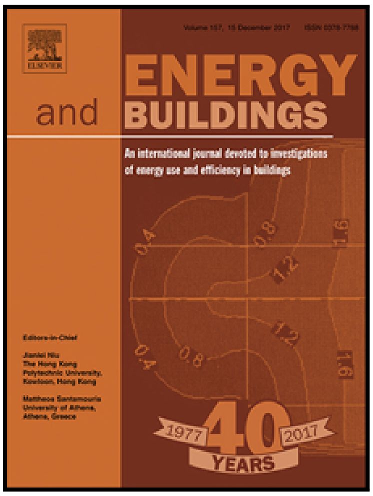

Planning energy retrofit on historic building stocks: Aa score-driven decision support system

Ruggeri Aurora Greta , Calzolari Marta , Scarpa Massimiliano , Gabrielli Laura , Davoli Pietromaria

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Highlights

- Building energy retrofit programs should also include conservation aspects;
- Building energy retrofit compatibility can be measured as a *restoration score*;
- Cultural heritage value includes architecture, materials and historical sense;
- Energy retrofits should be intended as an opportunity to protect the building.

Planning energy retrofit on historic building stocks: a score-driven decision support system

Authors Details

Ruggeri, Aurora Greta[a]; Calzolari, Marta[b]; Scarpa, Massimiliano[c]; Gabrielli, Laura[c]; Davoli, Pietromaria[d]

a= Department of Management Engineering, University of Padova, Stradella S. Nicola 3, 36100 Vicenza, Italy.
b= Department of Engineering and Architecture, University of Parma, Parco Area delle Scienze 181/A, 43124 Parma, Italy.
c= Department of Architecture and Arts, University IUAV of Venice, Dorsoduro 2206, 30123 Venice, Italy.
d= Department of Architecture, University of Ferrara, Via della Ghiara 36, 44121 Ferrara, Italy

- *Corresponding author*

Ruggeri, Aurora Greta
aurora.ruggeri@student.unife.it

Abstract

Among the policies and regulations aimed at reducing the energy use in building stocks, the retrofit of historic buildings is one of the hardest challenges both for research and practice, because it is necessary to combine the traditional energy/economy targets with safeguard programs and conservation theories.

In this paper, a decision support system is developed in order to plan and manage energy retrofit campaigns tailored for cultural heritage. Costs and energy uses are assessed, as well as the compatibility of interventions and their impact on indoor environmental quality. The energy use is seen under an economic, environmental, human and cultural perspective, providing a decision-making procedure that could be very useful for asset holders, public or private investors as well as for portfolio managers or agencies. The most important achievements in this work are the assessment of a so-called *restoration score* as a way to include conservation aspects in the selection procedure, and the integration of different appraisal techniques such as multi-attribute analysis, life cycle costing and analytic hierarchy process.

Key words:

historic buildings; decision-making; energy retrofit; analytic hierarchy process; multi-criteria analysis; life cycle costing; building stocks.

Abbreviations:

$[A]^{(h)}$ - pairwise comparison alternatives-matrix (per each h^{th} criterion) dimension Q x Q, entry $a_{ij}^{(h)}$
[C] - pairwise comparison criteria-matrix, dimension H × H, entry c_{ij}
[D] - decision matrix, dimension Q x H, entry d_{ij}
a – alternatives (in the AHP)
AHP - Analytic Hierarchy Process
B – available budget (€)
BEP - breakeven point (year)
B_k – buildings (War Wounded Houses in Italy), $k \in \mathbb{N}\{1, \dots, K\}$
C.I. - consistency index
C.R. - consistency ratio
c_h - conservation selection criteria (in the AHP), $h \in \mathbb{N}\{1, \dots, H\}$
Ci - investment cost (€)
Cl_1, Cl_2 and Cl_3 - clusters
Cop - operating costs (€/year)

Cop_{ele} - operating costs due to electric requirements (€/year)
Cop_{gas} - operating costs due to natural gas requirements (€/year)
D - debt
DCF - Discounted Cash Flow
E - equity
ES - energy savings (decision-making attribute)
F - financial subsidies delivered during a number of years s, $s \in \mathbb{N}\{0, \ldots, S\}$ (€/year)
G - metabolic generation rate
g_{ele} - growth rate on electricity
g_{gas} - growth rate on natural gas price
IC - internal comfort (decision-making attribute)
IEQ - indoor environmental quality
IRR - Internal Rate of Return
kd - cost of debt
ke - cost on equity
L - thermal load on the body
LCC - Life Cycle Cost (€)
NPV - Net Present Value (€)
NS - monetary net savings (€)
NS - net savings (decision-making attribute)
nZEB – nearly zero energy buildings
O - set O includes all the proposed O_q, $O = \{O_0, O_1, \ldots, O_q, \ldots, O_Q\}$
O_q - retrofit options, $q \in N\{0, \ldots, Q\}$
PB - Payback period (year)
PMV – Predicted mean vote
PPD - Predicted Percentage of Dissatisfied
r - discount rate
RB - reference building
RS - restoration score (decision-making attribute)
S_m - energy retrofit scenarios, $m \in N\{1, \ldots, M\}$, $\forall S_m = \subset v \subseteq O$
S_{m_opt} - optimum scenario
Sv - savings on energy use (€/year)
t - year in which costs occur, $t \in \mathbb{N}\{0, \ldots, T\}$ (year)
TH - threshold on energy requirements (kWh/m²·y)
TL – time limit (year)
v - vector of global scores
w- criteria weight vector, H-dimensional column vector, entry w_i
WACC - weighted average cost of capital
W_{ES}, W_{NS}, W_{IC}, W_{RS} - attributes' a-priori weighs
YED - yearly primary energy demand for space heating/cooling, hot water and lighting (kWh/m²·y)
λ_{max} - largest eigenvalue of a matrix

Declarations of interest:

None

1 INTRODUCTION

This paper presents a *score-driven decision support system* developed to plan and manage energy retrofit interventions specifically applied to cultural heritage and historic buildings. In this instance, it is necessary to combine the traditional energy/economy decision-making criteria with further considerations about the safeguard and the conservation of buildings and architectures. Energy retrofit actions applied to cultural heritage have to be not only cost-effective but also compatible with all buildings' features in terms of materials, aesthetics and historic significance.

To this end, we unify quantitative parameters, assessing costs and energy requirements, with qualitative parameters, estimating the compatibility of interventions and their impact on indoor environmental conditions. Economic, environmental and cultural issues are combined in an integrated approach, which is able to compare a plethora of retrofit options and identify the optimal design. The energy enhancement hence is considered as an optimization problem whose solution defines the retrofit configuration with the maximum benefit achievable.

1.1 Relevance of the topic

It is well known that energy efficiency and environmental sustainability, nowadays, have come to the forefront of worldwide scientific debates because of the urgent concern about climate changes [1]. A global transition towards a more sustainable economic system is underway. In this transition, the construction sector clearly embodies one of the most important factors in achieving a more efficient use of energy sources. Real estate stocks are extremely energy-intensive, being a major cause of energy waste and CO_2 emission. They are responsible for up to 40% of the worldwide energy use and more than 30% of the total greenhouse gas production. In Europe, building stocks account for almost half of the total energy demand, and the majority is due to older/existing properties rather than new buildings [2]. Besides, buildings' renovation rates are very low because the turnover is slow and expensive: it has been forecasted that about 70% of what will be the building stock in 2050 already exists today, but it is not feasible to achieve more than one deep refurbishment cycle in this 30-year timespan [3].

As a result, the building sector holds a strong potential in mitigating the energy shortage and reversing ongoing climate-changes, while international policies are focusing their attention on the deep decarbonisation of the building sector.

At European level, within Directive **2010/31/EU** on the energy performance of buildings [4], **Article 7** requires EU Members to grant that their existing assets meet minimum energy performance standards when they undergo a major renovation, while **Article 4** sets and describes minimum energy performance targets according to different categories of buildings. Besides, the revised Energy Performance of Buildings Directive (EU) **2018/844** [5], recently published in the EU Official Journal to update and supplement directive **2010/31/EU**, encourages the Member States to make their national stocks highly energy-efficient before 2050. This new Directive invites EU Members to carefully screen their stocks and organize refurbishment cycles based on global district approaches. Renovation schemes should therefore be applied to a group of buildings in a spatial context rather than to individual properties, and building stocks should be considered as a whole. This would allow to act in an integrated fashion on built assets, coordinating refurbishment schedules, leading to optimal designs.

We draw attention to the fact that although in Europe an extremely significant share of building stocks includes cultural heritage, historical properties are still often excluded from the interventions intended to reduce their energy use, because the legislation itself recognizes that their exceptional character must be preserved in the first place [6]. In fact, such buildings are officially protected as part of a designated environment, or because of their architectural or historic merit, and they cannot be altered either in their character or in appearance.

Nevertheless, cultural heritage is such a relevant portion of existing assets that its energy enhancement would bring key environmental and economic benefits. It has been assessed that European buildings built before 1919 are about 14% of the total, while the 12% dates between 1919 and 1945 [7]. As a consequence, their energy refurbishment could actively contribute to reach EU 2030 [8] and 2050 [9] targets about energy efficiency and climate. Among the European Countries, Italy, United Kingdom, France, Denmark, Sweden, Czech Republic and Bulgaria boast the largest amount of historic buildings [10]. Recent investigations underline that in Italy are located about 4,000,000 of the 5,367,000 monuments totally censed in Europe [11]. Among them, heritage buildings built before 1919 are estimated to be 19%, and those built between 1919 and 1945 are approximately 11-12% [12].

Given that European building stocks comprise built heritage in such a considerable proportion, integrated retrofit strategies cannot rely solely on energy-economy objectives, but conservation aspects have to be included as well.

1.2 Cultural heritage value

When designing energy retrofit measures for historic buildings, the main challenge is to find an appropriate equilibrium between energy efficiency improvement and heritage protection. The value of cultural heritage should be preserved in terms of architecture, materials, historic value, cultural significance and social meaning. It is a hard balance between several goals and constraints pulling towards two opposite directions: conservation on the one side, innovation on the other. Efficiency measures should be as effective as they are conservative, according to the conservation principles of architectural restoration, i.e. reversibility, distinguishability, compatibility, authenticity and minimum intervention [13]. Any energy retrofit improvement should be primarily intended as an opportunity to protect the building, and not as an action that could conflict against its conservational needs [14]. Historic buildings' inherent properties should never be overlooked; otherwise some retrofit measure could even turn out to be counterproductive or detrimental [15]. Retrofit designs should be thorough, well-integrated and compatible with the fabric [16].

Recently, a comprehensive literature review drafted by Lidelöw et al. [6] investigated the complex relationship between energy efficiency and heritage conservation of buildings. The authors compared a large set of studies on the topic and discussed whether these works were able to include the value of cultural heritage inside their energy retrofit programs. The majority of the papers analysed did not provide any discussion of cultural heritage values. Other works touched this issue just implicitly [17–19], while only a very few of them gave a fully explicit evaluation of the value of cultural heritage, integrating it both in the design and decision-making processes [20–24]. The authors stated it is not enough to assess the impact of retrofit measures on built heritage by referring to generic restoration concepts taken from conventions, agreements, guidelines or general theories. Conversely, greater transparency and accuracy are required in forecasting how energy retrofit actions will affect historic buildings. Restoration principles should not be left just as a general background, but they should be translated into practical applications and used to evaluate each design option [25]. The restoration theory should be the cornerstone that leads any modification process on cultural heritage [26]. Materials and shapes should be preserved [20], without forgetting that immaterial values also require specific protections [24].

The literature gap is, therefore, quite evident. There is still a great deal of uncertainty about which methods the assessment of cultural heritage values could be based on.

Specific value-assessments techniques need to be integrated with energy retrofit decision support systems, making explicit references to conservation paradigms and relevant theoretical frameworks. In [6], the authors invite future researchers to focus on this topic and develop selection processes able to incorporate the cultural heritage value. They also encourage to adopt a large-scale perspective (building stocks, wide assets) rather than a building-by-building approach. Besides, they suggest to go beyond the traditional assessment of reduced operational energy use, and prefer life-cycle approaches.

Following these recommendations, in the research presented in this paper, our goal is to develop a decision-making model to optimize energy retrofit investments applied to those building stocks that include historic buildings and cultural heritage. Specifically, we aim to integrate during the selection process four decision-making attributes, namely energy savings, economic profitability, indoor comfort enhancement and building preservation. While, in the case of the first attributes, assessment techniques exist, which include dynamic building energy simulations and detailed economic feasibility analyses, building preservation issues are still quite difficult to quantify. As such, in order to account for cultural heritage preservation aspects, we introduce the assessment of a **restoration compatibility score** through a tailored multi-criteria analysis.

The reminder of this article is structured as follows: **Section 2** presents the methodological approach adopted in this research. **Section 3** illustrates the model developed, while **Section 4** implements the model on a practical case study. **Section 5** discusses the results achieved, while **Section 6** outlines the conclusions of the work, introducing possible further developments.

2 METHODOLOGICAL APPROACH

Organizing and planning energy retrofit interventions on historic buildings is usually described in the specific literature as a balancing act between different (and often competing) goals and constraints [27]. Several publications have introduced a set of decision-making criteria to help the process [28–31]. In this research paper, and according to Amanda L. Webb [32], we identify four macro-categories of decision-making attributes to consider. They are:

1. Environmental benefits;
2. Economic profitability;
3. Improvement in indoor environmental conditions;
4. Protection and safeguard of the heritage.

Among these four macro-categories, a plethora of assessment techniques may be adopted to produce as many indexes/metrics measuring the performance of retrofit projects. Broadly recognized, the first two categories (energy-economy) have been extensively applied in a countless number of retrofit analyses, producing consistent results [33–39]. By contrast, the indoor comfort enhancement has been rarely included in these kinds of studies [40], while the measure of the value of cultural heritage still remains a topic under discussion [41].

As far as environmental benefits are concerned, they result from the comparison of the energy performance of a building before and after the implementation of retrofit interventions. The environmental benefits are usually estimated in terms of operating primary energy, greenhouse gases emissions or embodied energy [42]. In this paper, we assess the total energy saved per year, measured in kWh/m^2, as **energy savings** (**ES**). Ascione et. al, in [43], provided a replicable approach for the energy diagnosis and performance assessment in heritage buildings, which we also adopt in this research to predict the environmental benefits achieved after the implementation of various retrofit measures.

With regard to the set of criteria used to assess the economic viability of interventions, they are connected with the estimation of costs and savings in relation to any design option. The savings are due to a lower energy demand, or when on-site produced energy is sold to the grid. Instead, costs can be estimated using various techniques, including direct comparison, bill of quantities or mixed procedures [44–46]. The economic criteria evaluate the cost-effectiveness of retrofit investments, and ascertain if the monetary savings are able to cover (economic feasibility) or even exceed (economic profitability) the investment costs incurred. Among the most traditional economic assessment criteria, there are the Net Present Value (NPV), the Payback period (PB), and the Internal Rate of Return (IRR). They all result from the Discounted Cash Flow (DCF) technique, as illustrated in [47] and [48]. The NPV is the present value of all monetary incomes and outcomes after a period of analysis of a project [49,50]. The PB period is the time after which the investment expenditure is expected to be recovered from the produced cash inflows [51]. The IRR, used as a threshold to measure the profitability of energy investments, is the discount rate that makes the NPV of cash flows equal to zero [52]. Other popular economic indicators often applied in energy retrofit studies are the **net savings** (**NS**) and the breakeven point (BEP), both resulting from Life Cycle Cost (LCC) analyses [53-55]. The NS measure the difference between the discounted LCCs of two alternative projects over a given timeframe, while the BEP represents the time when two alternative designs are equal because they reach the same exact LCC value [56]. Specifically, the NS are chosen in this paper to account for the economic benefits produced by the investment.

Conversely, the set of criteria describing the indoor environment are related to occupants' comfort, indoor air quality levels, and specific humidity-temperature conditions. The indoor environmental quality (IEQ) is an index of occupants' satisfaction with the internal environment due to thermal comfort, air quality, light and sound [57]. The IEQ can be evaluated for existing buildings by straightforwardly comparing their performance against modern standards [58] or new constructions [59]. Otherwise, numerical indexes may also be employed to measure the acceptability/satisfaction of indoor conditions, such as the Predicted Mean Vote (PMV) or the consequent Predicted Percentage of Dissatisfied (PPD) [60]. In this work, the PMV is chosen to quantify the **internal comfort** (**IC**) after the implementation of retrofit enhancements.

The last category of criteria, which refers to the protection of the heritage, is the most difficult to handle, as non-measurable parameters are primarily involved, aimed at achieving the long-term use of the building and the preservation of its cultural value. Such criteria, like authenticity or reversibility, are hard to quantify due to their qualitative nature. However, the compatibility of energy retrofit interventions needs, somehow, to be measured, in order to evaluate and grant that any modification on historic buildings will not alter or compromise their significance, features and materials, their distinguishing character and those elements defining the buildings' sense of time and place [61]. Several publications are stressing the huge lack in the scientific literature of methodologies and techniques currently available to explicitly assess the impact that energy retrofit measures will produce on the value of cultural heritage [27]. This is a complex and multi-faced act, in which more than one aspect is pursued at a time. For this reason, multiple-criteria approaches may provide an appropriate framework [62] to address this issue. In the present work, an Analytic Hierarchy Process (AHP) is chosen for the creation of priorities among different alternative designs. Precisely, a **restoration score** (**RS**) is estimated for each design option so that a quantification of its compatibility is given.

3 MODEL DEFINITION

3.1 Overview

As introduced before, the model developed in this article aims to find the optimal combination of energy retrofit interventions on a building portfolio consisting of historic buildings. The four attributes described above (ES, NS, IC, RS) act synergistically in the selection process, whose goal is to obtain the greatest benefit in terms of energy saving, monetary saving, comfort enhancement and building preservation. Therefore, the set of interventions simultaneously maximizing the four attributes represents the best retrofit design scenario. The model, schematized in Figure 1, proceeds as follows:

- Global analysis of the building stock. At this preliminary stage it is important to define:
    a. For each building, the main characteristics, such as size, age, intended use, building type, etc.;

   b. Data and categories for building stock clustering;

- Consequent subdivision of the building stock into homogeneous categories of buildings;
- Selection of one reference building per stock/stock's category; In this phase, well documented buildings should be used as references, i.e. buildings with a lot of data and information, such as drawings, reports, energy bills, building management system data, or others. In further detail, a RB is one single property chosen among a group (the stock) due to its representative features and its ability to describe a building category or typology. There are two possible situations. If the building stock considered is small and homogeneous, the definition of one single RB will be adequate to represent the entire population. Otherwise, if the built asset presents numerous and heterogeneous properties, it should be subdivided into smaller groups, called categories, and one RB should be selected per each category. Under this perspective, detailed analysis, energy diagnosis and comparatives simulations can be performed for RBs only, with the purpose of being then extended to the stock using unitary parameters, such as €/(m²·y), kWh/(m²·y) or others.
- Design of a set of retrofit options (**O**), which could differ for the different building categories;
- Definition of every consequent energy retrofit scenario (**S**), i.e. all the possible combinations of the proposed options (so that each scenario represents one particular subset of retrofit options);
- Implementation of the retrofit scenarios on the reference building/s;
- Assessment of the corresponding decision-making attributes (**ES, NS, IC, RS**) for each scenario;
- Comparison and ranking of the retrofit scenarios according to the four attributes; In this instance, four decision-making attributes (both qualitative and quantitative) drive the selection process and, therefore, a scalarized multi-attribute optimization will be the adequate technique to define the optimal retrofit scenario among the proposed ones.
- Normalization and scalarization of the decision-making attributes (**ES, NS, IC, RS**) resulting on a min-max base, so as to guide the multi-attribute optimization;
- Identification of the optimal scenario, leading to the maximum overall benefits.

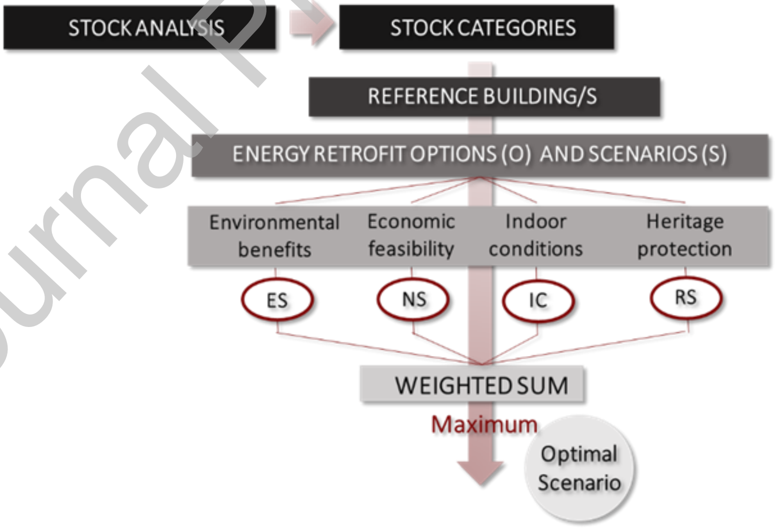


Figure 1 - decision-making model

The European Authorities have recommended the use of a RB approach promoting buildings' energy refurbishment cycles at a stock level, when it is unfeasible to reach an intimate knowledge of each individual property in a large asset [63]. Several works have already shown the usefulness of a RB strategy in organizing and managing complex retrofit programs in wide building portfolios, such as for several examples of commercial buildings in France and Poland [64], for a dwelling stock in Romania [65], for a residential portfolio in Ai Ain City (UAE) [66] and for numerous different assets in China [67].

In this paper, the "**score-driven decision support system**" developed will be demonstrated on one specific RB, namely the Cuneo War Wounded House (North Italy), a twentieth-century historic property. In particular, several retrofit options (O_q) are suggested for this demonstration. The set O includes all the proposed O_q, and it is defined as O = {O_0, O_1, …, O_q, …, O_Q}, with q ∈ N {0, …, Q}; q = 0 refers to the building in its current status, namely the "do-nothing" option, while 1 ≤ q ≤ Q refers to the proposed designs. Each option could be applied to the RB individually. Otherwise, a group of O may be implemented simultaneously on the building. Whatever possible combination of O_q defines one different energy retrofit scenario, denominated S_m, where m ∈ N {1, ..., M}. Therefore, each S_m is a particular subset of O, so that ∀ S_m = ⊂ v ⊆ O.

The four attributes previously discussed in Paragraph 2 are assessed for every S_m, resulting as ES_m, NS_m, IC_m and RS_m.

3.2 Four decision-making attributes

As regards the first attribute, **ES_m** measures the environmental benefit achieved through the building enhancement in terms of energy saved per year (kWh/m²·y) if compared to the do-nothing scenario. To this purpose, the yearly primary energy demand for space heating/cooling, hot water and lighting (YED_m) is assessed in the current status and in every design scenario using **EnergyPlus®** as simulation software [43]. ES_m is straightforwardly calculated in Eq. 1 by comparing the energy demand before and after the retrofit:

$$ES_m = YED_0 - YED_m \qquad \text{Eq. 1}$$

In particular, the YED, according to the primary energy sources, can be assessed as in Eq. 2:

$$YED = \left(\frac{Qheat}{\eta_{g\_heat}} * fp_{heat}\right) + \left(\frac{Qcool}{\eta_{g\_cool}} * fp_{cool}\right) + \left(\frac{Qdhw}{\eta_{g\_dhw}} * fp_{dhw}\right) + (Qelec * fp_{elec}) \qquad \text{Eq. 2}$$

Qheat, Qcool, Qdhw and Qelec represent the building energy demand for heating, cooling, daily hot water and electricity (lighting and equipment) in kWh. The building energy demand is that specific quantity of energy that needs to be be provided (or extracted) from a thermodynamic system (i.e. the building) so as to guarantee predetermined internal conditions and requirements of temperature, light and uses. The seasonal global yield η_g can be defined as the ratio between the heating/cooling energy required by the building over a year, and the energy required by the equipment to provide such amount of energy; η_g accounts the energy losses determined by energy production, distribution, emission and regulation. The primary energy factors fp, instead, indicate the primary energy required to produce a certain amount of energy delivered (i.e. required by building-installation), considering the different energy vectors (such as electricity, natural gas, district heating or others). The primary energy factors are established by convention, often for energy certification purposes. The primary energy demand is given by the quantities of energy vectors exported or delivered, including primary energy factors, and it can also be named YED.

The estimation of ES_m is crucial in the decision-making process because it provides a measure and a quantification of each retrofit designs' effectiveness, as far as operating energy use is concerned.

The second attribute, **NS_m**, regards the measure of the economic profitability of the interventions and takes into account the monetary savings obtained from the reduction in energy use. This criterion relies on a Life Cycle Cost (LCC) approach, as recommended by both the Directive **2010/31/EU** [4] and the Commission Delegated Regulation (EU) **244/2012** [63] on the cost-optimal strategy in buildings' energy efficiency. When it comes to provide an economic assessment of energy retrofit investments, the LCC certainly is one of the most suitable techniques to be adopted because it allows considering not only the investment costs but also the future operating costs due to management and maintenance. This kind of analysis leads to the identification of the retrofit option with the lowest whole-cost during a life cycle (or a period of analysis). Consequently, each retrofit scenario S_m in the present model is associated with its investment cost (Ci_m), operating costs (Cop_m) and savings on energy requirements (Sv_m). The investment cost Ci_m is the product of the unitary price of the retrofit actions and the quantity of material. The operating cost (Cop_m) is given by the yearly primary energy times the energy price (€/kWh), including (if any) maintenance costs. The operating costs consider separately the demand of natural gas (Cop_{gas_m}) and electricity (Cop_{ele_m}). Finally, the energy savings produced by any m^{th} retrofit scenario are assessed as $Sv_m = Cop_0 - Cop_m$, when $1 \leq m \leq M$.

Usually, energy retrofits in buildings may be promoted by the granting of financial subsidies (F_m). When a subsidy is available and delivered during a number of years s, s ∈ ℕ {0, ..., S}, it also has to be included in the NS_m calculation as additional savings. The monetary net savings are calculated in this model as in Eq. 3:

∀ m, m ∈ ℕ {1, ..., M}

$$NS_m = \sum_{t=0}^{T}\left(\frac{\mathrm{Cop}_{gas-0}\,(1+g_{gas})^t}{(1+r)^t} + \frac{\mathrm{Cop}_{ele-0}\,(1+g_{ele})^t}{(1+r)^t}\right) + \\ -\sum_{t=0}^{T}\sum_{s=0}^{S}\left(\frac{\mathrm{Ci}_m}{(1+r)^t} + \frac{\mathrm{Cop}_{gas-m}\,(1+g_{gas})^t}{(1+r)^t} + \frac{\mathrm{Cop}_{ele-m}\,(1+g_{ele})^t}{(1+r)^t} - \frac{(\mathrm{F}_m)}{(1+r)^s}\right) \qquad \textit{Eq. 3}$$

$t \in \mathbb{N}\ \{0, \ldots, T\}$

$s \in \mathbb{N}\ \{0, \ldots, S\}$

In this formula, r is the discount rate, g_{gas} is the growth rate on the price of natural gas, g_{ele} is the growth rate on electricity, and t is the year in which costs occur; t can vary between 0 and T, where T is the period of analysis.

Conversely, the third attribute, **IC$_m$**, measures the users' satisfaction with the indoor environment according to each retrofit scenario's effect on the perceived comfort. As mentioned before, the IC$_m$ is assessed through the PMV index. Firstly introduced by Fanger [68,69], the PMV quantifies the average thermal sensation response towards specific indoor conditions. The PMV can be calculated as a function of the thermal load on the body (L) and the metabolic generation rate (G), as in Eq. 4. The parameter L depends on air temperature, mean radiant temperature, air velocity, air humidity, clothing resistance, and activity level. Please refer to [70] for additional information on the PMV calculation. Therefore:

$$IC_m \;=\; PMV_m \;=\; (0.303e^{-0.036G_m} + 0.28) * L_m \qquad \textit{Eq. 4}$$

The PMV is expressed through the ASHRAE thermal sensation scale [71], where PMV $\in \mathbb{R}$ {-3, ..., +3}. In this scale +3 expresses hot sensation, +2 warm, +1 slightly warm, 0 is the neutral (optimal comfort), -1 expresses slightly cool sensation, -2 cool and -3 cold. In synthesis, the further from the 0, the greater the discomfort.

Finally, the fourth attribute we take into consideration addresses the compatibility of energy retrofit projects under a perspective of heritage safeguard and preservation. Unlike the others, this last parameter is hard to quantify since it expresses a multi-faced issue. It should account, in fact, for the contribution of several non-measurable aspects related to cultural heritage protection, restoration principles, and conservation theory. To this end, we introduce the assessment of a **restoration score**, **RS$_m$**, in order to, in a way, "objectively measure" the suitability of the retrofit scenarios. The RS is based on the evaluation of each S$_m$ according to a set of conservation criteria, as in Eq. 5. The following Paragraph 3.3 specifically delves into the assessment of the restoration score through a multi-criteria approach.

$$RS_m \;=\; f(conservation\ criteria)_m \qquad \textit{Eq. 5}$$

3.3 Assessing the restoration score (RS)

The RS$_m$ is obtained in this research from the application of the multi-criteria analysis. In particular, we use an AHP because this technique allows to evaluate and compare a set of different alternatives, balancing several and competing criteria, including also qualitative aspects. The AHP, firstly proposed and developed by Saaty [72,73], models subjective decision-making procedures based on a multiplicity of criteria organized in a hierarchical system. The decision problem is therefore shaped as a hierarchical structure: the first level of the AHP's structure indicates the goal of the problem. In the second level, the goal is decomposed into several decision-making criteria (and, whether necessary, into sub-criteria), while the lower level indicates the alternatives of the problem.

In this research, the intent is to assign each retrofit option O$_q$ a corresponding restoration score RS$_q$ based on a set of selection criteria c (the conservation criteria).

Afterwards, it will be possible to assess the total restoration score RS$_m$ for every scenario S$_m$ as the mathematical mean of all the RS$_q$ included in that particular scenario. Consequently, the AHP's alternatives (a) correspond to the retrofit options O$_q$, while RS$_q$ is the goal. A number H of conservation criteria (c$_h$) is introduced to assess the performance of each alternative with respect to the others, with h $\in \mathbb{N}$ {1, ..., H}. The conservation criteria adopted for this research are presented in Paragraph 4.7.

After the hierarchical structure of the analysis is set up, a pairwise comparison criteria-matrix [C] can be developed as follow. The matrix [C] is an H × H real matrix, whose c$_{ij}$ entries represent the importance of the ith criterion if compared to the jth criterion. When $c_{ij} > 1$, it means the ith criterion is more important than the jth criterion, whereas if $c_{ij} < 1$, the ith criterion is less important than the jth criterion. If two criteria have the same importance, c$_{ij}$ is equal to 1. The matrix is reciprocal to the main diagonal, so $c_{ij}=1/c_{ji}$. The relative importance between two criteria is measured according to a numerical scale from 1 to 9, as presented in [74] and reported in Paragraph 4.7.

$$C = \begin{vmatrix} c_{11} & c_{12} & \dots & c_{1H} \\ c_{21} & c_{22} & \dots & c_{HH} \\ \dots & \dots & c_{ij} & \dots \\ c_{H1} & c_{H2} & \dots & c_{HH} \end{vmatrix}$$

$c_{ij} / 1 \leq i \leq H$ and $1 \leq j \leq H$

From [C], it is obtained the criteria weight vector w, an H-dimensional column vector, whose entries are denominated w_i, with $1 \leq i \leq H$. Each w_i element is assessed through Eq. 6:

$$\forall\, i\ (c_{ij}),\quad w_i = \frac{\sum_{j=1}^{H} c_{ij}}{\sum_{i=1}^{H} \sum_{j=1}^{H} c_{ij}} \qquad \text{Eq. 6}$$

$$w = \begin{vmatrix} w_1 \\ w_2 \\ \dots \\ w_i \\ \dots \\ w_H \end{vmatrix}$$

$w_i / 1 \leq i \leq H$

At this stage, one pairwise comparison alternatives-matrix $[A]^{(h)}$ is built per each h^{th} criterion to compare the alternatives. Every matrix $[A]^{(h)}$ is of dimension Q x Q, where, again, Q is the total number of retrofit options. Each entry of the matrix is called $a_{ij}^{(h)}$, and it represents the evaluation of the i^{th} alternative compared to the j^{th} alternative, with respect to the h^{th} criterion. Each element $a_{ij}^{(h)} = 1/a_{ji}^{(h)}$, while $a_{ii}^{(h)} = 1\ \forall\, i$.

If $a_{ij}^{(h)} > 1$, then the i^{th} alternative is better than the j^{th} alternative, while if $a_{ij}^{(h)} < 1$, the i^{th} alternative is worse than the j^{th} one. If two alternatives are evaluated as equivalent with respect to the h^{th} criterion, then the entry is $a_{ij}^{(h)} = 1$.

$$\forall\, c_h,\ h \in \mathbb{N}\ \{1, \dots, H\} \rightarrow [A]^{(h)} = \begin{vmatrix} a_{11}^{(h)} & a_{12}^{(h)} & \dots & a_{1Q}^{(h)} \\ a_{21}^{(h)} & a_{22}^{(h)} & \dots & a_{2Q}^{(h)} \\ \dots & \dots & a_{ij}^{(h)} & \dots \\ a_{Q1}^{(h)} & a_{Q2}^{(h)} & \dots & a_{QQ}^{(h)} \end{vmatrix}$$

$a_{ij}^{(h)} / 1 \leq i \leq Q$ and $1 \leq j \leq Q$

Finally, the decision matrix is developed as a Q x H real matrix [D]. The entries d_{ij} represent the performance of every q^{th} retrofit option with respect to the h^{th} criterion. The decision matrix is calculated following Eq. 7:

$$\forall\, i\ (a_{ij}^{(h)}) / 1 \leq i \leq Q, \text{ then} \quad d_{ij(\forall j=h)} = \frac{\sum_{j=1}^{Q} a_{ij}^{(h)}}{\sum_{i=1}^{Q} \sum_{j=1}^{Q} a_{ij(h)}} \quad \text{if, } \forall\, j\ (d_{ij}) / j=h \qquad \text{Eq. 7}$$

$$[D] = \begin{vmatrix} d_{11} & d_{12} & \dots & d_{1H} \\ d_{21} & d_{22} & \dots & d_{2H} \\ \dots & \dots & d_{ij} & .. \\ d_{Q1} & d_{Q2} & \dots & d_{QH} \end{vmatrix}$$

$d_{ij} / 1 \leq i \leq Q$ and $1 \leq j \leq H$

Once the weight vector w and the decision matrix [D] have been computed, the AHP leads to obtain a vector *v* of global scores by multiplying [D] and w (see Eq. 8), such that:

$$v = [D] \cdot w \qquad \text{Eq. 8}$$

The i^{th} entry v_i of vector *v* is the score assigned to each alternative (Eq. 9), which represents the compatibility score of the restoration assessed for every q^{th} design option:

$$\forall\, i\, (v_i)\ /\ i=q, \text{ then} \qquad RS_q = v_i \qquad \text{Eq. 9}$$

$$v = \begin{vmatrix} v_1 \\ v_2 \\ \ldots \\ v_i \\ \ldots \\ v_Q \end{vmatrix}$$

$$v_i \ /\ 1 \leq i \leq Q$$

Since one RS_q is now assigned to each retrofit option, it is also possible to assess RS_m, the overall restoration score. RS_m is given by the average of all RS_q defining a scenario S_m, as in Eq. 10:

$$\forall\, m\, (S_m), \forall\, q\, (O_q)\ /\ O_q \in O \rightarrow S_m = \subset V \subseteq O, \qquad RS_m = \frac{\sum RS_q}{\Sigma q} \qquad \text{Eq. 10}$$

3.4 Multi-attribute optimization model

The four attributes, defined in the paragraph above, fully describe the performance of any m^{th} scenario when applied to the RB analysed. Furthermore, in order to allow any stakeholder giving different importance to the four attributes, a set of a-priori weighs is introduced, i.e. W_{ES}, W_{NS}, W_{IC}, W_{RS}. The weights express the decider's preferences of prioritizing one attribute over the others. The optimization model can be settled as the maximization of the four attributes (ES_m, NS_m, IC_m, RS_m), times their corresponding weights (W_{ES}, W_{NS}, W_{IC}, W_{RS}). The goal is to identify which set of O_q leads to the optimum scenario S_{m_opt}. The multi-attribute optimization problem is solved by calculating the overall ranking of the retrofit scenarios through a weighted and scalarized sum, such that to combine the objective functions into a single objective function (Eq. 11). Because the four attributes show different units of measurement, they are normalized in the interval [0;1], in order to make their scalarization into a single function consistent. The optimal scenario S_{m_opt} is defined as:

$$\begin{aligned} &\forall\, m \in \mathbb{N}\, \{1, \ldots, M\}, \\ &\text{if } max\, [(W_{NS} * NS_m) + (W_{ES} * ES_m) + (W_{IC} * IC_m) + (W_{RS} * RS_m)] \qquad \text{Eq. 11} \\ &\rightarrow m = m\_{opt} \text{ and } S_m = S_{m\_opt}, \end{aligned}$$

The major limitation of the model is the monetary resource limitation. So, if the available budget is identified as "B", the following inequality in Eq. 12 must be verified. Another constraint needs to be specified: the discounted payback period of the investment should respect a predefined time limit (TL) chosen by the investor (Eq. 13). In addition, the overall energy use is set to be lower than a fixed threshold (TH) (Eq. 14). Trough Eq. 14 we set the yearly energy demand to be lower than a TH which may depend on both the target of the retrofit (e.g. deep renovation level, nearly zero energy buildings or others) and on local codes and standards. In this way, we preventively exclude from the selection process those retrofit scenarios that would be unacceptable as far as minimum standards are concerned. Finally, the total NS produced need to be greater than zero (Eq. 15). Other technical or feasibility constraints could also be introduced according to specific requirements.

$$Ci_{m\_opt} \leq B \qquad \text{Eq. 12}$$

$$PB_{m\_opt} \leq TL$$ Eq. 13

$$En\ Cons_{m_{opt}} \leq TC$$ Eq. 14

$$NS_{m\_opt} \geq 0$$ Eq. 15

As a result, the optimization analysis simply identifies which scenario represents the optimal retrofit level according to the four attributes and the weighs previously discussed.

It is crucial to mention that other limitations could easily be added, such as a benchmark for indoor environmental quality (PMV $\geq$ treshold) or restoration score (RS $\geq$ treshold). In this research we limit the constraints to initial costs, payback period, yearly energy use and net savings produced over a life cycle costing, as further detailed in Section 4.9.

4 MODEL IMPLEMENTATION: A CASE-STUDY

4.1 War wounded houses: a wide property asset

In this study, the decision support system developed is implemented on a wide historic building stock. It comprises several Italian twentieth-century architectures, i.e. the War Wounded Houses [75,76]. These buildings have been erected mainly during the Fascist Era (1922-1943), in the aftermath of World War One, to provide medical and social assistance to war wounded soldiers.

In Italy, War Wounded Houses were considered important monuments and memorials to celebrate the warfare and the human's sacrifice for the Nation [77,78]. Today, these buildings no longer serve their original purpose of assistance to war invalids and remain almost uninhabited. They are in such a state of neglect that it rises the urgent issue of their restoration, while their technological obsolescence and energy-inefficiency recommend their deep refurbishment. Nevertheless, it is hard to plan and organise energy retrofit investments on War Wounded Houses, firstly, due to the large size and heterogeneity of the stock, and secondly, because their renovation should grant high effectiveness without compromising the **heritage value** they embody.

As shown in Figure 2, War Wounded Houses are widespread throughout Italy, encompassing all the six Italian climatic zones, and they present various building types, sizes and maintenance conditions. For these reasons, the same energy retrofit measures cannot be suitable for every building in the stock. On the other hand, the large size of the portfolio does not allow to analyse each building separately and design tailor-made solutions. As such, it is chosen to subdivide the portfolio into uniform subsets through partitional clustering, so as to regroup the buildings based on shared characteristics. The attributes defining the subsets are established according to the specific literature. The buildings in the portfolio are defined as B_k, $k \in \mathbb{N}$ {1, …, K}, K=36. The clustering algorithm used is the k-means, and the attributes considered for partitioning are climatic zone (A-F) [79], floor area (m^2) [56], maintenance conditions (0-5) and year of construction [80]. We chose to define three different clusters, as suggested by the graphic elbow method, named Cl_1, Cl_2 and Cl_3. Each object belongs to the cluster with the nearest mean, so that:

- $\forall B_k, k \in N \{1, 2, 3, 4, 5, 6, 7, 8, 9, 34, 35, 36\} \mid B_k \in Cl_1$,
- $\forall B_k, k \in N \{10, 11, 12, 13, 14, 28, 29, 30, 31, 32, 33\} \mid B_k \in Cl_2$,
- $\forall B_k, k \in N \{15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27\} \mid B_k \in Cl_3$.

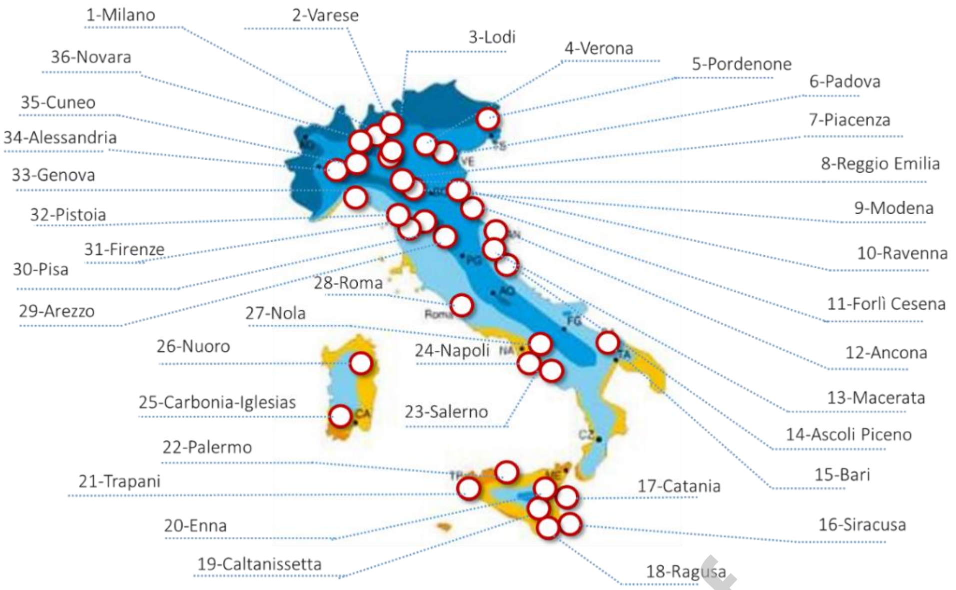


Figure 2 – War Wounded Houses in Italy

4.2 Reference building: Cuneo War wounded house

This paper focusses on cluster number 1 to demonstrate the *score-driven* model developed. Cl_1 may represent a significant example because it includes the properties located in the climatic areas F and E, the coldest in Italy, where there is the most urgent need to implement energy retrofit actions to reduce energy use in winter.

Due to its representative characteristics, the Cuneo House (Figure 3), is selected as the RB to represent Cl_1 [81]. Its structure (reinforced concrete), technologies (brick wall, windows and materials), architecture (a mixture of modern and classical elements), shape (compact) and maintenance conditions (obsolete equipment and inadequate energy-saving systems) are able to portray the population of the cluster comprehensively. The Cuneo House, designed by the engineers Augusto Toselli and Cesare Genovese, was built between 1935 and 1936.

Figure 3: Cuneo War Wounded House (reference building for Cluster 1)

The building energy simulations of the Cuneo House were performed via **EnergyPlus**, both for the pre-retrofit status and the post-retrofit configurations. However, in order to ensure reliable calculations, a detailed audit has been developed, aimed at decreasing uncertainty in the modelling assumptions and in the consequent input parameters. To this purpose, we performed accurate on-site investigations so as to calibrate the simulation model based on real data. In detail, the following inspections have been carried out:

- A general overview of the building by a thermal camera FLIR TG 167, in order to point out the presence of heat bridges, moisture, any discontinuities in the masonry or any other envelope issue to be taken into consideration during building energy modelling
- Test of reference building envelope constructions by Heat Flux Metering, to determine the corresponding U-values and consequently choose the fitting values for material thermal conductivity and windows characteristics. Heat-flux meter campaigns have been performed, in winter, on selected walls and windows for variable periods, depending on

their thickness and (assumed) thermal resistance. During this acquisition time, the heating system was running h24, keeping the internal temperature at 20°C. Since the heat-flux meter could not have been used on roofs and ground floors, the corresponding U-value for these components have been assessed in conformity to Italian Standard **UNI 10351** [82].

- Tracer-gas leak testing applied to two rooms, in order to correlate infiltration with indoor-outdoor pressure difference, and increase the reliability in the assumption of infiltration airflow rates in the building energy model.
- Register of presence of people, aimed to increase the reliability in the definition of occupancy intensity in the building.
- Survey about the building management and the use of lights and electric appliances. The survey has been supplied to a selected group of building users, in order to choose appropriate management definitions about lights, electric appliances and HVAC (Heating, Ventilation and Air Conditioning) systems in the energy model.

We ran the simulation of the building under the conditions defined after the inspections and the surveys mentioned above. We used a tailored weather file of Torino Caselle (a site close to Cuneo) built up via the actual weather records taken during 2018. We also collected the actual bills due to energy use of the same year. Then, in order to verify the actual reliability of the model developed, we performed a direct comparison between the simulation's results against the actual bills, and consequently calibrated the model by changing the input parameters (e.g. infiltration airflow rates, lights management, electric equipment power levels, set-point temperatures and occupancy levels) until the discrepancies were below 10%, which represents good reliability. The model characteristics and the boundary conditions chosen are presented in Table 1: We also considered an operation time from Monday to Friday, from 9 a.m. to 6 p.m., while the heating set-point temperature is 20°C (operative temperature).

	Mean value, averaged on the floor area of the relevant rooms	Mean value, averaged on the total floor area
People [p/m²]	0.1	0.07
Lights [W/m²]	22.5	14.6
Electrical equipment [W/m²]	36	30.2
Ventilation [ach]	2.15	1.86
Infiltration [ach]	0.65	0.65

Table 1 - Main input data about internal heat gains, ventilation and infiltration.

4.3 Energy retrofit interventions

A set of energy retrofit options is designed to reduce the energy demand of the property. Since it comes down to interventions on cultural heritage, much attention is given to the fact that the suggested measures are cost-effective as well as compatible with the restoration principles of architectural conservation [13]. For this reason, we take as an accredited reference the "Guidelines for energy-efficiency improvements in Cultural Heritage" [83], recently published by the Italian Ministry of Cultural Heritage and Activities. These guidelines describe energy improvement strategies strongly oriented towards conservation.

When defining the energy retrofit designs, it is important to consider that the Cuneo House, along with the other buildings in cluster 1, shows the highest energy demand because of lighting and winter heating. On the contrary, the building is very effective in summer, given the fresh climate and the huge thermal inertia of walls and slabs. Hot water production, instead, has a minor impact on total energy requirements.

Seventeen retrofit options (O_q) are designed and tested on the RB, $q \in \mathbb{N}$ {0, …, Q} and Q=17. Detailed information about the interventions and their investment costs are provided in Table 2. The listed unitary prices are equivalent to the construction cost of each intervention (Ci_q) [84], thus including the costs of materials, labour, plants and equipment, overheads and contractor's profit [85].

Option	Energy efficiency measures	Price per unit
O_0	**Do-nothing** option	-
O_1	Installation of **thermostatic valves** on heaters and radiators	120 € each
O_2	Installation of **mechanical ventilation** with heat recovery system, air treatment and humidification	150 €/m²
O_3	Traditional boiler substitution with a **condensing boiler** (efficiency 1.05)	5000 € each
O_4	**Low-emissivity films** on windows	30 €/m²
O_5	Installation of **triple glazing windows** (filled with Krypton) with low emissivity coating	500 €/m²
O_6	**Lighting** refurbishment with LED bulbs (100 lm/W)	20 € each
O_7	**Internal wall** insulation: perlite **thermalplaster**, thickness=3 cm, λ=0.08W/m·K	65 €/m²
O_8	**Internal wall** insulation: **stone wool** insulation, thickness=8 cm, λ=0,033 W/(m·K)	50 €/m²
O_9	**Internal wall** insulation: **stone wool** insulation, thickness=16 cm, λ=0,033 W/(m·K)	70 €/m²
O_{10}	**Internal wall** insulation: **aerogel**, thickness=1 cm, λ=0,015 W/(m·K)	110 €/m²
O_{11}	**External roof** insulation: **stone wool** insulation, thickness=8 cm, λ=0,033 W/(m·K)	50 €/m²
O_{12}	**External roof** insulation: **stone wool** insulation, thickness=16 cm, λ=0,033 W/(m·K)	70 €/m²
O_{13}	**Internal roof** insulation: perlite **thermalplaster**, thickness=3 cm, thermal conductivity=0.08W/m·K	65 €/m²
O_{14}	**Internal roof** insulation: **aerogel**, thickness=1 cm, λ=0,015 W/(m·K)	110 €/m²
O_{15}	**Internal floor** insulation: **stone wool** insulation, thickness=8 cm, λ=0,033 W/(m·K)	50 €/m²
O_{16}	**Internal floor** insulation: **stone wool** insulation, thickness=16 cm, λ=0,033 W/(m·K)	70 €/m²
O_{17}	**Internalfloor** insulation: **aerogel**, thickness=1 cm, λ=0,015 W/(m·K)	110 €/m²

Table 2 - Energy retrofit options

4.4 First decision-making attribute: environmental benefits

The seventeen retrofit options can produce 18,431 different scenarios S_m ($m \in \mathbb{N}$ {0, …, M} and M=18,431), that is the total number of possible combinations, provided that some options are mutually exclusive, while others may be applied simultaneously.

The assessment of the YED_m for each retrofit scenario leads to the measure of the corresponding environmental benefits ES_m achieved in terms of kWh/(m²·y) saved on heating, hot water and lighting. The YED_m is evaluated in the current status and in every scenario through the **EnergyPlus** calculation engine. According to Eq. 1, ES_m result from comparing the energy demand of any retrofit scenario against the pre-retrofit status. The main geometrical characteristics of the building simulation model are listed in Table 3 and Table 4:

Overall characteristics		
Floor area [m²]	Volume [m³]	Number of zones [-]
1133	3188	13
Maximum dimensions		
Length [m]	Width [m]	Height [m]
27	19	19 (included underground floor)

Table 3 - Overall building dimensions

Layout	Further specification	Area - Net [m²]	Area - Windows [m²]
Floor (slab on-grade)	-	426	-
Vertical walls	North	114	34
	East	268	48
	South	75	79
	West	149	37
	SUM	606	198
Roof	-	454	-

Table 4 - Overview of the building surfaces

Moreover, the set of options considered, implying a wide number of possible scenarios, is better specified in

Table 5, Table 6 and Table 7. Finally, the overall set of key characteristics corresponding to different designs is resumed in Table 8. As a result, Table 9 shows the environmental benefits assessed for each analysed scenario.

Layer 01		
Concrete layer		
Property	Value	Options
Thickness	0.2 m	Any
Thermal Conductivity	1.13 W/(m·K)	Any
Density	2000 kg/m^3	Any
Specific heat	1000 J/(kg·K)	Any
Water vapour permeability coefficient	$23.0 \cdot 10^{-12}$ kg/(m·s·Pa)	Any

Layer 02		
Possible internal insulation layer		
Property	Value	Options
Thickness	- m	O15 = 0 & O16 = 0 & O17 = 0
	0.08 m	O15 = 1 & O16 = 0 & O17 = 0
	0.16 m	O15 = 0 & O16 = 1 & O17 = 0
	0.01 m	O15 = 0 & O16 = 0 & O17 = 1
Thermal Conductivity	- W/(m·K)	O15 = 0 & O16 = 0 & O17 = 0
	0.033 W/(m·K)	O15 = 1 & O16 = 0 & O17 = 0
	0.033 W/(m·K)	O15 = 0 & O16 = 1 & O17 = 0
	0.015 W/(m·K)	O15 = 0 & O16 = 0 & O17 = 1
Density	- kg/m^3	O15 = 0 & O16 = 0 & O17 = 0
	50 kg/m^3	O15 = 1 & O16 = 0 & O17 = 0
	50 kg/m^3	O15 = 0 & O16 = 1 & O17 = 0
	230 kg/m^3	O15 = 0 & O16 = 0 & O17 = 1
Specific heat	- J/(kg·K)	O15 = 0 & O16 = 0 & O17 = 0
	1050 J/(kg·K)	O15 = 1 & O16 = 0 & O17 = 0
	1050 J/(kg·K)	O15 = 0 & O16 = 1 & O17 = 0
	1000 J/(kg·K)	O15 = 0 & O16 = 0 & O17 = 1
Water vapour permeability coefficient	- kg/(m·s·Pa)	O15 = 0 & O16 = 0 & O17 = 0
	$1.5 \cdot 10^{-12}$ kg/(m·s·Pa)	O15 = 1 & O16 = 0 & O17 = 0
	$1.5 \cdot 10^{-12}$ kg/(m·s·Pa)	O15 = 0 & O16 = 1 & O17 = 0
	$4.0 \cdot 10^{-17}$ kg/(m·s·Pa)	O15 = 0 & O16 = 0 & O17 = 1

Table 5– Detailed description of layers in available floor constructions

Layer 01		
Brick layer		
Property	Value	Options
Thickness	0.48 m	Any
Thermal Conductivity	0.72 W/(m·K)	Any
Density	1920 kg/m^3	Any
Specific heat	840 J/(kg·K)	Any
Water vapour permeability coefficient	$30.0 \cdot 10^{-12}$ kg/(m·s·Pa)	Any

Layer 02		
Possible internal insulation layer		
Property	Value	Options
Thickness	- m	O8 = 0 & O9 = 0 & O10 = 0
	0.08 m	O8 = 1 & O9 = 0 & O10 = 0
	0.16 m	O8 = 0 & O9 = 1 & O10 = 0
	0.01 m	O8 = 0 & O9 = 0 & O10 = 1
Thermal Conductivity	- W/(m·K)	O8 = 0 & O9 = 0 & O10 = 0
	0.033 W/(m·K)	O8 = 1 & O9 = 0 & O10 = 0
	0.033 W/(m·K)	O8 = 0 & O9 = 1 & O10 = 0
	0.015 W/(m·K)	O8 = 0 & O9 = 0 & O10 = 1
Density	- kg/m^3	O8 = 0 & O9 = 0 & O10 = 0
	50 kg/m^3	O8 = 1 & O9 = 0 & O10 = 0
	50 kg/m^3	O8 = 0 & O9 = 1 & O10 = 0
	230 kg/m^3	O8 = 0 & O9 = 0 & O10 = 1
Specific heat	- J/(kg·K)	O8 = 0 & O9 = 0 & O10 = 0
	1050 J/(kg·K)	O8 = 1 & O9 = 0 & O10 = 0
	1050 J/(kg·K)	O8 = 0 & O9 = 1 & O10 = 0
	1000 J/(kg·K)	O8 = 0 & O9 = 0 & O10 = 1
Water vapour permeability coefficient	- kg/(m·s·Pa)	O8 = 0 & O9 = 0 & O10 = 0
	$1.5\cdot10^{-12}$ kg/(m·s·Pa)	O8 = 1 & O9 = 0 & O10 = 0
	$1.5\cdot10^{-12}$ kg/(m·s·Pa)	O8 = 0 & O9 = 1 & O10 = 0
	$4.0\cdot10^{-17}$ kg/(m·s·Pa)	O8 = 0 & O9 = 0 & O10 = 1

Layer 03		
Possible internal insulation plaster		
Property	Value	Options
Thickness	- m	O7 = 0
	0.03 m	O7 = 1
Thermal Conductivity	- W/(m·K)	O7 = 0
	0.08 W/(m·K)	O7 = 1
Density	- kg/m^3	O7 = 0
	400 kg/m^3	O7 = 1
Specific heat	- J/(kg·K)	O7 = 0
	1000 J/(kg·K)	O7 = 1
Water vapour permeability coefficient	- kg/(m·s·Pa)	O7 = 0
	$9.0\cdot10^{-12}$ kg/(m·s·Pa)	O7 = 1

Table 6– Detailed description of layers in available external wall constructions

Layer 01		
Possible external insulation layer		
Property	Value	Options
Thickness	- m	O11 = 0 & O12 = 0
	0.08 m	O11 = 1 & O12 = 0
	0.16 m	O11 = 0 & O12 = 1
Thermal Conductivity	- W/(m·K)	O11 = 0 & O12 = 0
	0.033 W/(m·K)	O11 = 1 & O12 = 0
	0.033 W/(m·K)	O11 = 0 & O12 = 1
Density	- kg/m^3	O11 = 0 & O12 = 0
	50 kg/m^3	O11 = 1 & O12 = 0
	50 kg/m^3	O11 = 0 & O12 = 1
Specific heat	- J/(kg·K)	O11 = 0 & O12 = 0
	1050 J/(kg·K)	O11 = 1 & O12 = 0
	1050 J/(kg·K)	O11 = 0 & O12 = 1
Water vapour permeability coefficient	- kg/(m·s·Pa)	O11 = 0 & O12 = 0
	$1.5\cdot10^{-12}$ kg/(m·s·Pa)	O11 = 1 & O12 = 0
	$1.5\cdot10^{-12}$ kg/(m·s·Pa)	O11 = 0 & O12 = 1

Layer 02

Ceiling tiles

Property	Value	Options
Thickness	0.02 m	Any
Thermal Conductivity	0.056 W/(m·K)	Any
Density	380 kg/m³	Any
Specific heat	1000 J/(kg·K)	Any
Water vapour permeability coefficient	$1.3\cdot10^{-12}$ kg/(m·s·Pa)	Any

Layer 03

Wood hardboard

Property	Value	Options
Thickness	0.04 m	Any
Thermal Conductivity	0.12 W/(m·K)	Any
Density	880 kg/m³	Any
Specific heat	1340 J/(kg·K)	Any
Water vapour permeability coefficient	$0.8\cdot10^{-12}$ kg/(m·s·Pa)	Any

Layer 04

Possible internal insulation layer

Property	Value	Options
Thickness	- m	O14 = 0
	0.01 m	O14 = 1
Thermal Conductivity	- W/(m·K)	O14 = 0
	0.015 W/(m·K)	O14 = 1
Density	- kg/m³	O14 = 0
	230 kg/m³	O14 = 1
Specific heat	- J/(kg·K)	O14 = 0
	1000 J/(kg·K)	O14 = 1
Water vapour permeability coefficient	- kg/(m·s·Pa)	O14 = 0
	$4.0\cdot10^{-17}$ kg/(m·s·Pa)	O14 = 1

Layer 05

Possible internal thermal plaster

Property	Value	Options
Thickness	- m	O13 = 0
	0.03 m	O13 = 1
Thermal Conductivity	- W/(m·K)	O13 = 0
	0.08 W/(m·K)	O13 = 1
Density	- kg/m³	O13 = 0
	400 kg/m³	O13 = 1
Specific heat	- J/(kg·K)	O13 = 0
	1000 J/(kg·K)	O13 = 1
Water vapour permeability coefficient	- kg/(m·s·Pa)	O13 = 0
	$9.0\cdot10^{12}$ kg/(m·s·Pa)	O13 = 1

Table 7– Detailed description of layers in available roof constructions

Description of intervention	Involved options	Option combination	Key characteristics	
			Description	Value
Thermostatic valves	O1	O1 = 0	Regulation efficiency	93%
		O1 = 1		99%
Mechanic ventilation with heat recovery	O2	O2 = 0	Heat recovery efficiency	0%
		O2 = 1		60%
Condensing boiler	O3	O3 = 0	Generation efficiency	90%
		O3 = 1		104%
Windows	O4, O5	O4 = 0 & O5 = 0	U-Value Solar Transmittance	5.78 W/(m^2·K) 0.82
		O4 = 1 & O5 = 0		3.26 W/(m^2·K) 0.8
		O4 = 0 & O5 = 1		0.70 W/(m^2·K) 0.6
Light bulbs	O6	O6 = 0	Maximum lighting power density	4.5 W/m^2
		O6 = 1		3.4 W/m^2
External walls	O7, O8, O9, O10	O7 = 0 & O8 = 0 & O9 = 0 & O10 = 0	U-Value	1.50 W/(m^2·K)
		O7 = 1 & O8 = 0 & O9 = 0 & O10 = 0		0.96 W/(m^2·K)
		O7 = 0 & O8 = 1 & O9 = 0 & O10 = 0		0.32 W/(m^2·K)
		O7 = 0 & O8 = 0 & O9 = 1 & O10 = 0		0.18 W/(m^2·K)
		O7 = 0 & O8 = 0 & O9 = 0 & O10 = 1		0.75 W/(m^2·K)
		O7 = 1 & O8 = 1 & O9 = 0 & O10 = 0		0.29 W/(m^2·K)
		O7 = 1 & O8 = 0 & O9 = 1 & O10 = 0		0.17 W/(m^2·K)
		O7 = 1 & O8 = 0 & O9 = 0 & O10 = 1		0.59 W/(m^2·K)
Roofs	O11, O12, O13, O14	O11 = 0 & O12 = 0 & O13 = 0 & O14 = 0	U-Value	1.45 W/(m^2·K)
		O11 = 1 & O12 = 0 & O13 = 0 & O14 = 0		0.32 W/(m^2·K)
		O11 = 1 & O12 = 0 & O13 = 1 & O14 = 0		0.29 W/(m^2·K)
		O11 = 1 & O12 = 0 & O13 = 0 & O14 = 1		0.26 W/(m^2·K)
		O11 = 1 & O12 = 0 & O13 = 1 & O14 = 1		0.24 W/(m^2·K)
		O11 = 0 & O12 = 1 & O13 = 0 & O14 = 0		0.85 W/(m^2·K)
		O11 = 0 & O12 = 1 & O13 = 1 & O14 = 0		0.64 W/(m^2·K)
		O11 = 0 & O12 = 1 & O13 = 0 & O14 = 1		0.54 W/(m^2·K)
		O11 = 0 & O12 = 1 & O13 = 1 & O14 = 1		0.45 W/(m^2·K)
		O11 = 0 & O12 = 0 & O13 = 1 & O14 = 0		0.94 W/(m^2·K)
		O11 = 0 & O12 = 0 & O13 = 0 & O14 = 1		0.74 W/(m^2·K)
		O11 = 0 & O12 = 0 & O13 = 1 & O14 = 1		0.58 W/(m^2·K)
Slab on-grade	O15, O16, O17	O15 = 0 & O16 = 0 & O17 = 0	U-Value	5.65 W/(m^2·K)
		O15 = 1 & O16 = 0 & O17 = 0		0.38 W/(m^2·K)
		O15 = 0 & O16 = 1 & O17 = 0		0.20 W/(m^2·K)
		O15 = 0 & O16 = 0 & O17 = 1		1.19 W/(m^2·K)

Table 8- Overall set of key characteristics depending on intervention options.

Environmental attribute	Minimum	Maximum	Average
	kWh/(m^2·y)	kWh/(m^2·y)	kWh/(m^2·y)
Electricity	28.51	35.58	32.04
Natural Gas	6.39	78.98	33.04
EP total	76.28	167.18	112.24
Energy savings (ES)	**187.35**	**278.26**	**242.30**

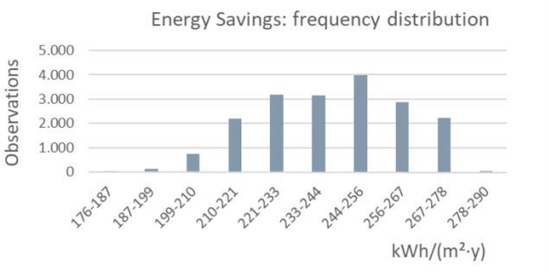


Table 9- Energy savings

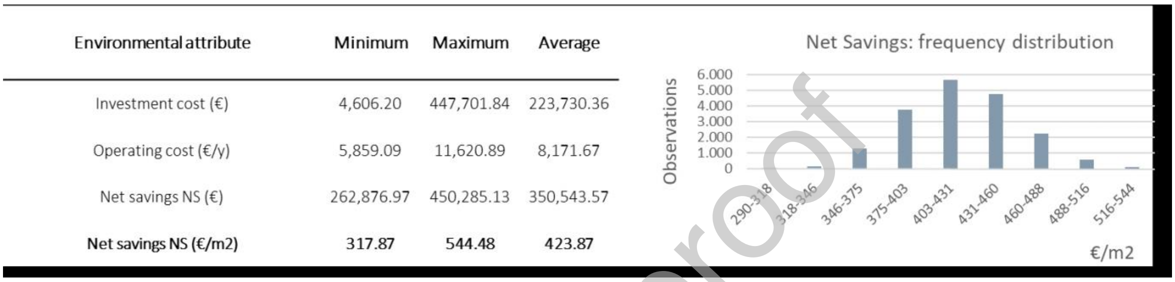
4.5 Second decision-making attribute: net monetary savings

The second decision-making attribute deals with the economic feasibility and profitability of the retrofit scenarios. Investment costs, operating costs and consequent monetary savings need therefore to be estimated. The costs of investment are assessed through a linear pricing model (please refer to Table 2 for unitary prices). The product between the energy demand times the energy price (0.78 €/m^{3}standard for natural gas, 0.23 €/kWh$_{El}$ for electricity) gives the operating costs. The savings are calculated as the difference in the operating costs between the do-nothing and any mth retrofit scenario.

Because the LCCing is a technique able to incorporate the time value of money, the discount rate "r" and the growth rates on energy prices ("g$_{gas}$" and "g$_{ele}$") have to be defined. The discount rate is assessed as the weighted average cost of capital (WACC), where:

$$r = WACC = D * Kd + E * Ke$$

In the equation above D represents the debt, while E is equity, kd is the cost of debt (cost of capital on loan), and ke is the cost on equity (cost of capital on self-financing). In our study, we assume 50% Debt and 50% Equity. Ke is calculated adding risk premiums for construction (0.5%) and illiquidity (1.0%) to a risk-free rate (3.90%=BTP30Y). Hence, Ke = 3.90% + (0.5% + 1.0%) = 5.40%. Instead, kd is assessed as the Eurirs rate (0.18%=IRS 30Y) plus the mortgage spread (2.0%). Then, Kd = 0.18% + 2% = 2.18%. The final calculation of the discount rate is solved as follow: r = WACC = 0.5*5.40% + 0.5*2.18% = 3.79% (as a nominal rate). The growth rates reflect the changes in the price of natural gas and electricity over time. Both "g_{gas}" and "g_{ele}" are calculated from the time series of energy prices over the last 10 years. A mildly growing trend is depicted, resulting in g_{gas}=1.71% and g_{ele}=2.12%. Conversely, the available Government subsidies considered in this analysis is a financial incentive program that provides public funding for 65% of investment costs in instalments. The subsidies, based on the funding program, are delivered during the first 10 years of the investment. According to Eq. 3, the economic benefits NS_m are summarized in Table 10.

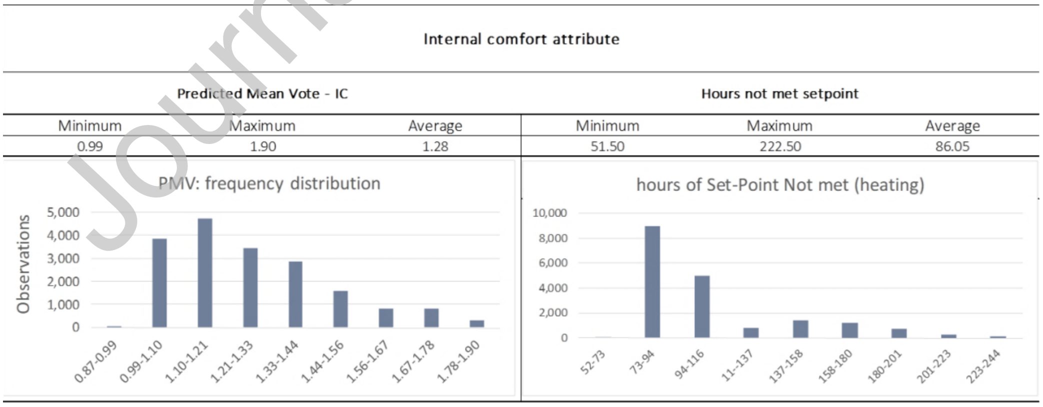


Environmental attribute	Minimum	Maximum	Average
Investment cost (€)	4,606.20	447,701.84	223,730.36
Operating cost (€/y)	5,859.09	11,620.89	8,171.67
Net savings NS (€)	262,876.97	450,285.13	350,543.57
Net savings NS (€/m2)	**317.87**	**544.48**	**423.87**

Table 10 - Net savings

4.6 Third decision-making attribute: internal comfort

The third criterion, i.e. the thermal comfort IC_m, is assessed through the standard deviation of PMV_m (neutrality: PMV = 0), and it indicates the level of satisfaction with the thermal environment indoor consequent to the implementation of each retrofit scenario. In Table 11, the frequency distributions of standard deviation of calculated PMV values and unmet heating set point hours are shown for the whole set of retrofit scenarios.



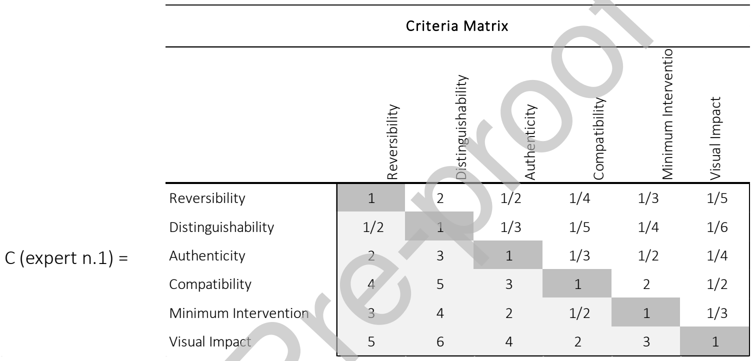
Internal comfort attribute					
Predicted Mean Vote - IC			**Hours not met setpoint**		
Minimum	Maximum	Average	Minimum	Maximum	Average
0.99	1.90	1.28	51.50	222.50	86.05

Table 11 - Internal comfort as PMV

4.7 Fourth decision-making criteria: restoration score

As explained in Section 3.3, an AHP leads to evaluate the compatibility of the energy retrofit options by associating to each O_q its correspondent restoration score (RS_q). In the AHP, the alternatives to be compared are represented by the seventeen retrofit options O_q, while six decision-making criteria (c_h), $h \in \mathbb{N}$ {0, ..., 6}, structure the selection process. They are, in accordance with the principles of restoration theory [32], c_1=reversibility, c_2=distinguishability, c_3=authenticity, c_4=material compatibility, c_5=minimum intervention and c_6=visual impact. Whereas, the goal of the AHP is the maximisation of the RS under the perspective of each criterion.

To perform the AHP analysis, a group of ten experts was brought together in a multidisciplinary team of specialists in the fields of energy efficiency, architecture, conservation, technical design, economy and cultural heritage. Among the people interviewed there are four architects specialized in architectural conservation and heritage protection, two architects specialized in buildings technologies and sustainable design, two experts in the field of building energy assessment, and finally two experts in real estate economics, finance and stock investments. They all are academics and have at least a 20-year long experience of work in these fields. They have been asked to define the priorities and the weights leading to the RS assessment under a real world perspective, by considering the need for acceptable compromises towards sustainability and functionality goals. Each expert was first given a criteria matrix [C] to fill out. An example (expert n.1) of a completed matrix is shown in Figure 4. It is a real matrix of dimensions 6 × 6, whose entries result from the pairwise comparison of every criterion against the others. The experts were given an ordinal scale from 1 to 9 to assess the relative importance of each criterion. The values assigned reflect the degree of preference of one entry versus another. In particular, 1 expresses equal importance, 3 moderate preference, 5 strong preference, 7 demonstrated preference and 9 extreme preference. Instead, 2,4,6,8 express intermediate values.



C (expert n.1) =

Criteria Matrix

	Reversibility	Distinguishability	Authenticity	Compatibility	Minimum Interventio	Visual Impact
Reversibility	1	2	1/2	1/4	1/3	1/5
Distinguishability	1/2	1	1/3	1/5	1/4	1/6
Authenticity	2	3	1	1/3	1/2	1/4
Compatibility	4	5	3	1	2	1/2
Minimum Intervention	3	4	2	1/2	1	1/3
Visual Impact	5	6	4	2	3	1

Figure 4 - *pairwise criteria matrix (expert n.1)*

As stated in Eq. 6, the criteria weight vector is calculated based on the set of criteria matrixes filled out by the experts. The criteria weigh vector, which expresses an average of each experts' judgments, results as W_1=0. 35, W_2=0.10, W_3=0.21, W_4=0.17, W_5=0.12, W_6=0.06.

In a second step, the experts were asked to compile six pairwise comparison matrixes $[A]^{(h)}$, each one referred to a different criterion: $[A]^{(1)}$, $[A]^{(2)}$, $[A]^{(3)}$, $[A]^{(4)}$, $[A]^{(5)}$, $[A]^{(6)}$. The seventeen retrofit options represent the alternatives to be compared pairwise. However, among these options, the ones that are equivalent in terms of restoration compatibility are clustered in order to reduce the total number of alternatives, as shown in Table 12. Therefore, nine alternatives are produced (alternatives a-i). In Figure 5 we provide an example of a filled out pairwise comparison matrix (again by expert n.1) when analysing the alternatives with respect to criteria n.1. The matrix $[A]^{(1)}$ is of dimensions 9 x 9.

Retrofit Options (Op)	Alternatives (a)
1	Alternative a
2	Alternative b
3	Alternative c
4	Alternative d
5	Alternative e
6	Alternative f
7 - 10	Alternative g
11 - 14	Alternative h
15 - 17	Alternative i

Table 12 - AHP alternatives clustering

Criterio n. 1: Reversibility

$[A]^{(1)} =$

	Alternative a	Alternative b	Alternative c	Alternative d	Alternative e	Alternative f	Alternative g	Alternative h	Alternative i
Alternative a	1	8	4	1	5	1	6	6	9
Alternative b	1/8	1	1/5	1/8	1/4	1/8	1/3	1/3	2
Alternative c	1/4	5	1	1/4	2	1/4	3	3	6
Alternative d	1	8	4	1	5	1	6	6	9
Alternative e	1/5	4	1/2	1/5	1	1/5	2	2	5
Alternative f	1	8	4	1	5	1	6	6	9
Alternative g	1/6	3	1/3	1/6	1/2	1/6	1	1	4
Alternative h	1/6	3	1/3	1/6	1/2	1/6	1	1	4
Alternative i	1/9	1/2	1/6	1/9	1/5	1/9	1/4	1/4	1

Figure 5 - pairwise alternatives matrix for criteria 1 (expert n.1)

The decision matrix [D] can finally be developed. It is a 9 x 6 real matrix (Figure 6). The restoration score for one alternative (RS_q) is assessed through the vector *v* of global scores, with *v*=[D]*w. In *v*, each entry v_i represents the global score assigned to the corresponding alternative, i.e. the compatibility score. Figure 6 also represents the RS_q obtained for the retrofit options, whereas Table 13 summarizes the final scores, RS_m calculated as in Eq. 10 for every retrofit scenario S_m: the higher the score, the more the compatibility criteria are fulfilled.

	Crit. 1	Crit. 2	Crit. 3	Crit. 4	Crit. 5	Crit. 6	**RSq**
Weighs	0.35	0.10	0.21	0.17	0.12	0.06	
Alternative a	0.220	0.183	0.120	0.174	0.201	0.156	0.94
Alternative b	0.024	0.111	0.021	0.029	0.014	0.014	0.16
Alternative c	0.111	0.111	0.077	0.115	0.157	0.156	0.58
Alternative d	0.220	0.183	0.178	0.174	0.157	0.156	0.97
Alternative e	0.081	0.058	0.120	0.115	0.123	0.156	0.52
Alternative f	0.220	0.183	0.178	0.174	0.201	0.156	1.00
Alternative g	0.055	0.058	0.077	0.075	0.072	0.115	0.36
Alternative h	0.055	0.058	0.178	0.115	0.051	0.045	0.46
Alternative i	0.014	0.058	0.050	0.029	0.023	0.045	0.16

Figure 6 - decision matrix

Rrestoration Compatibility attribute

Restorarion Score -RS

Minimum	Maximum	Average
0.16	1.00	0.50

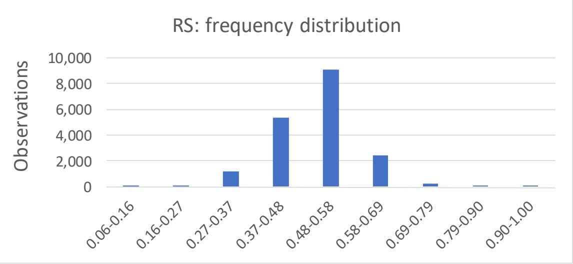


Table 13 - Restoration score

In order to check the consistency of the experts' judgements, the consistency index (C.I.) and the consistency ratio (C.R.) are calculated in association to each compiled matrix [74]. For the criteria matrixes (6x6) $C.I._{[C]} = (\lambda_{[C]\,max} - 6)/(6-1)$, while for the alternatives matrixes (9x9) $C.I._{[A]} = (\lambda_{[A]\,max} - 9)/(9-1)$. In these formulations, λ_{max} is the largest eigenvalue of the matrixes. The consistency indexes are verified to be lower than 0.1 (average = 0.068, minimum = 0.022, maximum = 0.089), which guarantees good reliability in the judgements. Whereas, the consistency ratio C.R is assessed as

$C.R._{[C]} = (C.I._{[C]}/1.25)$ and $C.R._{[A]} = (C.I._{[A]}/1.45)$. Consistency ratios are also verified, as they present values considerably lower than 0.2 (average = 0.051, minimum = 0.019, maximum = 0.076).

4.8 Optimization's weights definition

A set of a-priori weights (W_{ES}, W_{NS}, W_{IC}, W_{RS}) is established by the same commission of ten experts previously introduced in Section 4.7. The weights are supposed to reflect the importance of any attribute when compared to the others. Different weights distributions would change the impact that each attribute is producing on the optimization's results. A higher weight assigned to NS would express a preference for the financial aspects of the investment, and the economic profit would act as the main driver. A higher weight assigned to ES would indicate a specific concern for sustainability and environmental issues. A higher weight assigned to IC would give high importance to indoor comfort enhancement and occupants' satisfaction, while a higher weight assigned to RS would indicate a specific attention for the preservation of cultural heritage and the safeguard of historical values.

Each expert is thereby asked to fill in another matrix and provide his/her preference in weights distribution. Figure 7 shows the final synthesis-matrix, where the i^th^-j^th^ entry is the arithmetical average of the corresponding i^th^-j^th^ values assigned by the experts. As results, the following weights are obtained: W_{NS}=0.29, W_{ES}=0.24, W_{IC}=0.16, W_{RS}=0.31.

Optimization's weights	RS	NS	EB	IC	Normalized weights
RS	1.000	1.698	1.058	1.809	0.31
NS	0.589	1.000	2.008	1.633	0.29
EB	0.945	0.498	1.000	1.723	0.24
IC	0.553	0.612	0.580	1.000	0.16

Figure 7 - optimization's weights: synthesis matrix

4.9 Multi-attribute optimization

The optimization strategy adopted expresses a multi-attribute problem, which can be solved through a weighted sum scalarization approach [86]. The four attributes are combined into a single objective function as in Eq. 16. Given that the attributes show different units of measurement, they are normalized over their maximum value in the interval [0;100], making their scalarization into a single function consistent.

$$\forall \text{ m, if } max\,[(0.29 * NS_m) + (0.24 * ES_m) + (0.16 * IC_m) + (0.31 * RS_m)] \rightarrow \text{m=m\_opt and } S_m = S_{m\_opt} \qquad \textit{Eq. 16}$$

The budget allocated by the investor for the restoration of the Cuneo House is 250,000 €, as in Eq. 17. The discounted payback period of the operation is set out to respect a predefined time limit of 15 years, which is established by the investor himself (Eq. 18). We set the overall non-renewable primary energy demand for heating, domestic hot water and lighting to be, as stated in Eq. 19, lower than 82.706 kWh/(m²·y), which is the corresponding Class C reference for energy requirements, based on Italian regulations. Since we deal with the energy refurbishment of historic buildings, our goal is to achieve the most significant energy saving as possible, without compromising the building's characteristics. In this particular situation, it will not be feasible to reach either nZEB or deep renovation goals. We, therefore, set a minimum target of Energy Class C as a good compromise between energy efficiency goals and the safeguard of the historic fabric. In particular, we defined the Class C energy reference-requirements in accordance with the Italian implementation of the Energy Performance of Buildings Directive- RECAST [5], based on the parallel simulation of a baseline building. Clearly, the total savings produced by the investment have to be greater than zero (Eq. 20). Technical constraints are finally introduced because some interventions are mutually exclusives: interventions 4 and 5 are alternatives, as well as interventions 8, 9 and 10, interventions 11 and 12, and interventions 15, 16 and 17.

$$Ci_{m\_opt} \leq 250{,}000\ € \qquad \textit{Eq. 17}$$

$$PB_{m\_opt} \leq 15\ years \qquad \textit{Eq. 18}$$

$$En\ Cons_{m_{opt}} \leq 82.706\ kWh/(m^2 \cdot year) \qquad \textit{Eq. 19}$$

$$NS_{m\_opt} \geq 0 \qquad \text{Eq. 20}$$

We were able to assess NS_m, RS_m and other configuration outputs relevant for the given constraints, through mathematical functions for every retrofit scenario, according to what has been illustrated above. Instead, we used **jEPlus®** to provide ES_m and IC_m, by means of **EnergyPlus** simulations. Then, the overall model selected the configurations in accordance with the given constraints, normalized the values of NS_m, RS_m, ES_m and IC_m on a min-max base, and assessed the overall scores for each retrofit scenario, based on given weight factors. As a result, the optimal scenario was identified, hence the one which maximizes the overall score within the given constraints, i.e $S_m=S_{m\_opt}$.

5 RESULTS AND DISCUSSION

The decision support system leads to identify the optimal energy retrofit scenario, which is given by the set of options O_1, O_2, O_3, O_5, O_6, O_9 and O_{11} (please refer again to Table 2). This particular configuration of interventions will require an initial investment of 247,806€, and it will produce a net monetary saving of 394,730€ after a 30-year timeframe. The payback period is forecasted at year 7, and the energy demand is diminished to 76.60 kWh/m^{2}y (energy class C). As far as construction properties are concerned, we implemented in the **EnergyPlus** model the optimal scenario selected in order to test the proposed solution in further detail. In particular, we were able to verify that no interstitial moisture will occur in the building constructions. In addition, the optimal scenario includes internal insulation in the vertical walls and, according to current best practices, this retrofit solution is usually coupled with the vapour barrier. However, to be on the safe side, the barrier was not included in the **EnergyPlus** simulation, and still no interstitial moisture was occurring.

At this stage, a few more considerations on the outcome could be added performing a simple scenario analysis. In fact, this particular set of intervention corresponds to a specific weight configuration that has been provided by the ten experts interviewed. It is worth to question if different weights distributions would have affected the outcome significantly. A scenario analysis straightforwardly shows the changes in the output for each weights variation in the optimization model. In Table 14, several weights configurations are associated with the corresponding outcomes. We tested boundary conditions, giving the value of 100% to one weight at a time, and an average condition, assigning 25% to each weight. The results show small differences, leading to rather convergent solutions. In the following table, the consequent set of optimal options are presented: 1 selects the option, while 0 excludes the option.

W_{NS}	W_{ES}	W_{IC}	W_{RS}	EP (kWh/m^2 y)	Ci (€)	NS (€)	PB (year)	O_1	O_2	O_3	O_4	O_5	O_6	O_7	O_8	O_9	O_{10}	O_{11}	O_{12}	O_{13}	O_{14}	O_{15}	O_{16}	O_{17}
0.29	0.24	0.16	0.31	76.60	247,806	394,730	7	1	1	1	0	1	1	0	0	1	0	1	0	0	0	0	0	0
1	0	0	0	81.21	177,988	420,671	6	1	1	1	1	0	1	0	1	0	0	0	0	0	0	0	0	0
0	1	0	0	76.60	247,806	394,730	7	1	1	1	0	1	1	0	0	1	0	1	0	0	0	0	0	0
0	0	1	0	81.70	239,996	391,002	7	0	1	1	0	1	1	1	0	0	0	1	0	0	0	0	0	0
0	0	0	1	81.21	177,988	420,671	6	1	1	1	1	0	1	0	1	0	0	0	0	0	0	0	0	0
0.25	0.25	0.25	0.25	76.60	247,806	394,730	7	1	1	1	0	1	1	0	0	1	0	1	0	0	0	0	0	0

Table 14 - scenario analysis on different weights distributions

6 CONCLUSIONS AND POLICY IMPLICATIONS

Energy efficiency is an important, if not crucial, element in the enhancement of a building. Additional issues, including economic feasibility and heritage protection, often hamper the development of renovation programs aimed at improving the energy performance of existing buildings. However, the level of complexity of the problem makes it difficult to understand which approach is the most strategic. This task is even more difficult under the prospective of large building stocks.

In this research paper, a *score-driven decision support system* has been developed to program and handle energy retrofit campaigns on historic building assets. The might of this study lies in the combination of traditional feasibility indexes, such as energy or monetary savings, with matters of safeguard and protection of cultural heritage. In particular, the compatibility of interventions is assessed in terms of a **restoration score**, in the attempt to translate this qualitative aspect into a measurable parameter. The core idea is to fill the lack emerged from the specific literature of an acknowledged methodology to deal with energy retrofits in cultural heritage, and quantify the impact of interventions on historical fabrics.

The energy enhancement in this study is handled as an optimization issue, with the aim of identifying the energy retrofit options that lead to the maximum benefit, including economic, environmental, comfort and conservation targets. To this end, different techniques and methodologies are unified to assess the benefits produced: life-cycle costing, energy computer simulations, analytic hierarchy process, and multi-attribute optimization.

We implemented the model on a large historic building stock in Italy. Firstly, we analysed the stock and defined three different clusters, and one reference building was selected for each cluster. In particular, in this work, we focused on cluster 1. A set of seventeen retrofit options was also suggested, and we consequently developed an energy model in **EnergyPlus** of the reference building, so that the primary energy demand could have been assessed both in its current status and in any design option. Then, we defined four attributes (the benefits) to be maximized in the optimization analysis: monetary net savings, energy savings, indoor environmental quality enhancements, and restoration scores. We have also defined financial, feasibility, time and environmental constraints. Ultimately, the model allowed to select the set of design options producing the maximum overall benefit.

Among the key results obtained in this research, there is the strong support given to the decision-making process when planning energy retrofits on historic assets. However, the most significant achievement resides in the assessment of the restoration score as a way to quantify the compatibility of retrofit interventions. Another strength in the approach developed is the combined use of traditional financial techniques with multi-criteria analysis as a simple way to solve a complex selection process.

Owners and managers, both public and private, of large building stocks need tools and procedures able to accelerate and improve the estimation of retrofit interventions for existing buildings.

The proposed model aims to provide asset holders, portfolio managers and public/private investors a significant help in steering their decisions about the energy upgrade of historic building stocks:

- increasing the **energy savings** of the building stock;
- reducing the **costs** for the owners/managers;
- limiting the **environmental impacts**;
- enhancing the **indoor** environmental quality;
- preserving the **historic value** of buildings.

Thus, a wide application of the model proposed might result in a diffuse and cost-effective improvement of the built environment, in full agreement with the relevant energy policies.

Finally, this approach could also have effects in the construction sector: energy efficiency is related to the introduction of new high performing technologies and smart construction solutions.

Ultimately, the major limitation of the approach presented concerns the deterministic nature of the decision support system developed. Energy analyses are studied in the long-run, and depend on several uncertain factors, such as market conditions, climate changes or occupant's behaviour. The future is uncertain, and uncertainty may be included as a part of this model. As next steps of this study, we will consider identifying all sources of uncertainty which the output depends on, and add a risk assessment procedure to overcome this deterministic perspective. Moreover, we intend to apply the decision support system to a reference building for each of the remaining clusters: different climatic areas will, therefore, be analysed, and coherent energy retrofit interventions will be suggested. Nevertheless, we expect to follow a similar procedure because the model developed (as a general approach) is independent from the building analysed.

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ETHICAL STATEMENT

Hereby, we consciously assure that for the manuscript the following is fulfilled:

i. This material is the authors' own original work, which has not been previously published previously elsewhere.
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iv. The paper reflects the authors' own research and analysis in a truthful and complete manner.
v. The results are appropriately placed in the context of prior and existing research.
vi. All sources used are properly disclosed.
vii. All authors have been personally and actively involved in substantial work leading to the paper and will take public responsibility for its content.

AUTHOR DECLARATION OF INTEREST

We wish to confirm that there are no known **conflicts of interest** associated with this publication and there has been no significant **financial support** for this work that could have influenced its outcome.

We confirm that the manuscript has been read and approved by all named authors and that there are no other persons who satisfied the criteria for authorship but are not listed.

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Ethics in Publishing requirements have been read and checked carefully by all the authors named on the paper. We further confirm that any aspect of the work covered in this manuscript involving ethics in publishing have been respected.

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