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An AHP-Based Methodology for the Evaluation and Choice of Integrated Interventions on Historic Buildings

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Abstract: Historic buildings are at the center of cultural and economic interests, due to issues related to their conservation and protection as well as their use and technical-performance efficiency. They are often considered within the accepted meaning of 'assets-resource'. In recent years, there has been a significant increase in the research and development of methodologies to appropriately intervene on this type of heritage assets. This contribution defines a methodology to select interventions capable of combining protection requirements with performance upgrading, as part of integrated seismic improvement and energy-environmental retrofit strategies. The aim is to develop a tool that not only supports Public Administrations in the planning/designing of appropriate interventions but also private investors in a partnership perspective. Given the need to use a multidisciplinary and multi-criteria approach, the AHP (Analytic Hierarchy Process) method has been used; it allows for the comparison of various intervention alternatives on the basis of certain evaluation criteria, aimed at obtaining a preference index. This approach allows us to support the decision-maker in making the most appropriate choice, according to a rationally structured procedure.

Keywords: historic buildings; AHP-based methodology; integrated interventions; preservation; adaptation

1. Introduction

Historic buildings occupy a substantial part of built heritage. The need to preserve these buildings is primarily linked to the important material and immaterial values they have; in other words, the need for preservation is liked to the peculiar nature of goods belonging to the field of cultural heritage. Moreover, as recognized by various international organizations and institutions, they can play a central role in achieving a sustainable development objectives in an international scenario characterized by socio-economic disparities, urban transformation and climate changes. The United Nations Educational, Scientific and Cultural Organization (UNESCO), in a specific document [1] titled "Recommendations on the Historic Urban Landscape", stressed the need to promote the protection, preservation, conservation and enhancement of the historical urban landscape, intended as the historical stratification of cultural and natural values and attributes, while taking into account the related social and economic processes. The International Council on Monuments and Sites (ICOMOS) has recently presented a report, "The Future of Our Pasts", in which, through a multidisciplinary approach, it highlighted how cultural heritage, on the one hand, is subject to the negative impacts of climate change; on the other, it can become a resource in the development of mitigation strategies and can strengthen the resilience of communities [2].

The European Commission (EC) with the Horizon 2020 program strongly encouraged research and innovation in the field of cultural heritage to which it has recognized an intrinsic and social value [3]. In addition, the Commission set up a specific task force [4] to develop circular economy models for the adaptive reuse of cultural heritage and to examine the potential role that heritage buildings can play in improving environmental sustainability and urban regeneration [5].

It should also be noted that in recent decades, in the international scientific debate, alongside the concept of the cultural value of historic buildings, there has been a growing interest in the concept of economic value, intended both as the ability to produce income as well as to generate economic benefits for the community [6–8].

In light of the above, appropriate analysis methodologies and intervention strategies are needed to enable the recovery and conservation of this heritage, preserving its identity and value (through an appropriate and compatible reuse, it is possible to obtain significant environmental, social and economic benefits).

In the reuse project, generally, there is a first phase of choosing of the new uses and verifying the compatibility with the building, followed by a subsequent phase of defining the necessary adaptations. Both phases present considerable complexity, since there are numerous aspects involved. As far as the compatibility of the new uses is concerned, it is necessary to consider the regulatory constraints, the morphological-dimensional characteristics of an existing building (plan configuration, usable areas, internal heights, dimensions and distribution of the rooms, vertical connection cores), the historical-architectural characteristics, the availability of external spaces and accessibility to the building, etc. In current literature, several authors have proposed models for assessing the compatibility of new uses [9–14].

This paper examines the main factors to be considered when choosing the interventions to which these valuable buildings must be subjected for the best use and, at the same time, that ensure their preservation. This is a complex decision since, once the most compatible uses have been defined, the upgrading interventions must satisfy various requirements: functional upgrading, improvement of structural safety, energy-environmental sustainability, economic-financial sustainability and preservation of historical-architectural features. Regarding this last aspect, even if the debate on the theories of architectural restoration is ongoing, over time the general intervention criteria have been defined and are now commonly shared, including *compatibility*, *reversibility*, *distinctiveness* and *minimum intervention* [15].

In order to support complex decision-making processes, where the contextual assessment of many aspects is required, the use of multicriteria analysis is very useful. Several methods of multi criteria analysis have been proposed in current literature and applied in various fields [16]. These methods make it possible to compare alternative solutions to a decision-making problem on the basis of a set of suitably selected evaluation criteria. A multi-criteria approach for the choice between the recovery or demolition/reconstruction of an existing building, excluding historic buildings, was proposed by the authors in a previous study [17]. In the case of historic buildings, it is necessary to define specific evaluation criteria further in order to be able to combine the needs of preservation with those of the sustainable upgrading of a historic building. In Section 3, there is discussion of an extensive revision of current literature that was carried out with reference to the application of multi-criteria analysis to historic buildings. From this analysis, it appears that the different aspects of requalification are partially treated and a systematic approach that takes into account structural safety, energy efficiency, and a reduction of environmental impacts in relation to the conservation aspects, is missing. The proposed approach is therefore aimed at overcoming this gap through the use of a multi-criteria analysis methodology analytically described in Section 2.

The proposed approach, based on the Analytic Hierarchy Process (AHP) method [18], is aimed at supporting both public administrations in the planning/designing phase of interventions on their historic artistic real estate assets, as well as private investors who, within the stated principles, intend to give the asset an added value.

2. The AHP Decision-Making Method

The Analytic Hierarchy Process (AHP) is a decision support technique developed in the late 1970 s by mathematician Thomas L. Saaty [18]. The method is called "analytical" because it allows complex decisional problems to be broken down into their fundamental constituent elements, and it is "hierarchical" because it involves the decomposition of the problem into several levels of increasing detail.

The AHP analysis allows us to compare several decision alternatives and choose the optimal one on the basis of several criteria, both quantitative or qualitative. Since the criteria adopted may conflict with each other, the best alternative is generally not the one that optimizes each criterion, but the one that achieves the best compromise with respect to all the criteria. Moreover, the optimal solution may vary as the decision-maker varies, for example, according to different requirements, the criteria may be given a different relative importance.

The AHP method is divided into the following phases:

- definition of the general objectives of the analysis (*goals*);
- selection of the C_j Criteria and any sub-criteria for the evaluation;
- identification of Alternatives A_i to achieve the objectives;
- attribution of weights relating to the criteria and any sub-criteria;
- compilation of the "Decision Matrix";
- calculation of total scores and sorting of alternatives.

The relative weights are assigned through the construction of the matrices of the pair comparisons, where all the elements (criteria and sub-criteria) belonging to the same hierarchical level are compared in pairs in relation to the super ordinate element. The result of the single comparison is an a_{ij} dominance coefficient, which expresses a measure of the relative importance of element i with respect to element j. To determine the values of the a_{ij} coefficients, a nine-value "Saaty fundamental scale" [19] or other scales can be used. The Saaty scale correlates the first nine integers with as many judgments as capable of expressing the possible results of the comparison.

Considering a number n of elements, the generic matrix of pair comparisons W is a square matrix ($n \ x \ n$) that is reciprocal and positive. If the matrix W is consistent (i.e., satisfies the properties of reciprocity and transitivity), whose known elements a_{ij} are equal to the ratio between the weights w_i/w_j, the following vector equation applies:

$$W\,w = \lambda_{max}\,w \tag{1}$$

where λ_{max} is the maximum eigenvalue, the only non-zero eigenvalue, equal to the order n of the matrix, while w is the associated eigenvector to which corresponds the vector of the weights, i.e., of the searched variables. In general, the values a_{ij} derive from qualitative judgements that present inconsistencies and therefore from Equation (1), an approximate estimate of the weights can be obtained. The consistency of the values assigned by experts to w_i/w_j ratios depends on the deviation between λ_{max} and n, which tends towards zero when the judgement is consistent. In particular, the consistency index CI is given by the following:

$$CI = \frac{\lambda_{max} - n}{n - 1} \tag{2}$$

where as the inconsistency increases, the value of CI increases. The CI index should be compared with the Random Consistency Index (RCI), whose value depends on the number n of variables according to Table 1.

Table 1. Random Consistency Index (RCI) values.

n	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
RCI	0	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45

The consistency ratio, *CR* (Consistency Ratio) can finally be obtained from the following equation:

$$CR = \frac{CI}{RCI}. \tag{3}$$

The resulting vector of weights w can be accepted if:

- $CR < 5\%$ for $n = 3$;
- $CR < 8\%$ for $n = 4$;
- $CR < 10\%$ for $n > 4$.

The next step involves the assembly of the Matrix of Decisions D (Table 2), of order $n \ x \ m$ (with n number of alternative solutions and m number of judgement criteria) whose elements, under the logic of AHP, are obtained by means of comparison matrices in pairs of alternatives A_i ($i = 1, 2, \ldots, n$) with respect to each criterion C_j ($j = 1, 2, \ldots$, m).

Table 2. Matrix of Decisions consisting of n intervention alternatives and m evaluation criteria, each of which is associated with a relative weight w.

		Evaluation Criteria (Weights)		
		C_1 (w_1)	**C_2 (w_2)**	**C_m (w_m)**
Alternatives	A_1	x_{11}	x_{12}	x_{1m}
	A_2	x_{21}	x_{22}	x_{2m}
	A_n	x_{n1}	x_{n2}	x_{nm}

The last step involves calculating the total weights of the alternatives through the principle of hierarchical composition, i.e., the local weights of each element are multiplied by those of the corresponding upper elements and finally the products thus obtained are added together [20].

3. Applications of Multi-Criteria Analysis to Interventions on Historic Buildings

Several applications of the multi-criteria analysis for the evaluation of interventions on historic buildings are present in the national and international specialist literature (see Table 3).

Some studies deal with the choice of energy requalification interventions aimed at achieving a balance between a performance increase, economic feasibility and preservation criteria [21–25]. Berg et al.'s research [26] investigates the role of user behavior in decision-making processes for the requalification and energy management of historic buildings.

Rocha and Rodrigues develop a method for the multicriteria assessment of the maintainability of roof recovery interventions [27]. Roberti et al. [28] apply a multi-objective optimization methodology for energy efficiency and conservation of historic buildings, with particular reference to a medieval building.

Another specific problem faced with multi-criteria techniques relates to the evaluation of the priority of the intervention between several buildings, with reference to both restoration and/or requalification [29–32] and seismic improvement interventions [33]. With regard to ecclesiastical buildings, Sangiorgio et al. [34] used AHP analysis to define an exposure index linked to the artistic and architectural value, to be integrated in the vulnerability assessment. The AHP method has also been used in the implementation of a model for the choice of interventions to improve fire safety [35].

Piñero et al. [36] develop a multi-criteria methodology to establish the priority of intervention, for the purposes of safety, between the buildings of an entire historic center.

Table 3. Studies present in the literature on the application of multi-criteria decisional analysis to historic buildings.

Reference	Research Focus	MCDM Method Applied	Other Methods
Gigliarelli et al. [21]	Choice of energy requalification strategies compatible with protection constraints	AHP	
Roberti et al. [23]		AHP	Multi-objective optimization
Annibaldi et al. [24]			
Fard e Nasiri [25]	Choice of passive technologies for energy efficiency	ANP	Multi-objective optimization
Zagorskas et al. [22]	Choice of alternatives for thermal insulation	TOPSIS	
Berg et al. [26]	Role of users in energy requalification and management interventions	Multi-criteria method with scores	
Rocha e Rodrigues [27]	Assessment of the maintainability of roof recovery interventions	Multi-criteria method with scores	
Roberti et al. [28]	Energy retrofit and conservation of built heritage		Multi-objective optimization
Dutta e Husain [29]	Assessment of the conservation/restoration priority	Additive linear model	
Kim et al. [30]		S-AHP (Stochastic)	Delphi
Vodopivec et al. [31]	Assessment of the conservation/restoration priority over a set of castles	AHP	
Aigwi et al. [32]	Evaluation of the priority of the recovery intervention among several underused historical buildings	AHP	Fuzzy-Delphi
D'Alpaos e Valluzzi [33]	Assessment of the priority of seismic improvement and restoration among several ecclesiastical buildings	AHP	
Sangiorgio et al. [34]	Evaluation of an exposure index linked to the architectural value, to be integrated in the seismic vulnerability analysis	AHP	
Piñero et al. [36]	Assessment of the priority of safety measures in relation to buildings in a historic center	AHP	
Naziris et al. [35]	Choice of measures to improve fire safety	AHP	

An extensive review of the current literature on multicriteria applications to the conservation and reuse of historic buildings was carried out by Morkūnaitė et al. [37]. In accordance with the results of this research, it has been noted how:

- the number of applications related to the choice of the most appropriate requalification interventions (8 studies) or to the determination of the priority of intervention among several buildings (7 studies) is still relatively limited;
- the most widely used multicriteria method is AHP analysis;
- an increase in applications has occurred in recent years, in particular since 2016;
- there is a lack of applications to integrated intervention strategies for the performance upgrading of historic buildings, i.e., (for instance) strategies that simultaneously consider the different aspects of structural safety, energy efficiency, reduction of environmental impacts, etc., in compliance with conservation criteria.

4. AHP-Based Methodology for the Choice of Integrated Interventions

In this paper, multi-criteria analysis, in particular the AHP methodology, is used for the choice of integrated interventions, aimed at the seismic improvement and energy retrofit in relation to the aspects of preservation, environmental and economic sustainability. Seven evaluation criteria and nine sub-criteria were selected. Unlike the classical AHP method, in the proposed approach, the phase of compiling the Decision Matrix (see Section 2) does not take place through matrices of comparison in pairs of alternatives because the x_{ij} value assumed by the *i-th* alternative with respect to the *j-th* criterion is quantified directly through appropriate quantitative or qualitative indicators, chosen from regulations, guidelines and scientific studies.

4.1. Preservation, Seismic Improvement and Energy Retrofit

The modern restoration, following a long conceptual refinement work that lasted about two centuries, has assumed a prevalent "critical-conservative" declination, i.e., primarily based on the need for the protection and better conservation of the artefact and at the same time open, according to a "critical" approach and based on the specificity of the case, the reasons for a "lawful integration" of the gaps (however recognizable) or the removal of improper additions. The Restoration Charters are an important reference for choosing the most appropriate interventions. In them, the following fundamental concepts are declared: reversibility; distinctiveness; minimum intervention and compatibility [38].

Physical-chemical *compatibility* refers to the physical and/or chemical interactions that develop when the new materials used for the intervention come into contact with the original materials; physical-chemical compatibility is also used in relation to the characteristics of the environment (temperature, humidity, exposure to atmospheric agents, etc.) in which the historic building is located. Some materials, for example, by modifying the transpiration conditions of the surfaces, can increase the degradation phenomena; other cases relate to damage by disintegration caused both by reinforced concrete conglomerate that was used widely in the past in consolidations, and by cement-based products used as mortars and plasters. In the case of a consolidation with reinforced concrete elements, the disintegration of the old masonry is generally linked to the oxidative processes of the reinforcements with the consequent increase in volume and swelling of the surface layers; in the case of the use of cement mortars and plasters, the reaction between the cement and the old lime, in the presence of water, leads to the formation of salts capable of causing significant expansive actions on the wall support. To avoid problems of incompatibility, it is necessary to use only widely tested and certified materials [39].

The *reversibility* criterion regards the possibility of easily removing the materials and components used in the intervention, bringing the artefact or the parts concerned back to a state close to their previous state. The reversibility is fundamental for replaceability, maintainability and durability [15]. Interventions based on dry technology systems and with mechanical connections or other interventions of simple juxtaposition or overlapping between pre-existing parts and new elements generally have a good reversibility. Conversely, interventions in which the contact between old and new materials is diffuse, continuous and associated with transformative processes of physical and/or chemical type, are irreversible or have low reversibility. In the field of structural consolidation, for example, interventions that involve injections of binder mixtures into masonry, cement plasters reinforced with electro welded mesh, reinforced seams, reinforced concrete slabs at the extrados of vaults, insertion of reinforced concrete kerbs, are irreversible or with limited reversibility [40–43]. In the latter case, the removal of the new elements may take place only at the price of significant surface alterations and/or partial demolition of the pre-existing parts subject to intervention. More recently introduced reinforcing techniques such as reinforced plaster with composite mesh [44], reinforced remaking joints in the case of irregular exposed masonry [45] or the use of stainless steel strips that vertically and horizontally cross the wall thickness and close in a ring [46], have medium reversibility characteristics. The insertion of metal tie-rods to counteract the action of pushing structures or the ring or bracing systems with metal elements are examples of traditional interventions with good reversibility.

The criterion of *minimum intervention* requires us to limit the interventions according to the actual needs and potential risks, since any intervention always involves interactions with the original parts [47]. In order to calibrate the intervention, a detailed knowledge of the artefact is fundamental, from the point of view of its history, materials, construction techniques and state of conservation.

The need to alter the artefact as little as possible was widely supported by the English critic John Ruskin who, in 1849, called for the maximum limitation of restoration work to ensure the greatest possible material permanence [48]. The concept of minimum intervention has guided restoration workers since the 1960s and 1970s, although there were still some advocates of "stylistic restoration".

The attention to the respect of the principle of minimum intervention has recently been decisively reaffirmed in the Burra Charter [49]. The criterion of *distinctiveness* or recognizability is connected to the possibility of recognizing new elements, introduced with the intervention, with respect to the original parts. This criterion derives from the need to preserve the authentic image of the building with its values of historic and artistic testimony [50,51].

Article 9 of the Venice Charter is very explicit: "The process of restoration is a highly specialized operation. Its aim is to preserve and reveal the aesthetic and historic value of the monument and is based on respect for original material and authentic documents. It must stop at the point where conjecture begins, and in this case moreover any extra work which is indispensable must be distinct from the architectural composition and must bear a contemporary stamp" [38]. The insertion of new elements, considered necessary starting from a critical judgment of value ("for aesthetic and technical reasons"), must guarantee the harmony between old and new as well as showing that the heritage assets are "not to be ancient works, but to be works of today" according to the principle of "modern discrimination of additions" developed by Camillo Boito [52]. In relation to the protection criteria discussed, structural safety is a very sensitive issue. Structural consolidation measures are necessary to preserve these buildings, which are highly vulnerable to seismic action, but at the same time a low-invasive solution must be preferred whose maximum safety levels are limited by protection constraints. General principles for structural restoration work are set out in the ICOMOS Charter of 2003 [53]; the same document stresses that the application of the same safety levels for the design of new buildings would require excessive if not impossible interventions.

In Italy, the "Norme Tecniche per le Costruzioni 2018" (NTC 2018) allows limitation to "seismic improvement" interventions, i.e., interventions that increase pre-existing structural safety without necessarily reaching the safety levels set by the standard in the case of "seismic adaptation" [54]. In particular, for the design of interventions to reduce the seismic vulnerability of historic buildings, the regulatory reference is the D.P.C.M. 9 February 2011. Chapter six of the Decree also indicates the possible techniques of intervention, critically examined in relation to their effectiveness, costs and their impact on conservation.

Similarly to what has happened in the structural field, from the point of view of energy efficiency, both at European [55] and national level [56], an approach aimed at "energy improvement", i.e., (for example) the implementation of upgrading actions that do not tend to strictly comply with standards, but to increase energy performance to the limits deriving from protection requirements [57] has become widespread. In Italy, MiBACT has issued Guidelines for the improvement of energy efficiency in the cultural heritage with the aim of providing operational guidance to both designers and conservation bodies [56]. The document proposes a procedure to assess and improve energy efficiency and, in relation to restoration criteria, several interventions on the envelope, on the systems and for lighting are examined. In particular, with regard to the energy efficiency of the envelope, each intervention is associated with a sheet in which, according to a qualitative scale, the degree of compatibility, reversibility and invasiveness is evaluated. A paragraph of the Guidelines is also dedicated to the use of renewable sources.

4.2. A Novel Approach: Definition of the Evaluation Criteria and Associated Indicators

The aspects discussed in Section 4.1 define the first three assessment criteria in the proposed decision-making approach: C_1 "Preservation", C_2 "Seismic Safety", C_3 "Energy Efficiency". The C_1 criterion is in turn articulated into the four sub-criteria $C_{1.1}$ "Compatibility", $C_{1.2}$ "Reversibility", $C_{1.3}$ "Minimum intervention" and $C_{1.4}$ "Distinctiveness". These sub-criteria are associated with a qualitative assessment scale with three levels of satisfaction: low, medium and high, which correspond to the three numerical values 1, 2 and 3.

The criterion C_2 "Seismic Safety" is related to the relationship between structural capacity and seismic demand with reference to an assigned design earthquake. This ratio, also known as "Risk Index", can be expressed in terms of Peak Ground Acceleration (PGA):

$$I_R = \frac{PGA_C}{PGA_D} \tag{4}$$

where PGA_C is the peak ground acceleration that determines the achievement of the life-safety limit state (SLV), PGA_D is the design acceleration required by the standard for a new building on the same site and for the same limit state.

Criterion C_3 "Energy Efficiency" is associated with the overall energy performance index $EPgl$, which represents the primary energy consumption referred to the unit of useful floor area or gross volume for heating, cooling, sanitary hot water production, lighting and possible ventilation:

$$EPgl = EPci + EPacs + EPce + EPill \tag{5}$$

where:

- $EPci$ = energy performance index for winter air-conditioning;
- $EPacs$ = energy performance index for domestic hot water production;
- $EPce$ = energy performance index for summer air-conditioning;
- $EPill$ = energy performance index for artificial lighting.

The performance indices are expressed in kWh/m^2 year or kWh/m^3 year, according to the indications provided by the European and national standards in force. For the calculation of the energy performance indices of the building, reference is made to the methods reported in the UNI Technical Specifications of the 11,300 series [58].

It is specified that a static energy model has been chosen, because it is more easily implemented by end users who will have to use it, although the dynamic model is certainly more suitable for historic buildings [59]. The proposed methodology can be enhanced with a dynamic energy simulation for comparative purposes in the future development of the research.

The fourth criterion selected C_4 relates to environmental sustainability aspects and is divided into three sub-criteria: $C_{4.1}$ "CO_2 Emissions", $C_{4.2}$ "Embodied Energy" and $C_{4.3}$ "Energy from Renewable Sources". The related indicators have been chosen on the basis of the following considerations. Currently the most refined and comprehensive environmental impact assessment methodology is the Life Cycle Assessment (LCA) [60]. One of the most widely shared results in the literature indicates that the most impactful life cycle phase is the phase of use [61]. At this stage, together with the energy consumed, a particularly significant environmental impact indicator is the total amount of greenhouse gas emissions, or CO_2 equivalent in relation to the different types of fuel or energy source used. These emissions have a significant impact on global warming.

With the same performance levels achievable with alternative solutions, the choice of materials with low environmental impact plays a very important role in the sustainability of the intervention. A specific indicator is "Embodied Energy", i.e., the total amount of energy used to produce, transport and install a building material or component [62]. Several authors have highlighted the role of embodied energy in the choice of retrofitting historic buildings [63–66].

The values of incorporated energy, generally expressed in MJ/kg, can be extrapolated from the data reported in the Environmental Product Declaration (EPD), environmental certifications, or, for products not yet equipped with EPD, from databases, such as the ICE (Inventory of Carbon and Energy) database developed in 2005 at the University of Bath [67].

The third sub-criterion selected to assess environmental sustainability regards the use of energy from renewable sources. Increasing the use of energy from renewable sources is one of the main objectives of national and international energy policies and is considered an evaluation criterion in all the main protocols of environmental sustainability of buildings (LEED and BREEAM are among the most widespread examples at an international level; the ITACA protocol is used in Italy). In Italy, from a regulatory point of view, according to Legislative Decree no. 28 of 2011, there is an obligation for new and existing buildings subject to 'major renovations' to cover a minimum share of energy needs with renewable sources. The obligation also applies to buildings located in historic city centers, but does not apply to buildings protected under Legislative Decree no. 42 of 2004, or located in restricted areas, 'if the designer shows that compliance with the requirements implies an alteration incompatible with their character or appearance, with particular reference to their historic and artistic features' (Article 11, Section 2 of Legislative Decree no. 28 of 2011). The MiBACT Guidelines provide some considerations and indications for the integration of technologies for the production of energy from renewable sources in historic buildings, highlighting their limits and criticality. This topic has also had a growing interest in recent decades in the field of scientific research [68], with a prevalence of studies on the integration of photovoltaic systems [69–73].

The indicator used in the proposed approach is the percentage share of renewable energy QR is given by the following ratio:

$$QR = 100\frac{Q_{P,ren,\ tot}}{Q_{P,\ tot}} = 100\frac{Q_{P,ren,,tot}}{Q_{P,ren,tot}+Q_{P,nren,tot}} \tag{6}$$

where $Q_{P,ren,tot}$ is the total amount of primary energy from renewable sources 'on site' and 'off site', $Q_{P,nren,tot}$ is the total amount of non-renewable primary energy, $Q_{P,tot}$ is the total amount of primary energy. The calculation of the different quantities of energy can be made according to the UNI/TS 11300-5 standard [74].

Criterion C_5 "Disturbance to Users" considers the degree of "disturbance" caused by the implementation of the intervention to those who reside or carry out activities in the building. The level of disturbance is expressed by means of a score, assigned according to a qualitative judgment scale (see Table 4).

Table 4. Qualitative assessment scale for Criterion *n*. 5 "Disturbance to Users".

Disturbance Caused to Occupants, Activities and Interactions with the Site		Score
Low	Intervention that does not require the occupation of premises and does not involve the suspension of activities.	1
Medium	Intervention that requires the occupation of premises and involves the temporary suspension of activities or their reorganization.	2
High	Intervention that requires a partial relocation of users.	3
Very high	Intervention that requires the relocation of all users.	4

Criterion C_6 "Time of Realization" considers the duration of the intervention, estimated on the basis of the project schedule and expressed in working days. This criterion is important when choosing the intervention in relation to the need to be able to dispose of the work in a short time.

Two sub-criteria have been selected for the evaluation of the economic sustainability of the interventions: $C_{7.1}$ "Cost of the Intervention" and $C_{7.2}$ "Economic Convenience". The total cost of the intervention is evaluated through the estimate metric computation and is made up of the costs for the preparation and safety of the construction site, for the works of functional adaptation, seismic improvement and energy requalification, for the disposal of waste materials.

The economic convenience is assessed through the Cost-Benefit Analysis (CBA), which requires the estimation of costs (investment and management costs) and the estimation of benefits (in terms of energy consumption savings and avoided CO_2 emissions). In order to carry out the assessments, it is necessary to define a period of analysis that, for example, in the case of buildings of public interest can be extended up to 35 years [75]. CBA results are expressed through the Net Present Value (NPV) indicator. The analysis is also conducted taking into account the 'monetization' of the lower annual carbon dioxide emissions, quantified through the "Social Cost of Carbon" (SCC) per tonne of CO_2 produced [57]:

$$NPV = \sum\nolimits_{i=0}^{n} \frac{CF_i}{(1+r)^i} - I_0 \tag{7}$$

where CF_i is the cash flow per year *i-th*, including expenses for periodic maintenance and savings for lower CO_2 emissions, I_0 is the initial investment and r is the discount rate that can be assumed to be 4%, as suggested in the Guide to Cost-Benefit Analysis of Investment Projects [76].

Expected uncertainties that may affect the CBA analysis are related, for example, to the forecast of costs and benefits in the management phase and the assumption of the discount rate. The sub-criterion $C_{7.1}$ "Cost of the Intervention", which can be estimated with simplicity and greater reliability, also assumes the role of "mitigating" the weight of these uncertainties in the assessment of the economic sustainability of the intervention. Table 5 summarizes the various criteria, sub-criteria and indicators proposed.

Table 5. Evaluation criteria, sub-criteria and indicators.

n	Criterion	Sub-Criterion		Indicator
C_1	Preservation	$C_{1.1}$ $C_{1.2}$ $C_{1.3}$ $C_{1.4}$	Compatibility Reversibility Minimum intervention Distinctiveness	Qualitative evaluation scale with three values (low = 1, medium = 2, high = 3)
C_2	Seismic Safety			Risk Index, I_R
C_3	Energy Efficiency			Global Energy Performance Index, EP_{gl} (kWh/m^2/year)
C_4	Environmental Sustainability	$C_{4.1}$	CO_2 Emissions	Total amount of CO_2 emissions produced during the use phase (kg CO_2 eq)
		$C_{4.2}$	Embodied Energy	Embodied energy in the materials used for the intervention (MJ/m^2)
		$C_{4.3}$	Energy from Renewable Sources	% of energy production from renewable sources, QR
C_5	Disturbance to Users			Qualitative evaluation scale with four values (low = 1, medium = 2, high = 3, very high = 4)
C_6	Time of Realization			Estimation of the timing of the intervention through the project schedule (working days)
C_7	Economic Sustainability	$C_{7.1}$	Cost of Intervention	Cost of the intervention evaluated by estimate metric computation (€/m^2)
		$C_{7.2}$	Economic Convenience	Net Present Value (€)

4.3. Definition of the Evaluation Criteria and Associated Indicators

Through the indicators defined in the previous paragraph, it is possible to proceed with the compilation of the Decision Matrix D: for each intervention alternative, the values of the indicators associated with the different evaluation criteria and sub-criteria are calculated. The values thus obtained are uneven values and must therefore be normalized, i.e., transformed into dimensionless values between 0 and 1.

Compared to the evaluation criteria which, in relation to the objectives of the analysis, represent "costs" (criteria C_3, C_5 and C_6, sub-criteria $C_{4.1}$, $C_{4.2}$ and $C_{7.1}$), the elements of the matrix can be normalized through Equation (8); if, on the other hand, the criteria represent "benefits" (criteria C_1, C_2, C_4 and C_7, sub-criteria $C_{1.1}$, $C_{1.2}$, $C_{1.3}$, $C_{1.4}$, $C_{4.3}$ and $C_{7.2}$) the elements of the matrix can be normalized using Equation (9):

$$\text{Criteria to minimize } x'_{ij} = \frac{x_{j,min}}{x_{ij}} \tag{8}$$

$$\text{Criteria to maximize } x'_{ij} = \frac{x_{ij}}{x_{j,max}} \tag{9}$$

where $x_{j,min} = \min_j (x_{ij})$ e $x_{j,max} = \max_j (x_{ij})$.

Finally, by adopting the SAW technique, Simple Additive Weighting [77], the following synthetic "Decision Support Index" can be obtained with reference to the generic alternative:

$$I_{DS,i} = \sum_{j} w_j x'_{ij} \tag{10}$$

where w_j is a coefficient expressing the relative weight of the *j-th* criterion and the apex indicates the values normalized according to the two previous equations.

This index allows us to establish an ordering of the alternatives orienting the choice towards the "optimal" one, that is the one that, having a higher index, allows us to reach the best compromise between the different evaluation criteria.

5. Application Example and Results

As an example, the proposed methodology was applied to choose the optimal intervention strategy for the seismic improvement and energy efficiency of a former convent of Franciscan friars located in the Municipality of Montoro (AV) in Campania (Figure 1). The building, with a particular historic value, is bound according to Legislative Decree no. 42 of 2004 "Cultural Heritage and Landscape Code".

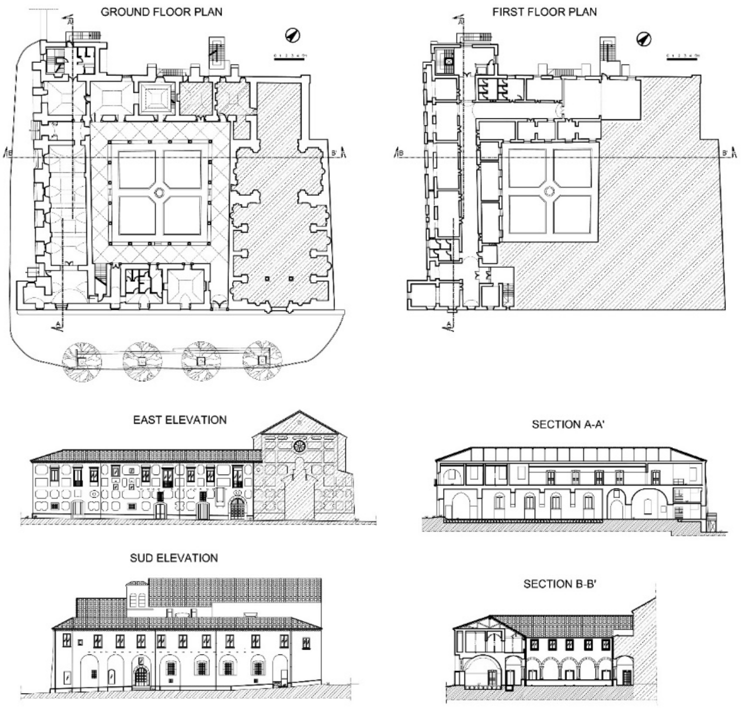


Figure 1. Former convent "S. Maria degli Angeli" in the province of Avellino (Italy): plans, elevations and sections.

In this study, three intervention alternatives were hypothesized, which include common and specific actions.

In particular, the following actions were foreseen in all alternatives:

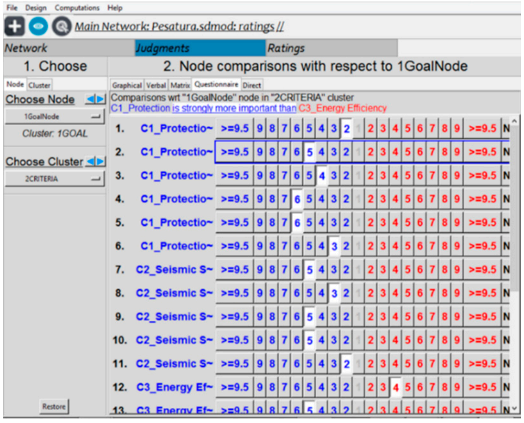
- replacement of the transparent closures of the first floor with wooden frames with triple glazing filled with Argon gas;
- screeds remaking with lightened material based on cement and expanded clay;
- relamping of the entire complex with LED technology;
- controlled mechanical ventilation of the conference room on the ground floor, through central installation of primary air treatment with regenerative recovery.

Specific interventions, however, differentiate the three alternatives:

- the alternative A_1 provides for a seismic improvement intervention through the application on both sides of the walls of thin plaster reinforced with mesh and GFRP connections. As far as energy efficiency is concerned, the following interventions were hypothesized:
    - thermal insulation of the walls with the application of a cork-based thermal insulation plaster 30 mm thick;
    - insulation of the slab at the intrados with 80 mm thick rock wool panels and plasterboard false ceiling;
    - centralized air conditioning system of the hydronic type with constant flow rate (with cooling units, reversible air/water heat pumps and fancoil);
    - installation of a 20 kW photovoltaic system;
- the alternative A_2 provides for the same seismic improvement intervention as A_1, while the following interventions were hypothesized with regard to energy efficiency:
    - thermal insulation of the opaque walls from the inside and the slabs (at the intrados) with plasterboard and Aerogel panels 40 mm thick;
    - construction of a trigeneration thermal system with the use of geothermal energy.
- the alternative A_3 provides for seismic improvement through the application of FRP tapes to the walls. As far as energy efficiency is concerned, the following measures were considered:
    - thermal insulation of opaque walls with internal counter-wall made up of 80 mm thick rock wool panels and a plasterboard finishing sheet;
    - thermal insulation at the intrados of the first floor slabs with 80 mm thick rock wool panels and plasterboard false ceiling;
    - construction of a trigeneration thermal system with the use of geothermal energy;
    - installation of a 20 kW photovoltaic system.

Once the objectives (*goals*) and intervention alternatives had been defined, the next step was to assign weights to the criteria and sub-criteria described in Section 4.2. This operation was carried out by the Authors through the technique of criteria pair comparisons, with the help of SuperDecisions v.3.2 software dedicated to AHP analysis (Figure 2). The CR consistency index was 8.6% and therefore the weight vector could be considered as acceptable. Figure 3 shows in a graphic form the relative weights obtained for the seven evaluation criteria. The same relative weight was instead attributed to the subcriteria, equal to 1/4 in the case of subcriteria $C_{1.1}$-$C_{1.2}$-$C_{1.3}$-$C_{1.4}$, to 1/3 for the subcriteria $C_{4.1}$-$C_{4.2}$-$C_{4.3}$ and 1/2 for subcriteria $C_{7.1}$-$C_{7.2}$.

The next step required the evaluation of each intervention alternative with respect to each criterion and sub-criterion, using the indicators described in Section 4.2. After these calculations, it is possible to compile the Matrix of Decisions D (Table 6). Through the Equations (8) and (9), we then proceeded to the normalization of the matrix (Table 7) and the calculation of the decision support index according to the Equation (10). The ordering of the alternatives is shown in Figure 4. In particular, A_2 is the optimal intervention alternative, i.e., the one that reaches the best compromise with respect to the different criteria and sub-criteria.



1. Choose

Cluster: 1GOAL

2. Node comparisons with respect to 1GoalNode

Comparisons wrt "1GoalNode" node in "2CRITERIA" cluster

C1_Protection is strongly more important than C3_Energy Efficiency

1. C1_Protectio~ >=9.5 9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9 >=9.5 N
2. C1_Protectio~ >=9.5 9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9 >=9.5 N
3. C1_Protectio~ >=9.5 9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9 >=9.5 N
4. C1_Protectio~ >=9.5 9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9 >=9.5 N
5. C1_Protectio~ >=9.5 9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9 >=9.5 N
6. C1_Protectio~ >=9.5 9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9 >=9.5 N
7. C2_Seismic S~ >=9.5 9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9 >=9.5 N
8. C2_Seismic S~ >=9.5 9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9 >=9.5 N
9. C2_Seismic S~ >=9.5 9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9 >=9.5 N
10. C2_Seismic S~ >=9.5 9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9 >=9.5 N
11. C2_Seismic S~ >=9.5 9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9 >=9.5 N
12. C3_Energy Ef~ >=9.5 9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9 >=9.5 N
13. C3_Energy Ef~ >=9.5 9 8 7 6 5 4 3 2 1 2 3 4 5 6 7 8 9 >=9.5 N

Figure 2. Implementation of the pairwise comparison method for weighing the criteria through the SuperDecisions software.

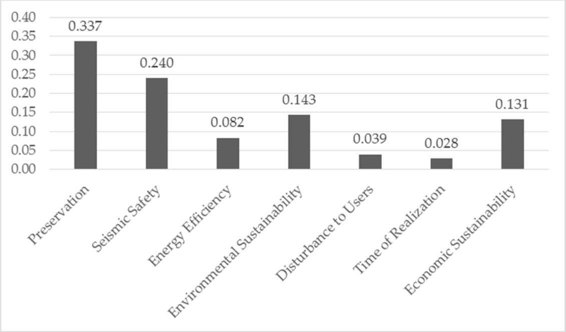


Figure 3. Relative weights of the seven evaluation criteria.

Table 6. Compilation of the Decision Matrix D.

	C_1 Preservation				C_2 Seismic Safety	C_3 Energy Efficiency	C_4 Environmental Sustainability			C_5 Dist. to User	C_6 Time of Realization	C_7 Economic Sustainability	
	$C_{1.1}$	$C_{1.2}$	$C_{1.3}$	$C_{1.4}$			$C_{4.1}$	$C_{4.2}$	$C_{4.3}$			$C_{7.1}$	$C_{7.2}$
						(kWh/(m^2 year))	(kg CO$_2$ eq)	(MJ/m^2)	(%)		(days)	(€/m^2)	(€)
A_1	2	2	2	2	0.76	27.256	54,600	890	35	1	310	944	118,789
A_2	2	2	3	2	0.76	23.837	45,150	1548	41	1	345	1322	136,679
A_3	2	2	2	2	0.68	21.199	40,950	1147	58	1	412	1550	145,890

Table 7. Normalization of the Decision Matrix D according to Equations (8) and (9) and calculation of the Decision Support Index $I_{DS,i}$ according to (10).

	C_1				C_2	C_3	C_4			C_5	C_6	C_7		
w_{Cj}	0.337				0.240	0.082	0.143			0.039	0.028	0.131		**Decision Support Index** $I_{DS,i}$
	$C_{1.1}$	$C_{1.2}$	$C_{1.3}$	$C_{1.4}$			$C_{4.1}$	$C_{4.2}$	$C_{4.3}$			$C_{7.1}$	$C_{7.2}$	
w_{Cj}	0.25	0.25	0.25	0.25			0.33	0.33	0.33			0.5	0.5	
A_1	1	1	0.67	1	1	0.778	0.750	1	0.603	1	1	1	0.814	0.911
A_2	1	1	1	1	1	0.889	0.907	0.575	0.707	1	0.899	0.714	0.937	**0.927**
A_3	1	1	0.67	1	0.895	1	1	0.776	1	1	0.752	0.609	1	0.903

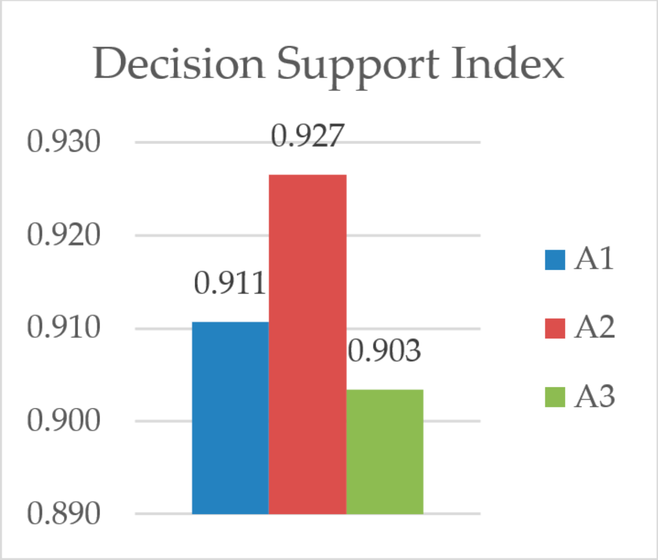


Figure 4. Priority of intervention alternatives.

6. Discussion

The proposed intervention alternatives aim at the seismic and energy retrofit of the former convent complex to allow its reuse as a training center. The choice of the different materials and technologies is controlled through the safeguard criterion which considers, according to qualitative scales of judgement, the appropriateness of the hypothesized interventions in terms of compatibility, reversibility, minimum intervention and recognizability. It is noted that each of the alternatives achieves a high decision support index value of more than 0.90. This indicates a high level of compliance of each alternative with the different criteria and sub-criteria proposed.

By benchmarking the alternatives against the single criteria (Figure 5) it is possible to highlight that:

- the seismic improvement interventions (A_1 and A_2 alternatives) with GFRP reinforced plaster are more effective than the application of FRP strips (A_3 alternative);
- as regards the criteria of historic-architectural safeguard, the A_2 alternative, which does not involve the installation of a photovoltaic system, whose integration is rather problematic in historic buildings, is more preferred;
- in terms of energy-environmental efficiency, the best performing alternative is A_3, which provides for a consistent use of renewable sources (geothermal and photovoltaic); in the intermediate position, there is the A_2 alternative, which combines the trigeneration thermal system and the envelope insulation from the inside using Aerogel panels. The latter material has excellent thermal insulation characteristics but also has a greater impact in terms of incorporated energy. The A_1 alternative, on the other hand, provides a thermal insulation plaster based on cork which has an excellent environmental profile in terms of incorporated energy, lower than both the EE of rock wool panels (A_3 alternative) and Aerogel panels. It has to be noted, however, that in the incorporated energy calculation, only the materials used for the seismic retrofit and for the efficiency of opaque walls have been taken into account: to these contributions should be added the energies incorporated by the installation systems;
- since the convent complex is currently in disuse, the works do not cause "disturbance" to possible users and therefore criterion C_5 takes on a minimum value in all alternatives (see Tables 4 and 6);
- in relation to economic sustainability, in terms of initial costs and NPV, the most satisfactory alternative is A_1, while the least satisfactory is A_3 with a more substantial initial investment.

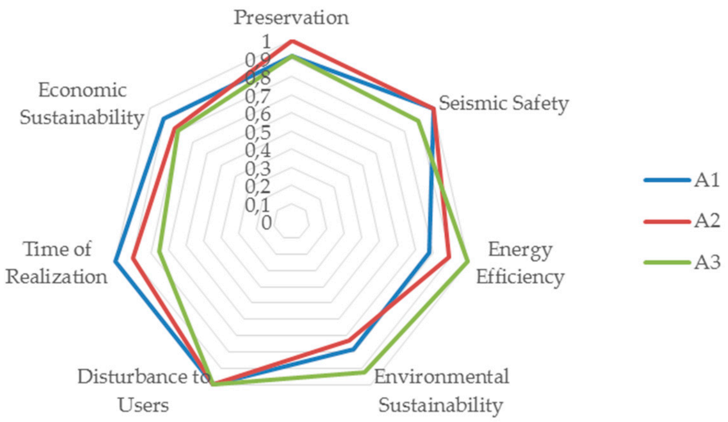


Figure 5. Radar diagram of alternatives to the seven criteria.

Following the analyses carried out, the proposed multi-criteria methodology orients decision-makers towards the A_2 solution as the optimal intervention strategy. Further evaluations, however, can be carried out by varying individual actions (e.g., the type of insulation of opaque walls) on a par with all other interventions. This would allow us to evaluate the impact of a particular intervention on the overall strategy, which could then be appropriately recalibrated and optimized according to the priorities of decision-makers.

7. Conclusions

Historic buildings constitute a spiritual, cultural, economic and social heritage of irreplaceable value [78]. The conservation and use of this heritage, in relation to the phenomena of urban transformation and the environmental and socio-economic changes taking place, is an issue of fundamental importance. Various studies highlight the significant contribution that historic buildings, through compatible reuse, can make in strategies of sustainable regeneration of the built environment. Their use, however, requires the implementation of maintenance and/or adaptation and requalification interventions.

For these valuable buildings, the choice of the most appropriate intervention must combine the needs of preservation with those of performance requalification. As part of integrated seismic improvement and energy-environmental retrofit strategies, the interventions must be compatible, reversible, non-invasive and recognizable, according to the most commonly shared principles of restoration. Therefore, unlike other types of buildings, it is unlikely that an increase in structural safety and energy efficiency levels can allow for a strict compliance with the regulatory requirements; in contrast, an “improvement” up to the limits deriving from preservation requirements is possible. Other important aspects concern the reduction of environmental impacts and the economic sustainability of the intervention. In addition, the management phase of the building is of considerable importance for sustainable conservation.

Given the multiplicity of factors involved, the choice of the intervention that best meets the different needs represented is complex. This paper proposed a multi-criteria methodology of decision support based on the AHP technique that lends itself effectively to the decomposition of complex problems in their constituent elements. To this end, seven evaluation criteria and nine sub-criteria were identified (Table 5), to which indicators deemed significant were associated on the basis of widely shared theoretical principles, regulatory references and scientific studies (see Section 4.2).

The first criterion “Preservation” is divided into four sub-criteria that correspond to the four principles of restoration set out above: in this case, the evaluation of the “performance” of the generic alternative intervention takes place through the use of a qualitative judgement scale. The second and third criteria, respectively “Seismic Safety” and “Energy Efficiency”, are instead associated with the analytical indicators defined in the specific technical standards. The fourth criterion, “Environmental

Sustainability", is divided into three sub-criteria associated with the environmental indicators generally used in literature and in national and international protocols. The fifth criterion, "Disturbance to Users", was introduced in order to assess, through a qualitative scale (Table 4), the level of interference between the execution of requalification/adaptation works and users' activities.

The sixth criterion is intended to measure the impact of the intervention in terms of the estimated implementation time through the project schedule. The seventh and final criterion selected aims to assess the economic sustainability of the intervention, taking into account both the initial costs of the investment and, through the Net Present Value indicator, the management costs and benefits in terms of the reduction of energy consumption and greenhouse gas emissions appropriately monetized. Finally, a synthetic decision-support index has been defined, which allows us to compare and order the intervention alternatives, orienting towards the best compromise solution.

It should be noted that the criteria and sub-criteria chosen are intended to promote, in compliance with the need to protect historic buildings, integrated and sustainable interventions, i.e., with positive effects on the three main dimensions of sustainability: environmental, social and economic.

In the development of the research, the implementation of the phase of relative weighting of criteria and sub-criteria is foreseen through the consultation of a sample of experts and the application of the proposed methodology to a case study. Finally, it should be noted that this methodology can be usefully adopted by Public Administrations during the planning phase of interventions on their historic buildings, as well as by private investors who intend to promote redevelopment and enhancement actions.

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References

1. UNESCO. *Recommendation on the Historic Urban Landscape*; UNESCO World Heritage Centre: Paris, France, 2011.
2. ICOMOS Climate Change and Cultural Heritage Working Group. *The Future of Our Pasts: Engaging Cultural Heritage in Climate Action*; ICOMOS: Paris, France, 2019.
3. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. Towards an Integrated Approach to Cultural Heritage for Europe. Brussels, 22.7.2014. 2014. Available online: https://ec.europa.eu/assets/eac/culture/library/publications/2014-heritage-communication_en.pdf (accessed on 2 May 2020).
4. CLIC Consortium, Circular models Leveraging Investments in Cultural Heritage Adaptive Reuse. Available online: https://www.clicproject.eu/ (accessed on 2 May 2020).
5. Foster, G.J. Circular economy strategies for adaptive reuse of cultural heritage buildings to reduce environmental impacts. *Ressour. Conserv. Recy.* **2020**, *152*, 1–14. [CrossRef]
6. Forte, C. Il valore di scambio e valore d'uso sociale dei beni culturali immobiliari. *Restauro* **1977**, *35*, 99–105.
7. Mossetto, G.; Vecco, M. *Economia del Patrimonio Monumentale*; FrancoAngeli: Milano, Italy, 2001.
8. Throsby, D. Cultural capital and sustainability concepts in the economics of cultural heritage. In *Assessing the Values of Cultural Heritage*; de la Torre, M., Ed.; The Getty Conservation Institute: Los Angeles, CA, USA, 2002; pp. 101–117.
9. Kincaid, D. *Adapting Buildings for Changing Uses: Guidelines for Change of Use Refurbishment*; Spon: New York, NY, USA, 2002.
10. Wang, H.J.; Zeng, Z.T. A multi-objective decision-making process for reuse selection of historic buildings. *Expert Syst. Appl.* **2010**, *37*, 1241–1249. [CrossRef]
11. De Medici, S.; Pinto, M.R. Public cultural heritage properties enhancement and reuse strategies. *TECHNE J. Technol. Archit. Environ.* **2012**, *3*, 140–147. [CrossRef]

12. Elsorady, D.A. Assessment of the compatibility of new uses for heritage buildings: The example of Alexandria National Museum, Alexandria, Egypt. *J. Cult. Herit.* **2014**, *15*, 511–521. [CrossRef]
13. Mısırlısoy, D.; Günçe, K. Adaptive reuse strategies for heritage buildings: A holistic approach. *Sustain. Cities Soc.* **2016**, *26*, 91–98. [CrossRef]
14. Pinto, M.R.; De Medici, S.; Senia, C.; Fabbricatti, K.; De Toro, P. Building reuse: Multi-criteria assessment for compatible design. *Int. J. Des. Sci. Technol.* **2017**, *22*, 165–193.
15. Carbonara, G. An Italian contribution to architectural restoration. *Front. Archit. Res.* **2012**, *1*, 2–9. [CrossRef]
16. Greco, S.; Ehrgott, M.; Figueira, J.R. *Multiple Criteria Decision Analysis. State of the Art Surveys*; Springer: New York, NY, USA, 2016.
17. Fiore, P.; Donnarumma, G. Proposal of a multicriteria decision-making approach for the choice between refurbishing or reconstructing an existing building. *Tema Technol. Eng. Mater. Archit.* **2018**, *4*, 36–46. [CrossRef]
18. Saaty, T.L. *The Analytical Hierarchy Process*; McGraw-Hill: New York, NY, USA, 1980.
19. Saaty, T.L. Deriving the AHP 1-9 scale from first principles. In Proceedings of the ISAHP 2001, Berne, Switzerland, 2–4 August 2001.
20. Saaty, T.L. Scaling Method for Priorities in Hierarchy Structures. *J. Math. Psychol.* **1977**, *15*, 234–281. [CrossRef]
21. Gigliarelli, E.; Cessari, L.; Cerqua, A. Application of the Analytic Hierarchy Process (AHP) for energetic rehabilitation of historical buildings. In Proceedings of the ISAHP 2011, Sorrento, Italy, 15–18 June 2011.
22. Zagorskas, J.; Zavadskas, E.K.; Turskis, Z.; Burinskienė, M.; Blumberga, A.; Blumerga, D. Thermal insulation alternatives of historic brick buildings in Baltic Sea Region. *Energy Build.* **2014**, *78*, 35–42. [CrossRef]
23. Roberti, F.; Oberegger, U.F.; Lucchi, E.; Troi, A. Energy retrofit and conservation of a historic building using multi-objective optimization and an analytic hierarchy process. *Energy Build.* **2017**, *138*, 1–10. [CrossRef]
24. Annibaldi, V.; Cucchiella, F.; De Berardinis, P.; Gastaldi, M.; Rotilio, M. An integrated sustainable and profitable approach of energy efficiency in heritage buildings. *J. Clean. Prod.* **2020**, *251*, 1–16. [CrossRef]
25. Fard, A.F.; Nasiri, F. A bi-objective optimization approach for selection of passive energy alternatives in retrofit projects under cost uncertainty. *Energy Built Environ.* **2020**, *1*, 77–86. [CrossRef]
26. Berg, F.; Flyen, A.C.; Godbolt, A.L.; Broström, T. User-driven energy efficiency in historic buildings: A review. *J. Cult. Herit.* **2017**, *28*, 188–195. [CrossRef]
27. Rocha, P.F.; Rodrigues, R.C. Maintenance as a Guarantee for Roofing Performance in Buildings with Heritage Value. *Buildings* **2016**, *6*, 15. [CrossRef]
28. Roberti, F.; Filippi Oberegger, U.; Lucchi, E.; Gasparella, A. Energy retrofit and conservation of built heritage using multiobjective optimization: Demonstration on a medieval building. In Proceedings of the Building Simulation Applications-BSA 2015, Bolzano, Italy, 4–6 February 2015.
29. Dutta, M.; Husain, Z. An application of Multicriteria Decision Making to built heritage. The case of Calcutta. *J. Cult. Herit.* **2009**, *10*, 237–243. [CrossRef]
30. Kim, C.J.; Yoo, W.S.; Lee, U.K.; Song, K.J.; Kang, K.I.; Cho, H. An experience curve-based decision support model for prioritizing restoration needs of cultural heritage. *J. Cult. Herit.* **2010**, *11*, 430–437. [CrossRef]
31. Vodopivec, B.; Žarnić, R.; Tamošaitienė, J.; Lazauskas, M.; Šelih, J. Renovation priority ranking by multi-criteria assessment of architectural heritage: The case of castles. *Int. J. Strateg. Prop. Manag.* **2014**, *18*, 88–100. [CrossRef]
32. Aigwi, I.E.; Egbelakin, T.; Ingham, J.; Phipps, R.; Rotimi, J.; Filippova, O. A performance-based framework to prioritise underutilised historical buildings for adaptive reuse interventions in New Zealand. *Sustain. Cities Soc.* **2019**, *48*, 1–10. [CrossRef]
33. D'Alpaos, C.; Valluzzi, M.R. Protection of Cultural Heritage Buildings and Artistic Assets from Seismic Hazard: A Hierarchical Approach. *Sustainability* **2020**, *12*, 1608. [CrossRef]
34. Sangiorgio, V.; Uva, G.; Ruggieri, S.; Adam, J.M. Calibration of seismic vulnerability index for masonry churches based on AHP including architectural and artistic assets. In Proceedings of the 3rd International Conference on Recent Advances in Nonlinear Design, Resilience and Rehabilitation of Structures-CoRASS 2019, Coimbra, Portugal, 16–18 October 2019.
35. Naziris, I.A.; Lagaros, N.D.; Papaioannou, K. Optimized fire protection of cultural heritage structures based on the analytic hierarchy process. *J. Build. Eng.* **2016**, *8*, 292–304. [CrossRef]

36. Piñero, I.; San-José, J.T.; Rodríguez, P.; Losáñez, M.M. Multi-criteria decision-making for grading the rehabilitation of heritage sites. Application in the historic center of La Habana. *J. Cult. Herit.* **2017**, *26*, 144–152. [CrossRef]
37. Morkūnaitė, Z.; Kalibatas, D.; Kalibatienė, D. A bibliometric data analysis of multi-criteria decision making methods in heritage buildings. *J. Civ. Eng. Manag.* **2019**, *25*, 76–99. [CrossRef]
38. Petzet, M.; Ziesemer, J. *International Charters for Conservation and Restoration = Chartes Internationales sur la Conservation et la Restauration = Cartas Internacionales sobre la Conservación y la Restauración*; ICOMOS: München, German, 2004.
39. Baiani, S.; Lucchi, E.; Pascucci, M. Old and Innovative Materials towards a "Compatible Conservation". In *Analysis, Conservation, and Restoration of Tangible and Intagible Cultural Heritage*; Inglese, C., Ippolito, A., Eds.; IGI Global: Hershey, PA, USA, 2019; pp. 170–195.
40. Jurina, L. La possibilità dell'approccio reversibile negli interventi di consolidamento strutturale (ovvero un inno al tirante e al puntone. In Proceedings of the XIX Convegno Scienza e Beni Culturali, Bressanone, Italy, 1–4 July 2003.
41. Borri, A.; Corradi, M.; Vignoli, A. Nuove Sperimentazioni per la Valutazione della Resistenza a Taglio delle Murature prima e dopo Rinforzo. In Proceedings of the 11th Italian Conference on Earthquake Engineering-ANIDIS 2004, Genova, Italy, 25–29 January 2004.
42. Borri, A.; Corradi, M.; Giannantoni, A.; Speranzini, E. Consolidamento e rinforzo di murature storiche mediante un reticolato di ristilature armate. *Boll. Ing.* **2008**, *7*, 11–19.
43. D'Agostino, S.; Bellomo, M. The concept of reversibility in the structural restoration of archaeological sites. In *Transactions on the Built Environment 66*; WIT Press: Southampton, UK, 2003.
44. Corradi, M.; Borri, A.; Castori, G.; Sisti, R. Shear strengthening of wall panels through jacketing with cement mortar reinforced by GFRP grids. *Compos. Part B* **2014**, *64*, 33–42. [CrossRef]
45. Borri, A.; Corradi, M.; Speranzini, E.; Giannantoni, A. Reinforcement of Historic Masonry with High Strength Steel Cords. *J. Int. Mason. Soc.* **2010**, *23*, 79–90.
46. Cilia, M.; Cipolla, I.; Colajanni, P.; Marnetto, R.; Recupero, A.; Spinella, N. Prove sperimentali in situ su tipica muratura messinese rinforzata con CAM: Arco in muratura a piena scala. *Progett. Sismica* **2014**, *3*, 159–173.
47. Zhang, Y.; Dong, W. Determining Minimum Intervention in the Preservation of Heritage Buildings. *Int. J. Archit. Herit.* **2019**, 1–15. [CrossRef]
48. Ruskin, J. *The Seven Lamps of Architecture*; Smith, Elder & Co.: London, UK, 1849.
49. Icomos, A. *The Burra Charter: The Australia ICOMOS Charter for Places of Cultural Significance*; Australia ICOMOS Incorporated: Burwood, Australia, 2013.
50. Carbonara, G. The integration of the Image Problems in the Restoration of Monuments. In *Historical and Philosophical Issues in the Conservation of Cultural Heritage*; Price, N.S., Kirby Talley, M., Jr., Melucco Vaccaro, A., Eds.; The Getty Conservation Institute: Los Angeles, CA, USA, 1996; pp. 236–243.
51. Martinez, A.H. Conservation and Restoration in Built Heritage: A Western European Perspective. In *The Ashgate Researche Companion to Heritage and Identity*; Graham, B., Howard, P., Eds.; MPG Books Ltd.: Bodmin, UK, 2008; p. 252.
52. Crippa, M.A. Camillo Boito. In *The New and the Old in Architecture*; Jaca Book: Milano, Italy, 1988.
53. Charter, I.C.O.M.O.S. *Principles for the Analysis, Conservation and Structural Restoration of Architectural Heritage*; Ratified by the ICOMOS 14th General Assembly in Victoria Falls: Zimbabwe, Africa, 2003.
54. Ministero delle Infrastrutture e dei Trasporti. *Aggiornamento delle "Norme Tecniche per le Costruzioni"-NTC 2018*; Ministero delle Infrastrutture e dei Trasporti: Roma, Italy, 2018.
55. European Standard. *Conservation of Cultural Heritage-Guidelines for Improving the Energy Performance of Historic Buildings (EN 16883:2017)*; European Committee for Standardization: Bruxelles, Belgium, 2017.
56. MiBACT. *Linee di Indirizzo per il Miglioramento Dell'efficienza Energetica nel Patrimonio Culturale*; Architettura, centri e nuclei storici ed urbani; Direzione generale BeAP: Roma, Italy, 2015.
57. Fiore, P.; Nesticò, A.; Macchiaroli, M. La riqualificazione energetica degli edifici monumentali. Un protocollo di indagine e caso studio. *Valori Valutazioni* **2016**, *16*, 45–55.
58. Comitato Termotecnico Italiano, Specifica Tecnica UNI/TS 11300 (UNI/TS 11300-1:2014, UNI/TS 11300-2:2019, UNI/TS 11300-3:2010, UNI/TS 11300-4:2012). Available online: https://www.cti2000.eu/la-uni-ts-11300/ (accessed on 2 May 2020).

59. Akkurt, G.G.; Aste, N.; Borderon, J.; Buda, A.; Calzolari, M.; Chung, D.; Costanzo, V.; Del Pero, C.; Evola, G.; Huerto-Cardenas, H.E.; et al. Dynamic thermal and hygrometric simulation of historical buildings: Critical factors and possible solutions. *Renew. Sustain. Energy Rev.* **2020**, *118*, 109509. [CrossRef]
60. ISO Standards. *Environmental Management-Life Cycle Assessment-Principles and Framework (ISO 14040:2006)*; ISO Standards: Geneva, Switzerland, 2006.
61. Buda, A.; Lavagna, M. LCA methodology to compare alternative retrofit scenarios for historic buildings: A review. In Proceedings of the 12th Italian LCA, Messina, Italy, 11–12 June 2018.
62. Cole, R.J.; Rousseau, D. Environmental Auditing for Building Construction: Energy and Air Pollution Indices for Building Materials. *Build. Environ.* **1992**, *27*, 23–30. [CrossRef]
63. Webb, A.L. Energy retrofits in historic and traditional buildings: A review of problems and methods. *Renew. Sust. Energ. Rev.* **2017**, *77*, 748–759. [CrossRef]
64. Monsù Scolaro, A. Embodied Energy e prestazione residua: Misurare il valore ambientale dell'esistente. *Techne* **2018**, *16*, 226–234.
65. Mourão, J.; Gomes, R.; Matias, L.; Niza, S. Combining embodied and operational energy in buildings refurbishment assessment. *Energ. Build.* **2019**, *197*, 34–46. [CrossRef]
66. Wise, F.; Moncaster, A.; Jones, D.; Dewberry, E. Considering embodied energy and carbon in heritage buildings—A review. In Proceedings of the Sustainable Built Environment Conference 2019, Wales, UK, 24–25 September 2019.
67. Inventory of Carbon and Energy (ICE Database), University of Bath. Available online: https://circularecology.com/embodied-energy-and-carbon-footprint-database.html (accessed on 2 May 2020).
68. Cabeza, L.F.; de Gracia, A.; Pisello, A.L. Integration of renewable technologies in historical and heritage buildings: A review. *Energ. Build.* **2018**, *177*, 96–111. [CrossRef]
69. Moschella, A.; Salemi, A.; Lo Faro, A.; Sanfilippo, G.; Detommaso, M.; Privitera, A. Historic buildings in Mediterranean area and solar thermal technologies: Architectural integration vs preservation criteria. *Energy Procedia* **2013**, *42*, 416–425. [CrossRef]
70. Polo López, C.S.; Frontini, F. Energy efficiency and renewable solar energy integration in heritage historic buildings. *Energy Procedia* **2014**, *48*, 1493–1502. [CrossRef]
71. Bellia, L.; d'Ambrosio Alfano, F.R.; Giordano, J.; Ianniello, E.; Riccio, G. Energy requalification of a historical building: A case study. *Energ. Build.* **2015**, *95*, 184–189. [CrossRef]
72. Manni, M.; Tecce, R.; Cavalaglio, G.; Coccia, V.; Nicolini, A.; Petrozzi, A. Architectural and energy refurbishment of the headquarter of the University of Teramo. *Energy Procedia* **2017**, *126*, 565–572. [CrossRef]
73. European Commission-Directorate-General for Environment, 3encult-Efficient Energy for EU Cultural Heritage. Available online: www.3encult.eu/ (accessed on 2 May 2020).
74. Comitato Termotecnico Italiano, Prestazioni energetiche degli edifici-Parte 5: Calcolo dell'energia primaria e dalla quota di energia da fonti rinnovabili (UNI/TS 11300-5). Available online: http://store.uni.com/catalogo/index.php/uni-ts-11300-5-2016 (accessed on 6 May 2020).
75. De Mare, G.; Nesticò, A.; Caprino, R.M. *La Valutazione Finanziaria di Progetti per il Rilancio del Territorio. Applicazioni a Casi Reali*; FrancoAngeli: Milano, Italy, 2012.
76. European Commission. *Guide to Cost-Benefit Analysis of Investment Projects*; Publications Office of the European Union: Luxembourg, 2015.
77. Hwang, C.L.; Yoon, K. *Multiple Attribute Decision Making. Methods and Applications: A State-of-the-Art Survey*; Springer: New York, NY, USA, 1981.
78. Committee of Ministers of the Council of Europe. European Charter of the Architectural Heritage. In *Congress on the European Architectural Heritage*; Committee of Ministers of the Council of Europe: Amsterdam, The Netherlands, 1975.