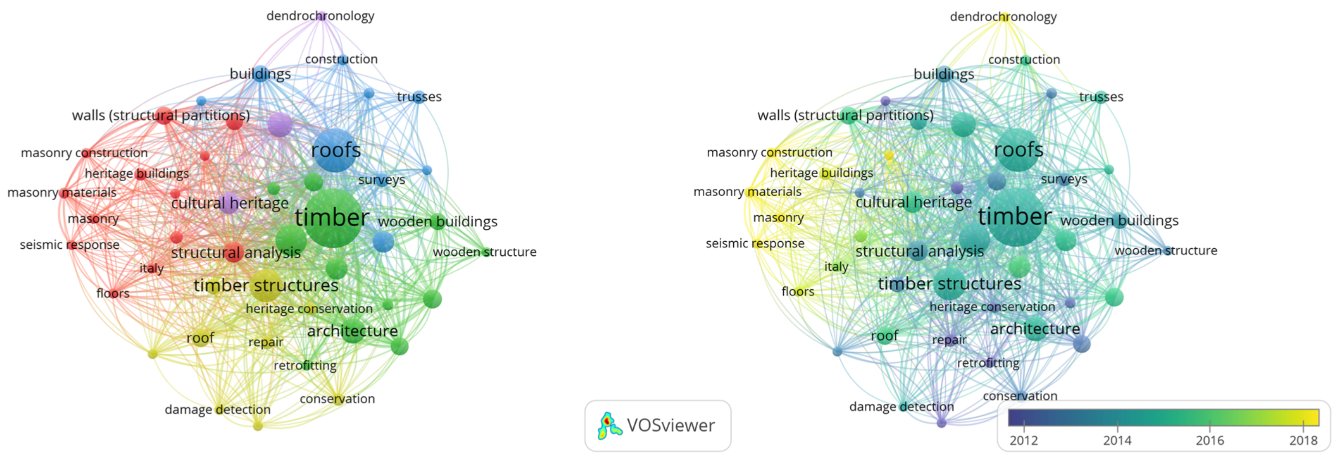
On the other hand, Equation (4) is used for the clustering:

$$d_{ij} = \begin{cases} 0, & x_i = x_j \\ 1/\delta, & x_i \neq x_j \end{cases} \tag{4}$$

with δ as a resolution parameter greater than zero. The higher the value of the parameter, the greater the resultant grouping is proportionally [19].

The mapping, carried out regarding the sustainability linked with timber roofs, selected 106 papers, grouped into five clusters with 46 items in all.

As shown in Figure 2a, five clusters are identified concerning dendrochronology (purple), which is significant for the mechanical strength of wood, modeling and analysis of masonry structures with timber roofs (red), restoration (yellow), survey (blue), and timber buildings (green). As shown in Figure 2b, the dendrochronology and analysis of masonry structures with timber roofs are the issues more studied and discussed in recent years.



(**a**) (**b**)

Figure 2. Maps of the keywords: (**a**) the five clusters of topics; (**b**) papers chronology.

From the literature, Italian case studies are rather limited, and only four of them concern the theme of sustainability. Overall, they focus on: the assessment and design of sustainable intervention, the criteria for deconstruction, the influence of temperature and humidity, biocomposites, and the wood panels with the oriented strand board (OSB) [20–23].

In the literature, there is only one paper on multi-criteria analyses for existing timber and it referred to an existing example from Chinese heritage; it combines analytical hierarchy process (AHP) with Grey theory [24,25].

As for the state-of-the-art process regarding sustainable interventions, the Green Building Council (GBC) has certainly allowed certain progress through the publication of manuals and certification methodologies [26]. The GBC protocol provides suggestions for the analysis of the following aspects: Historical Value VS; Site Sustainability SS; Water Management GA; Energy and Atmosphere EA; Materials and Resources MR; Internal Environmental Quality QI; Design Innovation IP.

3. Damages and Interventions on Historic Timber Roofs

In this section, the goal is to collect data about damages and interventions in Italy where there is no mapping because of private properties that illustrate the Italian heritage of timber roofs.

To this aim, a georeferenced GIS system was created, collecting data from the ISTAT [27] website and from the studies by Tampone [28], including damaged, analyzed, and monitored structures [29].

From the literature, 59 case studies were examined [3,30–33]. The available data have been statistically evaluated in order to highlight the main sources of damage (Figure 3) and the most affected structural elements (Figure 4).

For what concerns structural interventions, there is no database for an overall survey, at least in Italy. Nevertheless, there are three significant examples evaluated and certified according to GBC Historic Building protocol in Italy.

The first complex, in Figure 5a, is the Stables of the Benedictine Fortress of Sant'Apollinare in Perugia, where there was a rather degraded wooden roof with hollow clay flooring blocks.

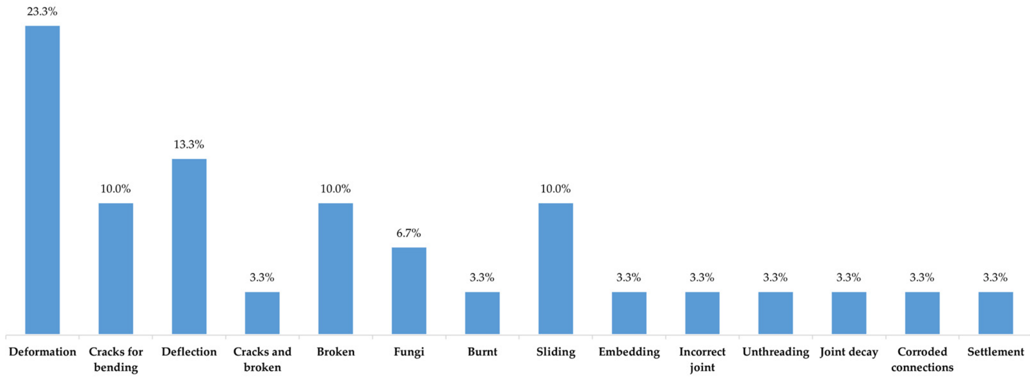


Figure 3. Distribution of damage, deformation, and breakage sources.

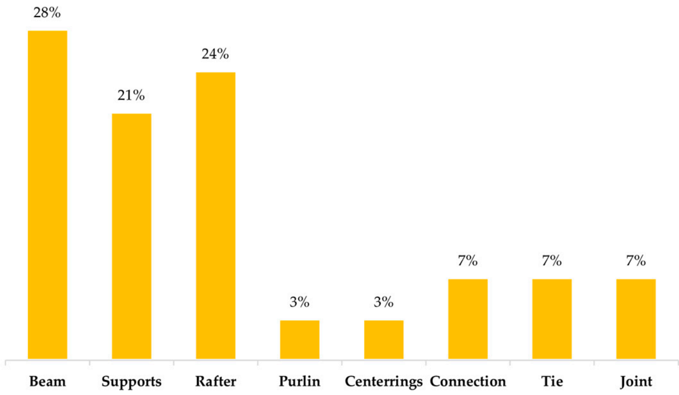


Figure 4. Distribution of affected structural elements.

(**a**) (**b**) (**c**)

Figure 5. (**a**) Scuderie della Rocca Benedettina di Sant'Apollinare in Perugia: replacement of the damaged wooden elements; (**b**) San Giuseppe dei Falegnami: new wooden roof after the collapse in 2018; (**c**) Palazzo Silvestri-Rivaldi: coating with external photovoltaic elements.

Here, energy efficiency has also been studied. Unfortunately, based on diagnostic investigations, it was decided to remove the wooden floor, but recycling the tile elements re-folded for the external flooring in the spirit of the circular economy provided by the recent European Action Plan [34]. The Benedictine complex of the XVII-XVIII sec. has obtained the gold certification thanks to seismic retrofitting.

The second example, in Figure 5b, is the wooden roof of the Church of San Giuseppe dei Falegnami in the historic center of Rome. The complex, whose restoration work was completed in 1884, suffered a partial collapse of the roof in 2018 due to unknown causes.

Most likely, the poor maintenance over the years has led to the weakening of connections, resulting in a loss of stability. The restoration involved the replacement of excessively damaged elements and the reuse of those that have preserved sufficient mechanical strength.

A third example, in Figure 5c, which is less significant but worthy of note, concerns the recovery project of Palazzo Silvestri-Rivaldi, the pilot application of the GBC Historic Building protocol in Rome in 2019. This adaptation is more aimed at energy efficiency connected to the building envelope rather than structural problems. However, the intervention on the perimeter coat and the covering is considered emblematic, where innovative brick elements have been inserted with an incorporated photovoltaic system, whose external appearance is consistent with the existing historical fabric.

In general, from this first bibliographical search, it has been noticed that not much research is carried out to understand how the diagnostics can avoid or prevent the total replacement of the structural elements. Nowadays, it is uncommon to consider structural restorations to avoid reconstruction and to preserve historical and cultural values. This is because diagnoses, monitoring, and potential reinforcement interventions are expensive. Cost-effectiveness is still one of the factors that is most frequently considered in an exclusive way.

In this context, the proposed methodology based on multi-criteria approaches that take into consideration more criteria of appraisal could return a more detailed scenario, including both sustainability and cultural value that such wooden elements cover inside the Italian architectural heritage.

4. Methodology

This study proposed a multi-criteria approach for choosing the most sustainable intervention for timber roof structures.

In the paper, the sustainability evaluation of various restoration alternatives used multi-criteria decision-making technique, which is not common in the restoration field.

Multi-Criteria Analysis is a method that has been used in a variety of fields since the second part of the last century. It is helpful to identify the best solution by selecting a goal to achieve, with the help of a few tools and software [35].

Four steps make up the process: the individualization of the aim, the selection of criteria and their hierarchical division, the evaluation of the options, and the final selection of one of them [36].

The fields of application are countless, but the most common are the medical and economic (which together with computer engineering cover 50% of publications with a total of over twenty thousand publications, followed by biochemistry, environmental science, and mathematics with 12%). Recently, multi-criteria analysis has been implemented in the field of engineering and architecture, where it is mainly used for the assessment of sustainability at the energy and economic levels [37].

The decision-making process is defined as Multi-Criteria Decision Analysis (MCDA) and is therefore based on analytical investigations that the so-called decision-maker (the one or ones who carry out such evaluations and who play an expert role) performs to solve complex problems [38].

There are countless types of analyses, but those that will be used here will concern a specific subset: an analysis based on the choice of multiple criteria (and not single-criteria) and multi-attribute decision-making (MADM), which includes a finite and predetermined number of alternatives to be considered and based on the pair comparison system (or pair-wise comparison). Reference is therefore being made to the AHP approach and the MIVES implementation [39,40].

Multi-criteria analyses are parametric evaluations where the role of the decision-maker is fundamental. The two methods chosen can be complementary and can be used in a combined way to define more specific values for the evaluation of alternatives. The AHP technique might be used on its own to do straightforward pair comparisons between different options (so the range of values is limited by ranking them as double, triple, half, or third, which is preferable to the other). The adoption of the MIVES approach enables a more precise and thorough quantification of the satisfaction percentage of each alternative.

The AHP is used to determine the hierarchy of evaluation criteria [41]. The MIVES is used to provide a quantitative evaluation for each criterion of the suggested alternatives [42].

A complex decision tree is planned, often branched as follows: the requirements (macro categories that incorporate broader themes, such as environmental, economic, social sustainability, etc.), then the criteria that lead the requirements into specific issues (carbon dioxide emissions, material consumption, etc.), and then the indicators that quantify the adopted criteria through measurable instruments (wood consumption, steel consumption, waste production, etc.).

By creating this hierarchy, it is possible to weigh the requirements, criteria, and indicators according to the AHP methodology and quantify the alternatives selected for each indicator with the MIVES.

This combined approach seeks to provide a sustainability index (SI) that can, in various contexts, return the most appropriate restoration intervention, as shown in Figure 6.

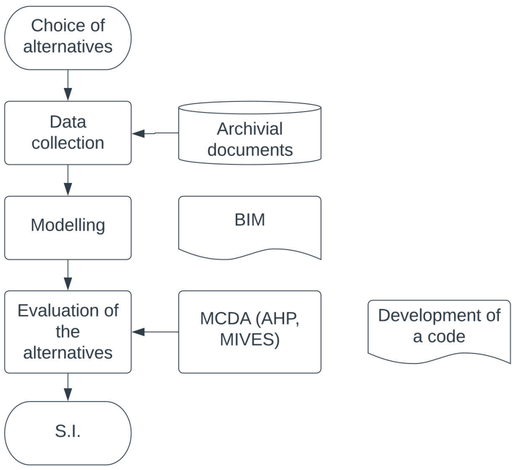


Figure 6. Flowchart with used methodology for the evaluations on the intervention alternatives.

To obtain these SI, some tools are used. To extrapolate all the information to run the analysis, modeling is developed in the Modeling HBIM environment, whose output data are processed by a tool developed in Python [43].

4.1. Analytical Hierarchy Process

The AHP methodology was proposed in 1970 by Saaty, and it is, to date, the most widely used MCDA methodology in every field. It is characterized by a tree structure of criteria aimed at achieving a common goal, using a matrix system to choose the best alternative. The only limitation is that it is difficult to obtain expert judgments in order to have reliable results and include a higher number of criteria, by which different solutions are assessed. The AHP can also be used alone; the only difference is that the alternatives evaluated are compared through judgments in pairs without quantifying an absolute value. For this reason, the MIVES approach has been combined to evaluate the different alternatives by giving each one a precise value. The AHP in this methodology remains to weigh the various criteria and succeeds in creating an evaluation hierarchy.

The first step in applying AHP is to split the problem into manageable ones using assessment criteria, making it easier to evaluate. Therefore, decision-makers must carefully assess and weigh the options, comparing criteria in pairs. The method, also compared to other methodologies, enables one to assign a numerical value to a judgment, producing reliable and consistent data.

Comparisons must be made for each decision branch after the tree and criteria have been built. The criteria are compared against one another in a matrix for each comparison.

The size of a matrix for pair comparisons is nxn, where n is the number of criteria being compared or the number of elements that make up the level of the hierarchy under consideration [44].

The matrix M in Equation (5) is constructed as follows, comparing criteria and establishing which is more relevant and by how much:

$$M = \begin{pmatrix} 1 & C_1/C_2 & C_1/C_3 \\ C_2/C_1 & 1 & C_2/C_3 \\ C_3/C_1 & C_3/C_2 & 1 \end{pmatrix} \quad (5)$$

where '1′ is equal to the ratio between the value of the criterion and the value of the same criterion.

This sample matrix should be used, making pair comparisons and establishing the hierarchy for each group of criteria.

It is sufficient to construct only half of the matrix in order to obtain the other half because the lower triangle appears to have reciprocal values.

Still, Saaty's model-scale is the one that is most frequently utilized today for judgment. The scale evaluates the relative importance of one choice over another by allocating values between 1 and 9, preferably utilizing odd numbers to increase the difference [45].

Judgments can be expressed in many ways, mostly qualitative due to the comparison to couples. The methodology could be used to compare alternatives if only AHP were to be used. Even numbers are mainly used as an intermediate judgment to find a meeting point between two decision-makers or between two values considered too distant.

Given an ordered pair of objects (C_i, C_j) of one level, the decision maker expresses a comparison judgment (C_{ij}) in Equation (6):

$$C_{ij} = \frac{1}{C_{ji}} \text{ with } C_{ii} = 1 \,, \ \ \forall i \quad (6)$$

At the end of the process, a weight w_i, shown in Equation (7), is given to each level, and the summatory of the weights must be 1, with an i value taken from 1 to n.

$$w_i = [w_1, \ldots, w_n] \ , \quad \sum_{i=1}^{n} w_i = 1 \quad (7)$$

It is necessary to verify the weights reported as percentages. It is important to validate the Consistency Ratio (CR), which is regarded as consistent if it is less than 0.10 when using the Saaty approach. This value is achieved by constructing the matrix eigenvector.

The CR is equal to the ratio between the Consistency Index (CI), obtained with the Equation (8), and the Ratio Index (RI).

$$CI = \frac{\lambda_{max} - n}{n - 1} \quad (8)$$

where λ_{max} represents the maximum eigenvalue.

In general, RI is a fixed number that depends on the number of criteria (n), as expressed in Table 1 [46].

Table 1. RI values with corresponding numbers of criteria.

n	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49

4.2. MIVES

Once the decision tree and weights have been processed, decision-makers must find the Value Function for each indicator in order to assign a value and a specific preference.

In order to reach the value, the incidence calculated using the AHP methodology must be multiplied by a value obtained from the MIVES [47].

The MIVES approach reaches the satisfaction value $V_{k_{j_i}}(x_{k_{j_i}}, {}_A)$, normalized by examining a Value Function (V_i) calculated in the assessed x, with respect to indicator i for each Alternative (A).

Therefore, the Value Function, which can be S-shaped, linear, concave, or convex, must be calculated for each considered Indicator. Other curve types (such as the parabola or the Gauss) can also be considered. The literature and decision-makers personal experiences indicate that monotony and the arrangement of functions are subjective.

Therefore, the first step in developing functions is to consider the following factors.

The reference Indicator x-values, called x_{min} and x_{max}, are fixed on the abscissa axis.

Instead, the highest and minimum approval values are entered into the y-axis and are always pairs of 1 and 0.

Given the function limit values (x_{min} and x_{max}), shape and monotony are therefore chosen based on discretionary factors by the opinion of the decision-maker.

Monotony is determined by a decision maker's choice, considering the existing curves in the literature that can help the decision, and his own experience, competence and skills. For instance, economic values are typically declining as carbon dioxide consumption because greater consumption corresponds to lesser satisfaction and vice versa. On the other hand, for instance, mechanical performance is a rising function [48].

It is thus reported the Value Function, identified with V_i, that is related to each indicator and serves to find the corresponding satisfaction value $(V_i(x_{i,\ A}))$, as in Equation (9), for each alternative, present on the y-axis, starting from the quantification value of each alternative (x), present on the x-axis:

$$V_{k_{j_i}} = A + B \cdot \left(1 - \mathrm{e}^{-k \cdot \left(\frac{|x_{i,\ A} - x_{min}|}{C}\right)^{P}}\right) \tag{9}$$

where B, in Equation (10), is the factor that allows the function to be kept within the range of values of 0 to 1, identified as follows:

$$B = \frac{1}{\left(1 - \mathrm{e}^{-k \cdot \left(\frac{|x_{max} - x_{min}|}{C}\right)}\right)} \tag{10}$$

where x_{min} is the minimum x-axis of the space within which interventions for the Indicator are carried out; $x_{i,A}$ is the quantification of the Indicator to be evaluated (different or not, for each intervention) related to the Alternative A; P is a form factor that defines whether the curve is concave, convex, linear, or "S"; concave curves are obtained for values of P < 1, convex shapes, and "S" shapes for P > 1 and almost straight lines for values of P = 1. In addition, P gives an approximation of the slope of the curve to the point of inflection; C approximates the x-axis of the inflection point; K approximates the ordinate of the inflection point. A is usually equal to zero. If it is not equal to zero, the function is translated according to y by a value equal to A [49]. All these data are summarized in Table 2.

Therefore, a summation that moves up the decision tree and combines the values of the MIVES functions with the weights produced by the AHP methodology is employed to reach the final value, *SI* (Equation (11)).

$$SI = \sum_{k=1}^{r} \alpha_k \sum_{j=1}^{c_k} \beta_{k_j} \sum_{i=1}^{n_{k_j}} \gamma_{k_{j_i}} \cdot V_{k_{j_i}}(x_{k_{j_i}}, {}_A) \tag{11}$$

where k = Requirement index; r = number of Requirements; j = Criterion index; c_k = number of Criteria of considered Requirement; i = Indicator index; n_{k_j} = number of Indicators of considered Criterion; α_k = Requirement weight; β_{k_j} = Criterion weight; $\gamma_{k_{j_i}}$ = Indicator weight; $V_{k_{j_i}}\left(x_{k_{j_i}}, {}_A\right)$ = satisfaction value expressed in percentage by examining a Value Function $V_{k_{j_i}}$ calculated in the assessed x with respect to Indicator i for each Alternative (A) [50].

Table 2. Increasing and decreasing function parameters.

Increasing Function	C	K	P
Linear	$C \approx X_{min}$	≈0	≈1
Convex	$X_{min} + ((X_{max} - X_{min})/2) < C < X_{min}$	<0.5	>1
Concave	$X_{min} < C < (X_{min} + (X_{max} - X_{min})/2)$	>0.5	<1
S-shaped	$X_{min} + ((X_{max} - X_{min})/5) < C < (X_{min} + 4(X_{max} - X_{min})/5)$	0.2/0.8	>1
Decreasing Function	**C**	**K**	**P**
Linear	$C \approx X_{min}$	≈0	≈1
Convex	$X_{max} < C < (X_{max} + (X_{min} - X_{max})/2)$	<0.5	>1
Concave	$X_{min} - ((X_{min} - X_{max})/2) < C < X_{min}$	>0.5	<1
S-shaped	$(X_{max} - 4(X_{max} - X_{min})/5) < C < X_{max} - ((X_{max} - X_{min})/5)$	0.2/0.8	>1

4.3. Modeling and Data Evaluation

To obtain the data to carry out the analysis, it is proposed the creation of the model through the HBIM environment.

The HBIM model was realized with parametric elements and the creation of new families. Otherwise, it would not have been possible to have the necessary data. The use of HBIM is more suitable for the design of new buildings rather than the restoration of existing buildings, so some simplifications have been made without the insertion of local damage. The digitization of damage and injuries for wood elements is currently not feasible in HBIM [51].

5. Case Study: The Cloister of Michelangelo in the Diocletian Baths

The Cloister of Michelangelo was erected in the XVI century inside the ruins of the Diocletian Baths in Rome together with the church of Santa Maria degli Angeli, which re-uses some of the great halls of the central body of the baths. In 1890, the cloister of Michel-angelo, the minor Ludovisi's cloister, and some of the great halls became the seat of the Museo Nazionale Romano, which nowadays hosts offices and exhibition space. It has a 360 meters perimeter and covers an area of 10,000 square meters.

Numerous restorations and structural interventions have been done in the cloister to rehabilitate and maintain severely deteriorated areas of the complex since the first years of the XX century.

As for timber roofs, the object of this paper, a number of interventions have been made throughout the years to replace, reinforce, or adapt the various elements. Although the original timber structure exact age is uncertain, it can be assumed that it dates back to 1910.

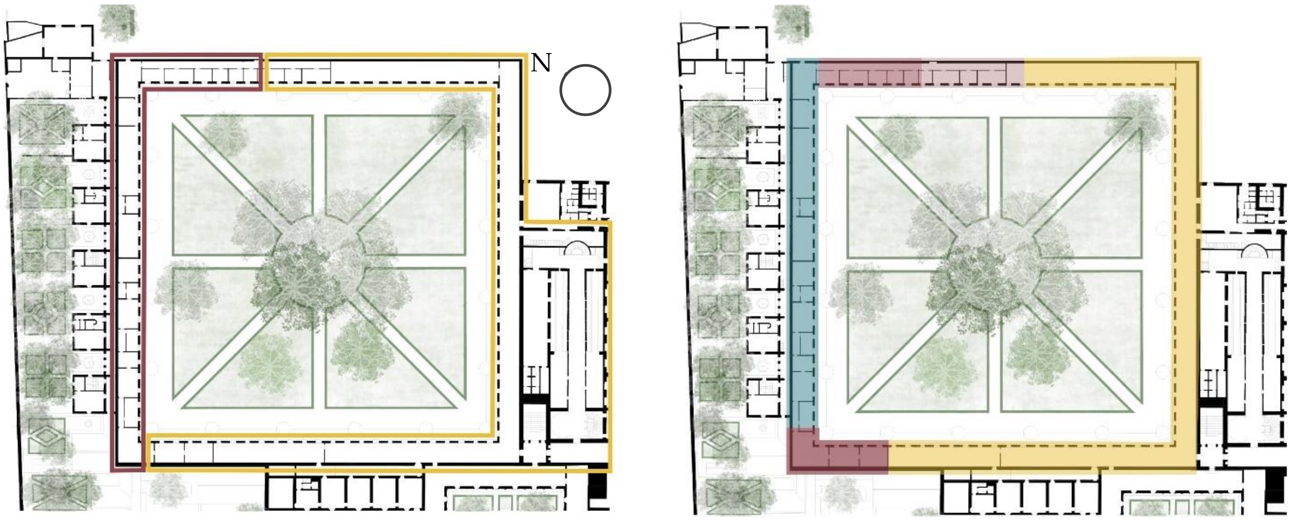
The office roof area is free from previous structural maintenance. In the museum, in the 1980s, interventions were carried out with braces and steel jacketing.

Recently, from 2014 to 2016, some bays of the roof were substituted with new chestnut wood elements; the initial on-site inspections for the first intervention were conducted in 2014 and were helpful in determining the general situation, the pre-existing conditions, and which beams had already been reinforced or replaced. As a result, some statistics have been conjectured due to the inability to conduct precise surveys.

The wooden supporting beams of seven spans were replaced in the west corner with the addition of new braced steel elements. No previous interventions were found.

After this first phase, also in the same period, it was continued with a first stretch of the NE wing of nine spans, extended subsequently. Given the general conditions, with insufficient sections and altered poorly monitored and maintained, it was decided to extend the same intervention by an additional eight spans.

Figure 7 offers a summary of these interventions.



(**a**) (**b**)

Figure 7. (**a**) Museum offices, in the upper floor (red), exhibition area (yellow); (**b**) The roof restorations, 2014–2015 (dark and light red); roofs with braces and steel jacketing (yellow); the original part, without intervention, except for some spans with braces (blue).

5.1. Alternatives of Intervention

Since the alternatives of intervention belong to several restorations carried out over the years, accurate technical information is lacking. Materials and structural properties, such as structural designs, are often unknown. In the authors' opinion, diagnostic investigations with local interventions would be more sustainable compared to invasive interventions due to limited confidence in the material. Four options (Figure 8) for different restoration interventions were therefore considered as follows:

(**a**) (**b**) (**c**) (**d**)

Figure 8. (**a**) A_1; (**b**) A_2; (**c**) A_3; (**d**) A_4.

Alternative 1 (A1): This uses a complete replacement of the wooden elements (two beams with section 26 × 26 × 573 cm and five purlins with section 20 × 16 × 280 cm, both in chestnut wood D24) with the consequent reconstruction of the roof and addition of braces in steel with braces (∅ 20) 510 cm long, tensioners, and anchors mounted on two C-beams of side support UPN 160. In this case, a pair of beams connected by such devices is analyzed;

Alternative 2 (A2): This uses a nondestructive test (NDT) to test the mechanical properties of timber, steel jacketing with four L-shaped retaining profiles (12 × 4 × 560 cm), and C-shaped steel connections welded in place;

Alternative 3 (A3): This uses NDT on timber and the insertion of two support beams below with 527 cm long and bolted L-profile, with the addition of braces in steel with braces (∅ 20) 510 cm long, tensioners, and anchors mounted on two C-beams UPN 160;

Alternative 4 (A4): This uses the NDT that involves the insertion of simple braces in steel with braces (∅ 20) of length 510 cm, tensioners, and anchorages mounted on two C-beams of side support UPN 160.

5.2. HBIM Modeling and Values

A structural HBIM model was built, shown in Figures 9 and 10, through the Autodesk Revit software, [52], as this methodology employed the seven dimensions of modeling (3D, cost, time, management, and sustainability) and allowed us to create a summary schedule that could be used to find the values needed to compare alternatives.

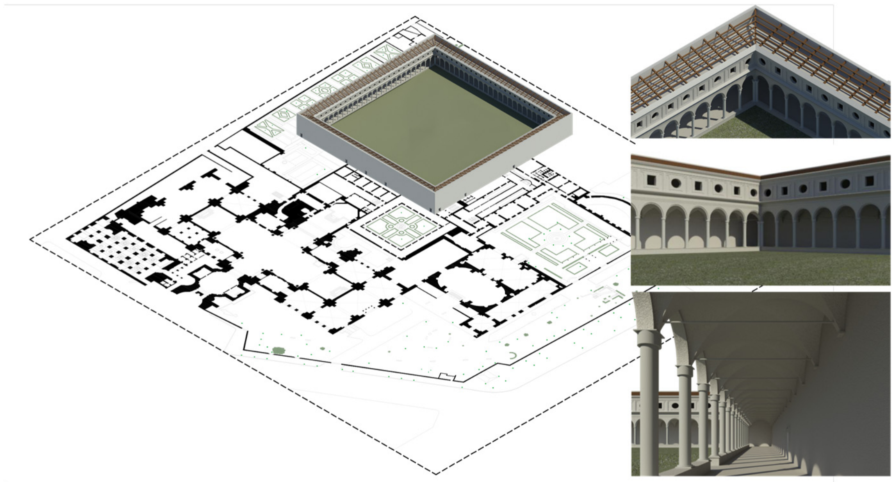


Figure 9. Model of the entire Cloister of Michelangelo realized with Autodesk Revit in HBIM technology.

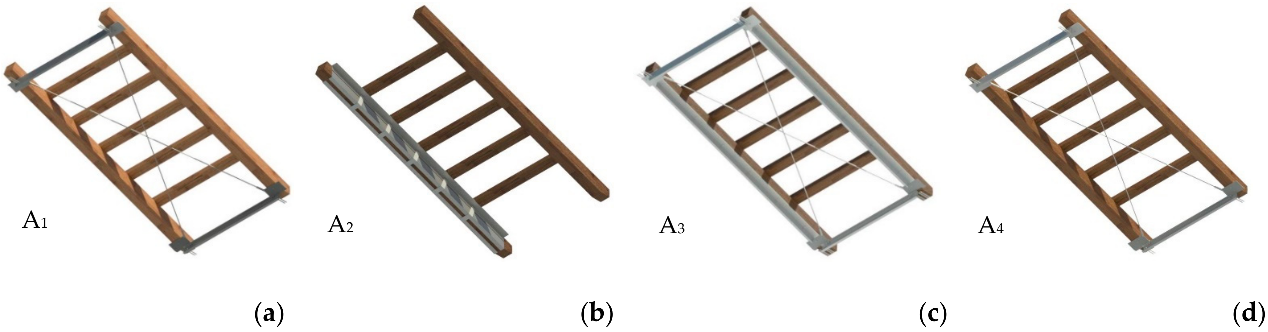


Figure 10. HBIM Modeling of (**a**) Alternative 1 with complete replacement of the wooden elements and the insertion of braces; (**b**) Alternative 2 with steel cladding with L-shaped retaining profiles welded in situ; (**c**) Alternative 3 with the insertion of two support beams below and braces; (**d**) Alternative 4 with insertion of simple braces.

Once the necessary data were obtained, it was possible to develop a structural construction model.

Then, the families of the elements were designed. Families with shared parameters were chosen to use so that it was possible to easily create the required schedule. After completing this first operation, the different interventions were modelled and placed. Each element was built according to UNI 11337 [53].

The Level of Details (LOD) geometry was equal to F and G depending on the elements since the degradation state was only partially done. Only the structure below the roof turned out to be an LOD D.

The alternatives to be analyzed, to find out the most sustainable intervention according to various aspects, were, therefore, the four presented: the complete replacement of the wooden element and the stiffening through the creation of steel bracing and a C-shaped beam connecting the bays inserted in the wall and used as a support to the bracing plate; the creation of a steel jacket with L-shaped profiles combined with each other and joined by support connectors; the use of a support beam with double steel L-profile to support the existing with the addition of braces in steel; and the use of only braces in steel, but always with C-beam inserted inside the wall.

The indices to be evaluated according to the decision tree are shown in Figure 11, where there are three fundamental Requirements for the assessment of sustainability (R_1 Environmental, R_2 Economic, R_3 Social), with the addition of a Requirement slightly investigated in the literature, R_4 Cultural/Structural. The addition of a combined Requirement was useful to define those parameters of cultural evaluation that also refer to structural functions but were typical of the theory of restoration for the approach to the historical heritage. In addition, the presence of codes or existing legislation was useful to evaluate the possibility of performing the interventions in a correct way.

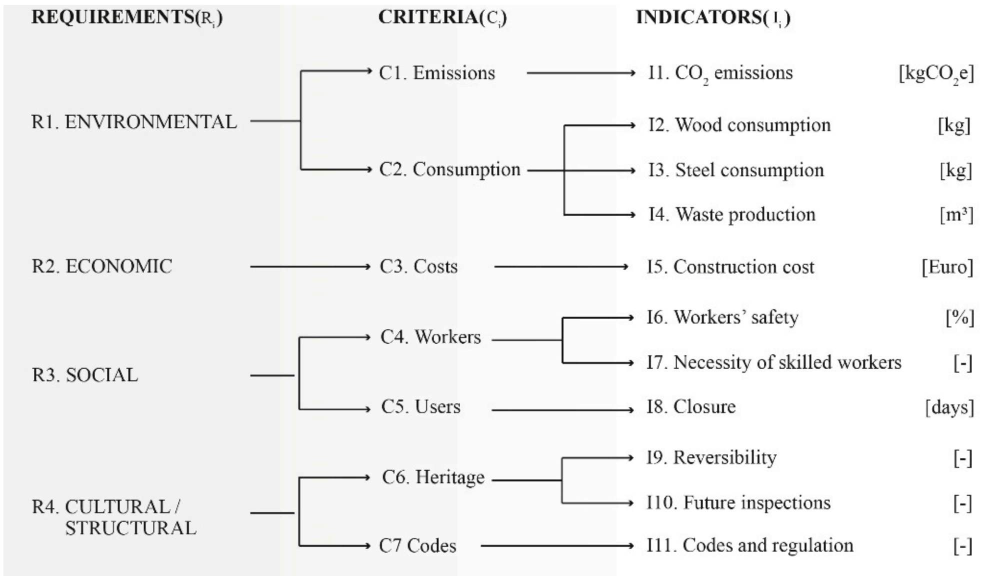


Figure 11. Decision tree.

The schedules were then extracted through HBIM modeling, which led to the construction of the following Table 3, with the indices and values for each alternative.

Emissions (I_1): The emissions in this analysis were related to the production and transport of the two main materials, chestnut wood and steel. To accomplish this, a task was considered, according to the standards ISO 14040 and ISO14044 [54,55], for the first four phases of the environmental product declaration (EPD). Then, the first four steps, Raw Materials, Transport, Manufacturing, and Transport, were analyzed. In essence, emissions were then counted "from cradle to gate", that is, from extraction to distribution locally.

Table 3. Values (V) of each alternative (A_1, A_2, A_3, A_4).

Indicators	Units	V_{A1}	V_{A2}	V_{A3}	V_{A4}
I_1. CO_2 emissions	[kg CO_2 eq]	1680	622	1152	602
I_2. Wood consumption	[kg]	3043	0	0	0
I_3. Steel consumption	[kg]	183	511	479	183
I_4. Waste production	[m^3]	1.3042	0.0128	0.0120	0.0046
I_5. Construction cost	[Euro]	59,253	3462	3079	1792
I_6. Workers' safety	[%]	0.30	0.25	0.27	0.26
I_7. Necessity of skilled workers	-	0	1	0.5	1
I_8. Closure	[days]	90	60	30	20
I_9. Reversibility	-	0	0.5	0.5	1
I_{10}. Future inspections	-	1	0	0.5	1
I_{11}. Codes and regulation	-	1	0.5	0	1

The transport from the headquarters to the construction-site must be added, which was counted in the document produced by the company. This transfer is regulated at the European level by the Association des Constructeurs Européens d'Automobiles (ACEA), which, since 2019, has been committed to the development of guidelines and software that can help such counting. VECTO [56] is an application that has already become mandatory for certain categories of heavy vehicles in 2019. This program provides the decision-maker with an absolute CO_2 emission value in grams in terms of the distance travelled in grams of emissions per kilometer and the load transported in grams per ton kilometer. The selected category falls into category 4 (truck carrying 16 tons or more), one of the first to be standardized along with categories 5, 9, and 10. Moreover, the category 4 with the acronym RD (Regional Delivery) must be identified, as it previewed mostly transportation from Tuscany to Lazio. The emission average, therefore, refers to a value of 198.1 [g/tkm]. The importance of this last added phase is because the heavy goods transport sector, within the transport sector (22.3% of total greenhouse gas emissions) covers 25% and 6% globally. Given the importance of these transports, the companies closest to the site have been chosen, which have made the EPD public and searchable for the necessary products.

Once the companies were identified through the quantities (in m, m^3, and kg as needed), the steel emissions were calculated, equal to 1033.10 [kgCO_2eq] per unit declared (tons) and wood, equal to 646 [kgCO_2eq] per cubic meter. It should be remembered that the extraction in the 4 phases is certainly considered the most relevant for emissions, which, for example, covers 71% for steel. The second, third, and fourth intervention (A_2-A_3-A_4) also includes emissions due to the journey from the laboratory to the construction site.

Consumption (I_2-I_3): As for material consumption, these are expressed in kg and are obtained from HBIM modeling, which guarantees a higher accuracy in the counting of the elements used. Having the volume, inserted as a shared parameter within the created families, the weight density was inserted through the modification of the properties of the material.

Waste (I_4): Waste is expressed in m^3 and is given by the material that has been substituted by the addition of the elements provided by the EPDs, divided into hazardous, non-hazardous, and radioactive waste. They were included because they are rarely taken into account, and, especially for large construction sites, they are a fundamental element to be considered. For the second, third, and fourth intervention (A_2, A_3, A_4), NDT waste was considered. In fact, some test apparatuses can deteriorate and require a replacement to maintain the reliability of the results.

Costs (I_5): The cost of interventions was considered using the "Prezziario (price list) della Regione Lazio per Opere Edili e Costi della sicurezza" [57]. The costs of the material, the workmanship, and the safety of the construction-site were added. The costs of the second, third, and fourth intervention (A_2, A_3, A_4) included the laboratory cost NDT investigations and technical staff. The list of prices for the first processing included the items of disassembly and reconstruction of the roof, so the price was higher than the other alternatives, where, instead, the incidence of the cost was mainly given by the metal profiles that were inserted and calculated per kg. The safety costs for the A_1, A_3, and A_4 were roughly the same; they differed from A_2 for the safety of welding work involving special equipment, such as shielding and masks.

Worker safety (I_6): The probability–damage matrix was used to verify the safety rate. This compares the probability of damage occurring to several activities and the damage they would cause. The values obtained are then multiplied by factors of reduction, based on training and information of workers. The risks considered in this case related to the work at the height and the possibility of inhaling dust (a factor that also weighed heavily in the calculation of safety costs).

Need for skilled workers (I_7): This index, like the following, was expressed with a binary code identified with 0 as absence or difficulty in finding and 1 as present or easy. An intermediate value was added to indicate difficulties, but not impossibilities, in order to have an alternative value. The need to find skilled workers is essential for restoration work that is difficult to achieve without the appropriate knowledge, skills, and know-how. The total renovation of a roof is certainly less complex than welding on site in a crawl space. These are all elements to consider, albeit with lower weights.

Closure (I_8): The closure is considered relevant in an area used as offices or museum, creating problems related to staff and visitors.

Reversibility (I_9): Reversibility and compatibility are the fundamental characteristics to be taken into account for a restoration of structures. As it is made of wood and steel elements, the second has always occurred, so it considered only the first. Reversibility provides a fundamental requirement for modern restorations, as it allows them to take a step back if deemed necessary. Moreover, the total substitution, insofar as is necessary in very serious cases, represents a loss in terms of material, historical value, and constructive tradition.

Future inspections (I_{10}): This field has been added based on the authors' experience, as often, during on-site inspections, conducting non-destructive monitoring, and diagnostics investigations, it is impossible to see the structural elements or their defects. The use of fire retardant covering paints, for example, leads to problems related to the poor visibility of surface defects, not allowing the inspection of nodes, lesions, or biotic attacks, making it impossible to do a visual inspection introduced by the technical norm UNI 11119:2004 [58]. The same goes for steel claddings that allow even less visibility for monitoring. Awareness of the state of the conservation is a fundamental requirement to be considered.

Codes and regulations (I_{11}): The presence of legislation is a fundamental element for the preparation of a restoration intervention through structural design. If there is no performance or prescriptive regulation, it is more complex to manage the design or maintenance of an intervention. Even the mere presence of guidelines is considered relevant. Substitution intervention (A_1) is nationally regulated by NTC2018, but there are also guidelines proposed by the Tuscany region that, for example, describe the fundamental characteristics of the material together with details of technology necessary for proper use. There is also a specific chapter on regulatory references; these guidelines provide design principles with indispensable tools for effective and safe design [59]. As for the other interventions, the cladding (A_2) can be made either in r.c. or in steel. Made of steel, they are poorly described by the Standard for the beams, but they are mainly used for reinforcements of structures in elevation. In Chapter C8.7.4.2.2, entitled "Steel cladding", it addresses the issue mainly by pointing out the increase in the shear strength of the pillars [60]. In addition, the third intervention (A_3) concerning the reinforcement beam has no normative references.

Other inventions (A_4), on the other hand, which have been amply regulated, concern the applications of steel bracing. First, the elements (bracing for structural consolidation) must be manufactured in accordance with the UNI EN 1090-1 [61] standard and must bear the CE marking, as required by the standard. This intervention is described in chapter C8.4.1 of the Circular 2019, where it is reported that "The restoration or reinforcement of existing links between individual components or between parts of them or the creation of new connections (for example between walls, between walls and beams or floors, including through the introduction of chains/tie rods, nails between wooden elements of a roof or a slab, between prefabricated components) fall into this category".

6. Analysis and Discussion

The multi-criteria analysis has been run in accordance with the decision tree after examining the values of each Indicator for the four Alternatives A_1, A_2, A_3, and A_4 (see Table 3). First, the four Requirements are taken into consideration separately (as if one need were given 100% of the importance and the other three 0%). This makes it feasible to identify the best options for each requirement and later conduct judgments considering each requirement with the appropriate weights (r). In this procedure, implemented in Python, it was chosen to combine MIVES, used for determining the satisfaction level, with the weights obtained through the AHP pair comparison. Finally, the sustainability index (SI) for each intervention alternatives are computed considering the 100% reference requirement.

6.1. Results

In order to compare SI with each other and establish the best alternative, in this work, it was chosen to apply a procedure that combines MIVES with the weights extracted from AHP (listed in Table 4 for Criteria and Table 5 for Indicators).

Table 4. Criteria weights (β) obtained with AHP.

C_1	C_2	C_3	C_4	C_5	C_6	C_7
0.50	0.50	1.00	0.75	0.25	0.75	0.25

Table 5. Indicator (γ) weights obtained with AHP.

I_1	I_2	I_3	I_4	I_5	I_6	I_7	I_8	I_9	I_{10}	I_{11}
1.00	0.22	0.67	0.11	1.00	0.83	0.17	1.00	0.67	0.33	1.00

The environmental Requirement (R_1) is met by satisfying the Criterion related to emissions (C_1) and consumption (C_2). The first corresponds only to emissions related to the entire life cycle (I_1) of all materials while the second Criterion refers to the consumption of wood (I_2) and steel (I_3) and to waste products (I_4). For each Indicator, the four corresponding values of the alternatives for that parameter are identified in Figure 12a–d and are inserted in the x-axis, then the corresponding satisfaction index between 0 and 1 is obtained (based on the function chosen and extreme values that change from Indicator to Indicator) on the y-axis.

C_1 and C_2 are compared by considering them with the same relevance. To obtain this, a 0.50 (β_1, β_2) reciprocal weight is decreed for each of the two Criteria.

In the literature, there are references to the weight of the criteria where consumption is worth half of the emissions. The authors referred to works where the values were both close to 0.50, or, in the presence of more criteria, to the equal value [62,63].

The second Indicator (I_2) was considered less important than the third one (I_3) because wood consumption is only present in A_1, so this disparity had to be counted, giving more importance to I_3. The evaluation of I_3 foresees a count of the waste produced, a factor to be taken into account, but less relevant than consumption.

The economic Requirement has only one Criterion (C_3) from which it can be satisfied, where all material and construction costs are computed. Indicator I_5 is linked to this Criterion (Figure 12e).

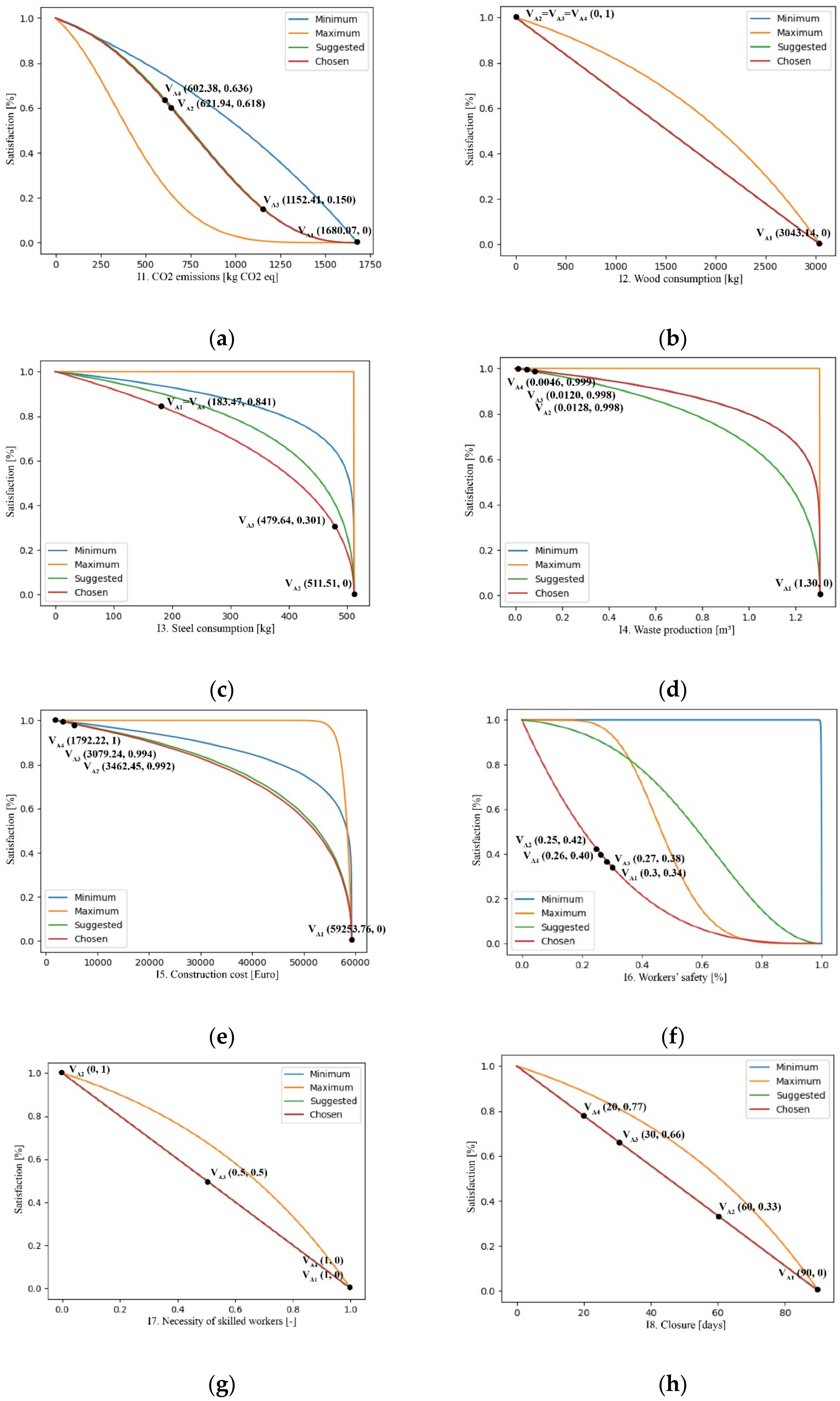
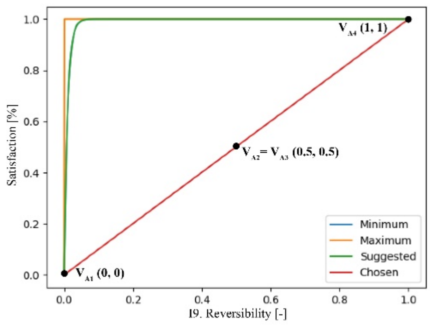
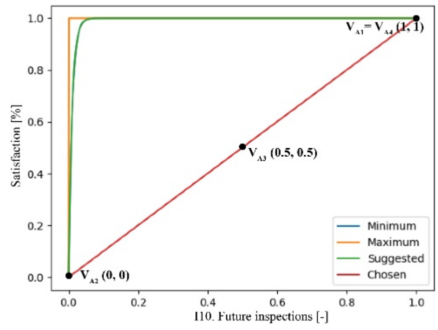


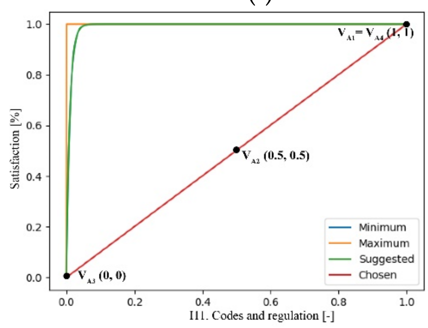
Figure 12. *Cont*.



(**i**)



(**j**)



(**k**)

Figure 12. Value functions for different criteria (**a**) I_1; (**b**) I_2; (**c**) I_3; (**d**) I_4; (**e**) I_5; (**f**) I_6; (**g**) I_7; (**h**) I_8; (**i**) I_9; (**j**) I_{10}; (**k**) I_{11}.

The third Requirement (R_3) is social, and it is met by satisfying the interests of workers (C_4) and users (C_5). The first deals exclusively with the workforce in terms of safety on site (I_6) and ease of availability (I_7). For users, the closure of the museum and the offices required for the work (I_8) is analyzed (Figure 12f–h).

C_4 was considered more relevant because it contains the safety of workers, which is considered fundamental for the social assessment, to the detriment of the closing days of the building.

The fourth Requirement (R_4) is met by satisfying the Criteria of cultural (C_6) and structural (C_7) analysis. The first Criterion includes speeches related to reversibility (I_9) and future inspections (I_{10}). The second, however, refers to the presence or not of current legislation (I_{11}) (Figure 12i–k).

The structural criterion is composed only of the parameter about the present of codes and Regulations, for this reason, although the fundamental was considered inferior to the possibility of reversibility and future inspections, which represent the major problems in the case of restoration since the criteria proposed by the authors have no known references in the literature.

To obtain the satisfaction of each alternative, value functions for each criterion are established with the following parameters: I_1 decreasing and s-shaped with p = 2.5, c = 850.0, and k = 0.5; for I_2 decreasing and linear with p = 1.0, c = 2043.14, and k = 0.01; for I_3 decreasing and concave with p = 0.5, c = 1000.0, and k = 0.75; for I_4 decreasing and concave with p = 0.2, c = 0.65, and k = 0.5; for I_5 decreasing and concave with p = 0.5, c = 20,000.0, and k = 0.75; for I_6 decreasing convex with p = 3.0, c = 120.0, and k = 0.5; for I_7 decreasing linear with p = 1.0, c = 1.0, and k = 0.01; for I_8 decreasing linear with p = 1.0, c = 90.0, and k = 0.01; for I_9 increasing linear with p = 1.0, c = 1.0, and k = 0.01; for I_{10} increasing linear with p = 1.0, c = 1.0, and k = 0.01; and for I_{11} with p = 1.0, c = 1.0, and k = 0.01.

6.2. Discussion

As seen in the previous paragraphs, each Requirement has been evaluated individually with the aim of finding the best alternative for each sector and, only then, the most suitable one combining all the Requirements.

From these first analyses, it has been possible to collect the following data highlighted in Tables 6 and 7, where the values of each alternative (that is, the liking obtained by the y-axis) for each Indicator multiplied by the weights of the decision tree are shown.

Table 6. Values weighed for each indicator.

	A_1	A_2	A_3	A_4
I_1. CO_2 emissions	0.00	0.31	0.07	0.32
I_2. Wood consumption	0.00	0.11	0.11	0.11
I_3. Steel consumption	0.28	0.00	0.10	0.28
I_4. Waste production	0.00	0.05	0.05	0.05
I_5. Construction cost	0	0.992	0.994	1
I_6. Workers' safety	0.21	0.26	0.24	0.25
I_7. Necessity of skilled workers	0.13	0	0.06	0
I_8. Closure	0	0.08	0.17	0.19
I_9. Reversibility	0	0.25	0.25	0.50
I_{10}. Future inspections	0.25	0	0.12	0.25
I_{11}. Codes and regulation	0.25	0.12	0	0.25

Table 7. Results for each Requirement.

	A_1	A_2	A_3	A_4
Environmental	0.28	0.47	0.34	0.76
Economical	0	0.99	0.99	1.00
Social	0.34	0.35	0.47	0.45
Cultural/Structural	0.50	0.38	0.37	1.00

These values were then added to have the final SI and the assessment of sustainability.

The interesting part is going to analyze in detail what the differences are between the complete substitution and the diagnostics including small local interventions. Seeing the strengths and weaknesses of each alternative returns a complete picture of sustainability in this case study.

The environmental analysis has revealed a fairly obvious fact. Less material is used, resulting in decreased consumption, waste production, transportation, and emissions. The authors consider how structural optimization can result in less pollution and less carbon dioxide consumption in light of this evidence, which is frequently taken for granted. When considering the significance of ongoing maintenance and diagnostics, this concept is not immediately apparent.

It is important to remember that these two components are frequently missing and that doing so can have negative effects on the ecosystem.

The fourth alternative is considered the preferable while the complete replacement is the less convenient. More interesting is to see the preference of the steel jacket rather than the insertion of a support beam. The detachment of the two SI, although short, is indicative of a preference not found in the literature.

The economic analysis confirmed the previous assessment. In fact, it is important to note that, in spite of what is usually thought, the economic interest can coincide with environmental sustainability. Consciously designed and regularly performed diagnostics can ensure structural safety, saving in greenhouse gas emissions and economic benefits. This is certainly the result that should be analyzed and understood more to ensure that such interventions can have wider diffusion at the expense of entire replacements (always providing structural safety).

The social aspect is a parameter that shows less dispersed results compared to other evaluations. The most suitable alternative is the third one. The restoration is quick to perform and does not involve specialized workers. The safety of workers shows little dispersed values.

As for the structural and cultural factor, there is no doubt about the best alternative with a big difference compared to the others. This demonstrates a superiority with regard to the presence of legislation that regulates it, the reversibility of the intervention, and the possibility of future inspections. The intervention is certainly regulated and suitable from the point of view of restoration and conservation, keeping in mind the safety of the structure.

The alternative that is most suitable in several fields is, therefore, the fourth. However, to have a definitive test, it is definitely necessary to weigh the Requirements, so as to have a general vision. As a result, four distinct scenarios with various weights were created with the intention of determining, with the least amount of analysis, whether changing the weights also changes the outcome. The following table evaluates the scenarios with the corresponding Requirements weights.

In order to analyze the change in the output with considerable weight changes, it was decided to develop, for each of the scenarios, a Requirement that was half (0.50) of the entire value and three times higher than any other Requirement (0.16). Then, the results have been obtained for each alternative. In the first scenario, the environmental Requirement weighs 0.50, in the second the economic, in the third the social, and in the last the cultural/structural.

The results have therefore been drawn up for each alternative (Table 8).

Table 8. Finale SI with Requirements weights.

	A_1	A_2	A_3	A_4
Scenario 1	0.27	0.52	0.47	0.79
Scenario 2	0.18	0.69	0.69	0.87
Scenario 3	0.30	0.48	0.52	0.68
Scenario 4	0.35	0.48	0.49	0.86

The study has demonstrated that the best alternative is still the fourth, even with different weights for the requirements. The alternatives are largely the same, and the comparisons are consistent. To properly illustrate the changes, considerations were made by maintaining some variables while changing others. The second, which is nearly identical to the third, is a possible alternative. This demonstrates the accuracy with which the evaluations were conducted and the matrices produced.

In order to execute this effort, the alternatives were examined individually before assuming four possible weight combinations for the Requirements. Through matrix inquiry, this analysis may be further examined as a future development.

The weights were changed to provide a broad and impersonal perspective because the study had to be conducted with a constrained number of decision-making specialists. To make weighted decisions and judgements in their areas of expertise, large groups of decision-makers and experts are typically assembled, which ought to be commonplace. In fact, the weights' volatility has shown that more analysis is required to determine whether the results are reliable. These findings highlight the value of diagnosis and possible localized small-scale interventions.

7. Conclusions

The protection of cultural heritage is an interdisciplinary undertaking where the knowledge, skills, and experience of earthquake and structural engineers assisted by architects, art historians, and material scientists are required.

Structural maintenance involves sophisticated and specialized competences and necessarily includes a preventive diagnosis to reduce the demolition and reconstruction of the built heritage in favor of sustainable conservation.

In this paper, a procedure has been proposed to evaluate the sustainability of the intervention, including the effort of diagnosis. The case study is the timber roof of the Michelangelo Cloister in Rome (Italy) with evaluation of the interventions from the environmental, economic, structural, and social points of view in a heritage framework.

Accurate geometric modeling in the HBIM environment has made it possible to obtain the quantitative elements necessary to apply the MIVES method.

The expert judgment of the research team made it possible to obtain the weights to be attributed to the various aspects of the procedure, such as Requirements, Criteria, and Indicators, according to the AHP method.

The multiple scenarios examined have tried to highlight how the variation of the weights, based on subjective judgment, can alter the final SI.

Even with varied weights for the requirements, the analysis has shown that the intervention with the insertion of simple braces is still the best choice. Other comparisons are essentially equivalent. Another option is the steel jacketing, which is essentially identical to the support beam.

A further development of the research should consider the interaction of the aspects more properly related to conservation and those related to structural safety. For conservation issues, it would be a question of investigating the weight to be attributed to reversibility, as well as to the criterion of minimum intervention. As far as structural safety is concerned, the weights to be attributed to the results of the diagnosis, to scheduled maintenance, and to the oversized requests of the customer should be evaluated.

This methodology enables the creation of a quantified and comparable sustainability index, which is dependent on the decision maker's judgment (and thus not absolute), but which is nonetheless useful to comprehend the sustainability of the proposed interventions. The case study is very simple, but the proposed methodology can be applied to more complex situations.

Author Contributions: HBIM, MCDM and MIVES processing, V.B.; conceptualization of the paper and scientific direction of the work S.S.; supervision and validation C.B. All authors have contributed to the writing and reviewing. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Riggio, M.; Dilmaghani, M. Structural health monitoring of timber buildings: A literature survey. *Build. Res. Inf.* **2020**, *48*, 817–837. [CrossRef]
2. Tampone, G. *Il Restauro delle Strutture di Legno, il Legname da Costruzione: Le Strutture Lignee e il Loro Studio il Restauro Tecniche di Esecuzione del Restauro*, 1st ed.; Hoepli: Milan, Italy, 1996.
3. Bertolini Cestari, C.; Marzi, T. Conservation of historic timber roof structures of Italian architectural heritage: Diagnosis, assessment, and intervention. *Int. J. Archit. Herit.* **2018**, *12*, 632–665. [CrossRef]
4. UNESCO. World Heritage List Statistics. Available online: https://whc.unesco.org/en/list/stat/ (accessed on 28 August 2022).
5. UNESCO. World Heritage Interactive Map. Available online: https://whc.unesco.org/en/interactive-map/?search= (accessed on 28 August 2022).
6. Istat. Available online: https://www.istat.it/ (accessed on 28 August 2022).
7. Holický, M.; Sýkora, M. Structural assessment of heritage buildings. *WIT Trans. Built Environ.* **2012**, *123*, 69–80. [CrossRef]
8. Santini, S.; Baggio, C.; Sguerri, L. Sustainable Interventions: Conservation of Old Timber Roof of Michelangelo's Cloister in Diocletian's Baths. *Int. J. Archit. Herit.* **2021**. [CrossRef]

9. *ISO 2394:2015*; General Principles on Reliability for Structures. ISO: Geneva, Switzerland, 2015.
10. *ISO 13822:2010*; Bases for Design of Structures—Assessment of Existing Structures. ISO: Geneva, Switzerland, 2010.
11. Sýkora, M.; Holický, M.; Jung, K.; Kvaal, K.; Thiis, T. Optimum Target Reliability Levels for Industrial Heritage Structures. In Proceedings of the European Safety and Reliability ESREL, Rhodes, Greece, 5–9 September 2010.
12. Hájek, P.; Fiala, C.J.; Jensen, B.; Láníková, I. *Integrated Life Cycle Assessment of Concrete Structures*; State of Art Report; FIB Bulletin no. 71; International Federation for Structural Concrete (FIB): Lausanne, Switzerland, 2013; 64p, ISBN 978-2-88394-111-3.
13. Thakkar, J.J. *Multi-Criteria Decision Making. Studies in Systems, Decision and Control*, 1st ed.; Springer: Singapore, 2021; 336p. [CrossRef]
14. Boix-Cots, D.; Pardo-Bosch, F.; Blanco, A.; Aguado, A.; Pujadas, P. A systematic review on MIVES: A sustainability oriented multi criteria decision making method. *Build. Environ.* **2022**, *223*, 109515. [CrossRef]
15. White, H.D.; Griffith, B.C. A literature measure of intellectual structure. *J. Am. Soc. Inf. Sci.* **1981**, *32*, 163–171. [CrossRef]
16. Klavans, R.; Boyack, K.W. Quantitative evaluation of large maps of science. *Scientometrics* **2006**, *68*, 475–499. [CrossRef]
17. Osinska, V.; Bala, P. Study of Dynamics of Structured Knowledge: Qualitative Analysis of Different Mapping Approaches. *J. Inf. Sci.* **2015**, *41*, 197–208. [CrossRef]
18. *VOS Viewer*, version 1.6.18; 24 January 2022. Available online: https://www.vosviewer.com/ (accessed on 28 August 2022).
19. Waltman, L.; van Eck, N.J.; Noyons, E.C.M. A Unified Approach to Mapping and Clustering of Bibliometric Networks. *J. Informetr.* **2010**, *4*, 629–635. [CrossRef]
20. Bertolini-Cestari, C.; Brino, G.; Cestari, L.; Crivellaro, A.; Marzi, T.; Pignatelli, O.; Rolla, S.; Violante, A. The Great Timber Roof of Porta Nuova Railway Station in Turin: The Role of Assessment and Diagnosis for Sustainable Repair and Conservation. *Int. J. Archit. Herit.* **2019**, *13*, 172–1912. [CrossRef]
21. Leso, L.; Conti, L.; Rossi, G.; Barbari, M. Criteria of design for deconstruction applied to dairy cows housing: A case study in Italy. *Agron. Res.* **2018**, *16*, 794–805. [CrossRef]
22. Valluzzi, M.R.; Nardon, F.; Garbin, E.; Panizza, M. Moisture and temperature influence on biocomposites to timber bonding. *Adv. Mater. Res.* **2013**, *778*, 561–568. [CrossRef]
23. Cont, M.; Cantone, M.; Torresani, S. The new Arpa research centre in Ferrara: Composite wood panels in non-conventional timber structures. In Proceedings of the 11th World Conference on Timber Engineering 2010, WCTE, Trentino, Italy, 20–24 June 2010; Volume 2, pp. 1786–1791.
24. Guo, X.; Fu, T.; Xu, S. Safety Assessment of Timber Ancient Buildings Based on Gray Clustering Analytical Method. *Beijing Gongye Daxue Xuebao/J. Beijing Univ. Technol.* **2017**, *43*, 780–785.
25. Deng, J.L. Introduction to grey system theory. *J. Grey Syst.* **1989**, *1*, 1–24.
26. GBC Italia. Recmagazine_Restauro e Sostenibilità. Available online: https://www.recmagazine.it/sostenitore/gbcgreen-building-council-italia.html (accessed on 28 August 2022).
27. Istat. Archivio. Available online: https://www.istat.it/it/archivio/222527 (accessed on 28 August 2022).
28. Tampone, G. *Atlante dei Dissesti delle Strutture Lignee-Atlas of the Failures of Timber Structures Parte Prima*, 1st ed.; Nardini: Florence, Italy, 2016; 200p.
29. Betti, M.; Galano, L.; Lourenço, P.B. Territorial seismic risk assessment of a sample of 13 masonry churches in Tuscany (Italy) through simplified indexes. *Eng. Struct.* **2021**, *235*, 111479. [CrossRef]
30. Marzo, A.; Marghella, G.; Indirli, M. The Ancient Timber Roofing Structures in Emilia-Romagna Region. *Adv. Mater. Res.* **2013**, *778*, 968–975. [CrossRef]
31. Bertolini Cestari, C.; Biglione, G.; Cestari, L.; Corradino, G.; Crivellaro, A.; Luca, D.; Marzi, T.; Panosch, P.; Pasquino, R. Restoration of historic timber structures: The great roof structures of the Cathedral of Vercelli. In Proceedings of the 11th World Conference on Timber Engineering 2010, WCTE, Trentino, Italy, 20–24 June 2010. [CrossRef]
32. Bernabei, M.; Marchese, F. Analyzing the medieval roof of the San Francesco's church in Prato (Italy): A dendrochronological interpretation. *J. Cult. Herit.* **2022**, *54*, 103–107. [CrossRef]
33. Aloisio, A.; Battista, L.D.; Alaggio, R.; Antonacci, E.; Fragiacomo, M. Assessment of structural interventions using Bayesian updating and subspace-based fault detection methods: The case study of S. Maria di Collemaggio basilica, L'Aquila, Italy. *Infrastruct. Eng.* **2021**, *17*, 141–155. [CrossRef]
34. Parlamento Europeo. Piano D'azione per L'economia Circolare. Available online: https://www.europarl.europa.eu/doceo/document/TA-9-2021-0040_IT.html (accessed on 28 August 2022).
35. Nadkarni, R.R.; Puthuvayi, B.A. Comprehensive Literature Review of Multi Criteria Decision Making Methods in Heritage Buildings. *J. Build. Eng.* **2020**, *32*, 101814. [CrossRef]
36. Yu, P.L. *Multiple-Criteria Decision Making: Concepts, Techniques, and Extensions*; Springer Science & Business Media: New York, NY, USA, 2013; 402p.
37. Vaidya, O.S.; Kumar, S. Analytic Hierarchy Process: An Overview of Applications. *Eur. J. Oper. Res.* **2006**, *169*, 1–29. [CrossRef]
38. Great Britain; Department for Communities and Local Government. *Multi-Criteria Analysis: A Manual*; Communities and Local Government: Wetherby, UK, 2009.
39. Saaty, T.L. The Analytic Hierarchy Process: Decision Making in Complex Environments. In *Quantitative Assessment in Arms Control*; Springer: Boston, MA, USA, 1984. [CrossRef]

40. Alarcon, B.; Aguado, A.; Manga, R.; Josa, A.A. Value Function for Assessing Sustainability: Application to Industrial Buildings. *Sustainability* **2011**, *3*, 35–50. [CrossRef]
41. Skibniewski, M.J.; Chao, L.C. Evaluation of advanced construction technology with ahp method. *J. Constr. Eng. Manag.* **1992**, *118*, 577–593. [CrossRef]
42. Gilani, G.; Hosseini, S.M.A.; Pons-Valladares, O.; de la Fuente, A. An enhanced multi-criteria decision-making approach oriented to sustainability analysis of building facades: A case study of Barcelona. *J. Build. Eng.* **2022**, *54*, 104630. [CrossRef]
43. *Python*, version 3.11.0b5; July 2022. Available online: https://www.python.org/ (accessed on 28 August 2022).
44. Kulkarni, A.J. *Multiple Criteria Decision Making: Techniques, Analysis and Applications*; Springer Nature, Studies in systems, decision and control; Springer: Singapore, 2022; Volume 407. [CrossRef]
45. Saaty, T.L. Relative Measurement and Its Generalization in Decision Making Why Pairwise Comparisons are Central in Mathematics for the Measurement of Intangible Factors. The Analytic Hierarchy/Network Process. *Rev. R. Acad. Cien. Ser. A Mat.* **2008**, *102*, 251–318. [CrossRef]
46. Franek, J.; Kresta, A. Judgment scale and consistency measure in AHP. *Procedia Econ. Financ.* **2014**, *12*, 164–173. [CrossRef]
47. Pons, O.; de la Fuente, A.; Aguado, A. The Use of MIVES as a Sustainability Assessment MCDM Method for Architecture and Civil Engineering Applications. *Sustainability* **2016**, *8*, 460. [CrossRef]
48. Santiago, I.P.; Arrieta, L.G.; Lombera, J.T.S.-J. Metodología Para la Priorización de Estructuras Degradadas. *Hormigón y Acero* **2017**, *68*, 11.
49. UPC Manual Mives Modelo Integrado de Valor para Evaluaciones Sostenibles. Available online: https://upcommons.upc.edu/handle/2117/9704 (accessed on 28 August 2022).
50. Hosseini, S.M.A.; Ghalambordezfooly, R.; de la Fuente, A. Sustainability Model to Select Optimal Site Location for Temporary Housing Units: Combining GIS and the MIVES–Knapsack Model. *Sustainability* **2022**, *14*, 4453. [CrossRef]
51. Santini, S.; Borghese, V.; Micheli, M.; Orellana Paz, E. Sustainable Recovery of Architectural Heritage: The Experience of a Worksite School in San Salvador. *Sustainability* **2022**, *14*, 608. [CrossRef]
52. *Revit*, version 2022; April 2021. Available online: https://www.autodesk.it/products/revit/ (accessed on 28 August 2022).
53. *UNI 11337-1:2017*; Edilizia e Opere di Ingegneria Civile—Gestione Digitale dei Processi Informativi delle Costruzioni. UNI: Milano, Italy, 2017.
54. *ISO 14040:2006/AMD 1:2020*; Environmental Management—Life Cycle Assessment—Principles and Framework—Amendment 1. ISO: Geneva, Switzerland, 2020.
55. *ISO 14044:2006/AMD 2:2020*; Environmental Management—Life Cycle Assessment—Requirements and Guidelines—Amendment 2. ISO: Geneva, Switzerland, 2020.
56. *VECTO*, version v3.3.11.2675; 1 January 2019. Available online: https://climate.ec.europa.eu/eu-action/transport-emissions/road-transport-reducing-co2-emissions-vehicles/vehicle-energy-consumption-calculation-tool-vecto_en (accessed on 28 August 2022).
57. Regione Lazio. Tariffa dei Prezzi (Lavori Pubblici). Available online: https://www.regione.lazio.it/cittadini/lavori-pubblici-infrastrutture/tariffa-prezzi-lavori-pubblici (accessed on 28 August 2022).
58. *NI 11119:2004*; Beni Culturali—Manufatti Lignei—Strutture Portanti Degli Edifici—Ispezione In Situ per la Diagnosi Degli Dlementi in Opera. UNI: Milano, Italy, 2004.
59. *Linee Guida per L'edilizia in Legno in Toscana*; Tuscany Region: Florence, Italy, 2008.
60. Istruzioni per L'applicazione Dell'«Aggiornamento delle "Norme Tecniche per le Costruzioni"» di cui al Decreto Ministeriale 17 Gennaio 2018; CIRCOLARE 21 gennaio 2019, n. 7 C.S.LL.PP. 2018. Available online: https://www.gazzettaufficiale.it/eli/id/2019/02/11/19A00855/sg (accessed on 21 December 2022).
61. *BS EN 1090-1:2009*; Execution of Steel Structures and Aluminum Structures Requirements for Conformity Assessment of Structural Components. The British Standards Institute: Milano, Italy, 2009.
62. Pons, O.; Casanovas-Rubio, M.M.; Armengou, J.; De La Fuente, A. Sustainability-Driven Decision-Making Model: Case Study of Fiber-Reinforced Concrete Foundation Piles. *J. Constr. Eng. Manag.* **2021**, *147*, 10. [CrossRef]
63. Sadrolodabaee, S.M.P.; Hosseini, A.; Claramunt, J.; Ardanuy, M.; Haurie, L.; Lacasta, A.M.; de la Fuente, A. Experimental characterization of comfort performance parameters and multi-criteria sustainability assessment of recycled textile-reinforced cement facade cladding. *J. Clean. Prod.* **2022**, *356*, 131900. [CrossRef]