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Energy Efficiency: A Multi-Criteria Evaluation Method for the Intervention on Built Heritage

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Abstract: The awareness that a historic building is a complex system made up of interdependent parts and endowed with a specific energetic behavior is now widespread. Therefore, the energy improvement of a historic building does not only consist of designing individual construction elements or high-performance materials. On the contrary, it is based on the ability to analyze the buildings and recognize and enhance the specific thermal characteristics of each individual situation. Over the past two decades, the publication of European directives aimed at improving the energy efficiency of existing buildings has led each country to promulgate national guidelines in order to help operators planning and implementing energy improvement actions for historic buildings. The guidelines of the Italian Ministry of Cultural Heritage prescribe a method to evaluate the effectiveness of different energy improvement interventions in historic buildings through a qualitative-quantitative analysis based on static energy simulation. However, the ministerial guidelines do not prescribe any method for the analytical evaluation of other key issues aimed at the success of any energy improvement action for the historic building. Based on the literary and standard review on EEHB 2000–2020, this paper presents a multi-criteria comparative analysis method of energy improvement techniques for historic buildings in order to support operators in choosing the most suitable action for each case study. The method analyses each energy improvement technique according to four parameters: energy efficiency (increase in expected efficiency), compatibility (ability to ensure the protection of the morphological, material, and architectural features of the historic building), durability, and cost effectiveness. The method is based on descriptive and analytic forms for the different parts of the historic building and for the different improvement actions. These have been experimentally verified on a masonry case study, representative of widespread built heritage. The result opens the possibility of implementing the national guidelines and increasing their effectiveness.

Keywords: energy improvement; energetic analysis; knowledge; historic buildings; territorial fragility

1. Introduction

The issue of energy efficiency for built heritage is currently much debated, especially in the Italian context, where, since the early 1980s, the construction market has largely concentrated on the recovery of existing buildings.

The issue is more far-reaching if we also consider that among the latter there are not only the so-called valuable buildings protected by the Codice dei Beni Culturali e del Paesaggio [1] but also the numerous ones not bound by national legislation, which have peculiar characteristics to be safeguarded in their material and architectural integrity [2]. Historic buildings are an integral part of our cities and their characteristics contribute considerably to determining the identity of the different places. Although this is a well-established fact, still today most professionals in the sector believe that the aspects related to safeguarding are difficult to reconcile with the innovative techniques of energy improvement, considering that these are mostly designed for the new buildings. However, case studies and regulations show that designing in harmony with the building and the environment is a priority that should become a common practice [3] even in the case of existing buildings. It is, therefore, more important than ever to establish common guidelines and to identify as much as possible the appropriate interventions for each area and need.

The contribution, therefore, arises in this context and proceeds to meet these requirements, combining as much as possible the numerous opposing requests involved. The energy improvement interventions must follow the criteria, methods, and specificities of the restoration intervention, based on the principle of conservation, in order to outline a more balanced synergy with the energy needs. The challenge we face, sustainability, must lead us to reconcile the principles of environmental protection with those of innovation, competitiveness, economic efficiency, and social equity. These objectives can be achieved only through close collaboration by all stakeholders [4]. Considering the heterogeneity of the involved users, who are not all entirely informed and aware of the different issues, full cooperation can take place in the presence of clear tools and methods. The aim is to define, specify, and evaluate the different components related to conservation and the energy improvement purpose, hoping that a simplified system can be included within future ministerial guidelines and European directives. The standardization of the processes of knowledge, description, and evaluation could lead to a further benefit for the stakeholders: a structured container of homogeneous and comparable data. This must be accessible at least to orient on the criticisms, perhaps already faced in similar contexts from the point of view of historical, material, and architectural characteristics.

The research would like to bring attention specifically to the energy improvement interventions concerning the opaque and transparent envelopes of the buildings without involving heating, ventilation and air-conditioning systems (HVAC). Despite the thermal systems providing a significant energy improvement to the whole building if properly designed, such as the energy improvement interventions on the envelopes, it is now crucial to deepen the architectural problem and above all the tangible possibilities of losing many of the peculiarities of the historical buildings.

For these reasons, the main objectives that have been set are aimed at safeguarding the historic, architectural, and material characteristics of the buildings to guarantee effective energy improvement through a descriptive system and a simple methodology for evaluating the effectiveness of the energy improvement interventions on built heritage.

1.1. The Regulatory Framework

The first regulations on energy saving in Italy date back to the mid-1970s, but we must wait for Article 6 of the European Directive 2002/91/CE [5] to focus attention on existing buildings. This directive forces specific energy parameters to be met in the event of major renovations as far as is technically, functionally, and economically possible, and may not be applied in the case of buildings of particular value in the event that the compliance with the requirements would imply an unacceptable alteration of their character or appearance. However, the problem does not exist only for these buildings, but above all for the existing ones that are characterized by some elements of historic and architectural value that could be lost in the occurrence of interventions that do not take them into consideration.

The application of European Directive 91 has created many problems from an architectural point of view. As an example, the replacement of existing windows has completely changed the perception of the structures, and interventions on external walls have also created strong consequences from the landscape point of view. At this stage, therefore, we can talk about not only an energy problem, but also an architectural one. The legislation considers the possibility of exemptions, which can be adopted in the event of operations that are incompatible with the characteristics of the building involved.

The importance of the topic and its impact on the environment and the economy has meant that the European Community has developed further regulations with the aim of investigating this issue in all its sides.

Directive 2006/32/CE [6] has in fact established the indicative objectives, principles of operation, incentives, and the institutional, financial, and legal framework necessary to eliminate the obstructions and imperfections existing on the market that have hindered an efficient end use of energy. With the subsequent Directive 2009/28/CE [7], on the promotion of the use of energy from renewable sources, attention has shifted to the importance of controlling energy consumption, increasing the efficiency of buildings.

In recent years changes and additions have become necessary, which have merged into Directive 2010/31/UE [8] on energy performance in construction and in the European standard EN 16883/2017 in order to give clearer indications on the application of the previous regulations.

In addition to the European regulatory framework, in Italy the publication in 2015 of the "Linee di indirizzo per il miglioramento dell'efficienza energetica nel patrimonio culturale. Architettura, centri e nuclei storici ed urbani" by the Ministero per i Beni e le Attività Culturali e per il Turismo [9] allows interesting insights.

The purpose of these guidelines was to provide exhaustive indications to both the designers and the officials of the Ministry. The text focuses extensively on the analysis of the constructive technical characteristics of historic buildings, offering some ideas regarding the assessment of the environmental quality and the analysis of the existing thermal system in order to further investigate the issue of calculating energy efficiency for the built heritage. Subsequently, the guidelines delve into the matter of the energy improvement interventions by specifically analyzing the building envelope and above all by providing appropriate case studies in terms of compatibility, reversibility, and invasiveness.

The lines of intervention are not configured as real prescriptions, but rather have the purpose of providing the authorities responsible for the protection of the built heritage with tools and criteria for a critical evaluation of the projects in order to "guide the intelligence and perception of staff and designers for the primary institutional achievement of the protection and conservation of cultural heritage, optimizing, where possible, the level of energy performance" [9] (p. 6).

Finally, in 2017 the UNI EN 16883/2017 [10] regulation entered into force. This is applicable not only to buildings officially designated as cultural heritage, but also to historic buildings of all types and ages. The text discusses the regulatory procedure for the assessment and identification of direct operations useful for the purpose of improving energy performance through the full knowledge of the subjects of intervention. This cognitive study initially takes into consideration the building itself and then moves on to the structures, diagnostics, and meaning behind it being cultural patrimony. The standard deepens the interventions and their impact on the individual technological element by the power of the connected state of conservation that characterizes it.

The critical analysis of the regulatory framework highlights the lack of an overall theoretical elaboration. Although energy saving in the field of restoration and sustainability are very topical issues [11], univocal and shared procedures were not seen until 2017. However, on the contrary, there is a wide margin of interpretation noting the need to set up an adequate methodological framework. With the introduction of the MiBACT guidelines in 2015 and the UNI EN 16883/2017 regulation, there was a significant step in this direction. However, it must be absorbed in the design phase of energy retrofit interventions and implemented in particular concerning the different possibilities of action also in relation to the restricted buildings. The MiBACT guidelines are framed in this perspective by providing some interesting ideas and useful tools for evaluating and selecting the most suitable interventions without, however, examining all the necessary implications that the energy improvement project has in relation to historic structures. The analytic tables and forms at the end of the document can also be considered a valid starting point for good knowledge of the building from an energy point of view, but they should be accompanied by further information regarding the interventions and above all the comparison between the variables at stake: energy efficiency before and after the intervention and the level of invasiveness and conservation for the involved technological units [2].

1.2. Research and Innovation

In the construction sector, attention to environmental and energetic issues is giving new value to the building envelope as a dynamic and interactive interface between interior and external climatic and environmental factors. While in the past there were studies focused only on the goal of increasing the functionality and effectiveness of a specific intervention or material often at the expense of the conservation of technical and architectural characteristics of a historic building, in the last 15 years we have been trying to overcome this approach in favor of operations aimed both at satisfying certain energetic and qualitative standards and at safeguarding these peculiarities [11,12]. This is testified by the numerous integrated research projects aimed at increasing the knowledge of methodologies, techniques, and new materials, with particular attention to the issue of safeguarding [13–16]. Among those analyzed, the European projects 3encult [17], RESTART [18], New4Old [19], BRITA in Pubs [20], EFFESUS [21,22] and RIBuild [23] have contributed significantly to the advancement of research since they are positive examples of the application of these principles.

They took into consideration bound and unbound buildings that are heterogeneous with respect to historic period, materials, and typologies, and focused on different aspects related to energy retrofitting. They allowed us to verify how numerous methodologies and interventions on built heritage can be positively implemented. The common strengths were, first of all, the in-depth knowledge of the elements on which to operate; the multidisciplinary and multisectoral approach to the issue; particular attention to architectural, technical, and economic characteristics; the involvement of professionals and operators; and finally the dissemination of information and processing to raise the level of awareness of these issues.

Interventions on historic windows are one of the areas on which many of these research projects have focused, considering that in the past European funds were simply used to replace the original windows with brand-new thermal windows, consequently losing some representative elements of the architecture. Therefore, some institutions, including English Heritage [24] and Historic Scotland [25], have developed useful and detailed intervention guidelines to ensure adequate energy efficiency while safeguarding the historic details and characteristics of the building. Both associations have reached the same conclusion: Rather than carrying out integral replacements, even with copies of the historic windows, it is recommended to replace the simple glass with high-performance double glazing, to insert seals against drafts, or to add a second frame internally. This is to increase the seal if it is not possible to work on the original window frame, which would simply be affected by conservation operations. The main guiding element for the choice remains the real state of preservation of the window, not only the reduction of heat loss [26–29].

The preservation of historic windows and doors has been a hotly debated topic in Italy since the 1990s [30,31], but in the last decade, there has been a significant change of course. The contribution relating to the conservation of the curtain wall of the Torre Galfa in Milan [32] is an example. In fact, the authors started by analyzing the original structure from the 1950s to understand how and if it was possible to bring it back into use by meeting the current functional and regulatory requirements. To answer this question, technological solutions, including geometries, have been studied to prefigure different kinds of intervention. These were in turn evaluated while simultaneously considering the energy efficiency, the maintenance costs of the fixtures, and the level of conservation achieved regarding both the components and the materials used.

By changing the scale of analysis instead, the IEE projects TABULA (Typology Approach for Building Stock Energy Assessment, 2009–2012) [33] and EPISCOPE (Energy Performance Indicator Tracking Schemes for the Continuous Optimisation of Refurbishment Processes in European Housing Stocks, 2013–2016) [34] should also be mentioned. They have deepened the energy renovation using a typological approach, developing operational models for building-stock analysis [35].

The TABULA project extended the research to a local, regional, or national level in 17 countries of the European Union with the aim of identifying and creating residential building types characterized by a set of buildings with comparable energetic characteristics and performances. This research considered different buildings by the construction period and by extension to obtain the largest possible study sample in order to map the current state and energy performance for each of the building stocks considered. In addition, the project assessed the potential energy savings that can be achieved through the renovation of the building envelopes and the thermal systems, dividing them into two categories: traditional energy redevelopment and advanced energy redevelopment thanks to the use of innovative materials and technologies [36]. A standard reference calculation procedure for determining the heat need and the delivered energy demand was used in accordance with the Energy Performance of Buildings Directive 2002/91/CE. Finally, the energy performances before and after the redevelopment were compared. These data, therefore, made it possible to associate verified performance indicators to building categories as a model for estimating the energy performance of the building stock in each country [37].

The EPISCOPE project progressed in continuity with the previous one by extending the case studies to a total of 20 countries in order to make energy saving processes in the European housing sector more transparent and effective through the definition of energy improvement interventions on existing residential buildings. Here the building classification also extended to new buildings, including the nearly zero energy buildings (NZEBs). The operations identified made it possible to evaluate the energy savings achieved and to verify the energy efficiency and sustainability aims with different times and intervention scenarios. The two projects, in conclusion, highlighted the difficulty in achieving certain energetic targets through the current renovation practices with the need to find ways to significantly increase the renovation rate and depths [35].

In addition to these, it was considered appropriate to analyze projects concretely completed on buildings with historic and architectural characteristics. This allowed us to highlight the main critical issues that emerge from the attempt to combine the energy improvement project with the conservative needs of the operations.

In this direction, the interventions on Villa Amalia in Ferrara (Arch. A. Mantovani and L. Bruzzo—Archenergy) stands out for the quantity and quality of the characteristics of historic and architectural value on which it was intended to work. The project for this residential building from the early 1900s made it possible to identify the main causes of energy inefficiency through an accurate analysis of the building [38].

This is true as well for the recovery of Palazzo dei Forestieri in Treviso (Studio Feiffer & Associati), a building from the early 1800s, where work was carried out on the complete restoration of the windows in an energetic crux in addition to the usual operations of intervention on the opaque envelope. The number of inspected elements, the quality, and the attention of the applied methodologies resulted in a net energetic advantage after the intervention [39].

Finally, we considered the Glauber house in Bolzano (Arch. M. Benedikter), a building from 1750. If on the one hand the experimental character of the intervention was appreciated because it was preceded by a careful study of the building and very complex simulations of its thermal behavior [40], on the other, the massive use of heat proofing applied to the opaque envelope made it impossible to preserve some important historic characteristics of the building, thus changing its perception. Despite this, the project won the "energy optimization in renovations" award, even if the failure to recognize the heavy alterations in the appearance of the building indicates an altered interpretation of the concept of authenticity and conservation of the historic and architectural characteristics.

The analysis and systematization of the studies highlighted a crucial aspect of the energy improvement intervention on built heritage: the design of the intended use. The functional definition of the environments that make up the building plays a very important role especially in the setting phase of an energy improvement intervention. Through adequate design, functional arrangement of the spaces, and careful selection of the technologies to be applied, it is possible to obtain great benefits in the thermal behavior of the building and environmental comfort while avoiding interventions that cancel important historic and architectural features in order to comply with the stringent energy efficiency limits required by regulations [2].

The intervention on the Fagus Factory by W. Gropius and A. Meyer is an evident example, where the historic iron and glass windows of the stairwell were restored only by placing sealing gaskets.

This was because the environment did not require specific temperatures and climatic conditions, unlike the surrounding environments, which had to host different activities and people.

A second crucial point that the analysis highlighted concerns the different elements that make up the historic buildings. When they undergo a major renovation, they must go through limit values of thermal transmittance. These values are assigned to construction elements that are grouped by categories, such as the opaque vertical structures with the floors. In other cases, they are distinguished by the openings by dividing them into frame and glass. Attempting also to simply adapt materials different from those of today and construction techniques no longer in use towards restrictive limits designed for the new is ineffective especially if we consider only the need to comply with the numerical factor of the problem.

2. The Multi-Criteria Comparative Analysis

Although the topic is highly relevant, it has been noted that the proposed solutions affected only some areas and problems without the aid of a valid methodological tool for the intervention. The result is the structuring of analysis forms and tables created from the specific needs that an energy improvement project poses for historic buildings. This consists of different sections, the first regarding the general information useful for the definition of the main peculiarities to be safeguarded and the critical issues that the building's construction components present, while the subsequent are useful for identifying the most suitable actions for the specific case [2].

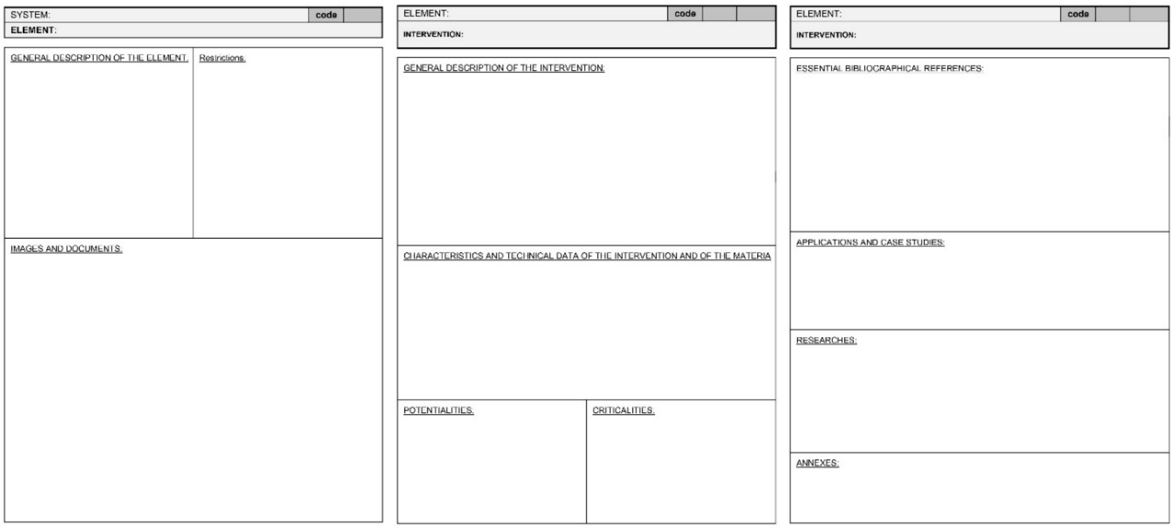
The operations are then evaluated on the basis of the definition of four parameters (compatibility, energy efficiency, durability, and cost effectiveness) in order to obtain direct feedback on the potential of the operations. This tool, therefore, allows the comparison of information and technical data of a different nature constituting the main apparatus to understand the differences between the interventions on the same element of the building and to evaluate the effects of an energy improvement program. The forms are also conceived as an aid system for operators towards practices that can lead to a project capable of reducing energy dispersions by intervening on the main elements of a building without necessarily having a high background of knowledge.

2.1. The Descriptive Form for Elements and Interventions

The first sheet is arranged to describe each construction element that composes the building. To facilitate the subsequent selection of interventions and direct comparison, it was necessary to divide the building into systems (the opaque and transparent envelope) and elements:

- opaque envelope: roofs;
- opaque envelope: external vertical walls;
- opaque envelope: slabs or horizontal divisions towards attic or cellar spaces;
- opaque envelope: slabs or horizontal divisions in contact with the ground; and
- transparent envelope: fixtures, doors, and windows.

This form provides a field for the description of the general characteristics of the element; the dimensional, material, and construction data; and for the collection of information regarding the state of conservation. At the same time, there is a field for indicating the restrictions imposed by the characteristics of the construction element and a section dedicated to images and/or documentary examples of the main construction and material peculiarities (Figure 1a). The restrictions are applicable both in the case of an energy improvement intervention and in the case of a restoration intervention. These arise mainly from the geometric, typological, and material characteristics of the structure, constituting the limits within which to act. These should not be considered restrictive from the point of view of the operations, but rather an aid in the setting of the energy improvement interventions, as they highlight all the main historic and architectural features to be safeguarded. Generally, they can be divided into two main categories: conservation of the geometric and stylish characteristics and conservation of the material attributes of the elements.



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

Figure 1. (**a**) Descriptive form of the elements; (**b**,**c**) descriptive forms of the energy improvement interventions.

Conservation of the geometric and stylish characteristics:

- conservation of geometries and shapes of the building;
- conservation of geometries and shapes of the openings;
- conservation of geometries and shapes of the fixtures, doors, and windows;
- conservation of geometries and shapes of the floors and ceilings;
- conservation of geometries and shapes of the roofs;
- conservation of geometries and shapes of the architectonic ornaments; and
- maintenance of the height of the planking levels and roofs.

Conservation of the material characteristics:

- conservation of historic materials of the walls;
- conservation of historic materials of the finishes;
- conservation of historic materials of the fixtures, doors, and windows;
- conservation of historic materials of the floors;
- conservation of historic materials of the roofs; and
- conservation of historic materials of the architectonic ornaments.

The subsequent parts of the datasheet are dedicated to the individual interventions that can be selected for the element taken into consideration (Figure 1b,c). The technical execution phases are described first, then the characteristics and specific features of the used materials highlighting their potentialities and criticalities. This was designed to raise awareness of the possible effects that the combinations of interventions and materials used may have on the single element while creating an easy-to-use database that can be managed by all the operators.

2.2. Parameters and Method of Evaluation for the Energy Interventions

To quickly highlight the potential and the critical aspects of the energy improvement interventions and with the aim of allowing a simple comparison between the different operations, four distinct evaluation parameters were identified: compatibility, efficiency, durability, and cost effectiveness. The parameters were determined by the need to evaluate the level of conservation of the morphological and material characteristics of the historic buildings (compatibility) as well as to specify the actually achievable energy improvement (energy efficiency and durability), while taking into consideration the overall costs of these operations (cost effectiveness). These parameters were identified as the fundamental factors to establish a unitary evaluation criterion that would allow us to obtain a qualitative index for each energy efficiency intervention.

The four indicators are described and inserted with different worth both within the research projects on energy improvement for built heritage and within the European and Italian standards. Among these parameters, efficiency obviously plays a central role in the debate and is flanked by different facets of the issue.

In fact, within the MiBACT guidelines [9], the term "efficiency" is used in association with energy improvement interventions for historic buildings as a result of a functional design project, the functional efficiency [9] (p. 14), as one of the calculation parameters for the improvement of the environmental quality—for example, the ventilation efficiency [9] (p. 19). It is largely attributed to the energetic field. In this specific area, however, there are distinctions. In some cases efficiency refers to the evaluation of the pre-intervention energetic situation, and in others it is configured as an evaluation parameter of the planned energy retrofit operations or is associated with the technical characteristics of cooling and heating systems and non-conducting materials. It should instead be noted that in the EN 16883/2017 [41] regulation and in its Italian transposition [10], the term "efficiency" plays a very well-defined role as "measurable results related to energy use and energy consumption" and as an "evaluation of energy performance of a building based on the weighted sum of the calculated or measured use of energy carriers" [41] (p. 12).

On the contrary, the term "durability" is never stated in the aforementioned guidelines and regulations, and is indicated only generically within European research projects on the energy efficiency for built heritage and in the technical bibliography. However, durability is always associated with energy improvement interventions as a performance characteristic of technological packages or individual insulating materials [3] while remaining in close connection with efficiency. It is possible to notice how the term is often used to underline a quality, positive or negative, rather than being used as a parameter of evaluation or comparison between interventions or individual materials with non-conductive properties.

Still remaining within the scope of energy improvement projects for historic buildings, the term "compatibility," on the other hand, is used in guidelines, regulations, research projects, and texts with various meanings and significances resulting of primary value. The issue of compatibility, as for efficiency, deserves further and targeted in-depth analyses not appropriate here. However, it is interesting to trace at least the most relevant lines within the regulatory framework currently in force and mostly updated. Compatibility is indicated as one of the targets for the execution of the operations as "technical compatibility with the existing structural, constructional, technical systems" [41] (p. 20) or to define an assessment category, the technical compatibility, always connected to the technical intervention possibilities [41] (p. 21). In this specific case, the compatibility is specified as one of the criteria to evaluate how energy actions physically affect the building and its heritage significance and is defined by EN 16883/2017 regulation as the "extent to which one material can be used with another material without putting heritage significance or stability at risk" [41] (p. 9). The MiBACT guidelines also introduce the term "compatibility" first of all in association with the principles of conservation and protection of cultural heritage and immediately thereafter as a characteristic and operational criterion of intervention at a physical–chemical and aesthetic level, dependent on the historic–architectural quality of the technological element and reliant on its susceptibility to transformation [9] (pp. 8, 43, 45).

Unlike the EN 16883/2017 standard, compatibility is never indicated as a possible evaluation parameter to which to attribute a numerical or qualitative value, but always and only as a condition deriving from conservation and as expressed by the Codice dei Beni Culturali e del Paesaggio [1].

Finally, cost effectiveness, or more simply the cost of the energy interventions, has a fairly shared position in the regulatory and bibliographic framework. The term is often used to indicate economic sustainability in general as all the economic factors that should enable the long-term use of a historic building, or as an evaluation parameter and macro-category—economic viability—which includes the capital costs, the operating costs, the maintenance costs, the economic return, and the economic savings [41] (p. 21). The only difference lies in its use, while in regulations and research projects, it plays the role of indicator, often quantitative and comparative. In the Italian guidelines it has a most informative and accessory value.

The methods for calculating the parameters were conceived in such a way as to provide results that are as objective and easy to calculate as possible, thus characterizing interventions for simpler selection and to provide the users with a known support base. Considering the different nature of the data, it was necessary to define worksheets for each category, within which are the numerical characteristics derived from the technical tables provided by various material producers, from research and analysis. Figure 2 exemplifies the composition and functioning of the forms and shows the data obtained from interventions on a specific construction element.

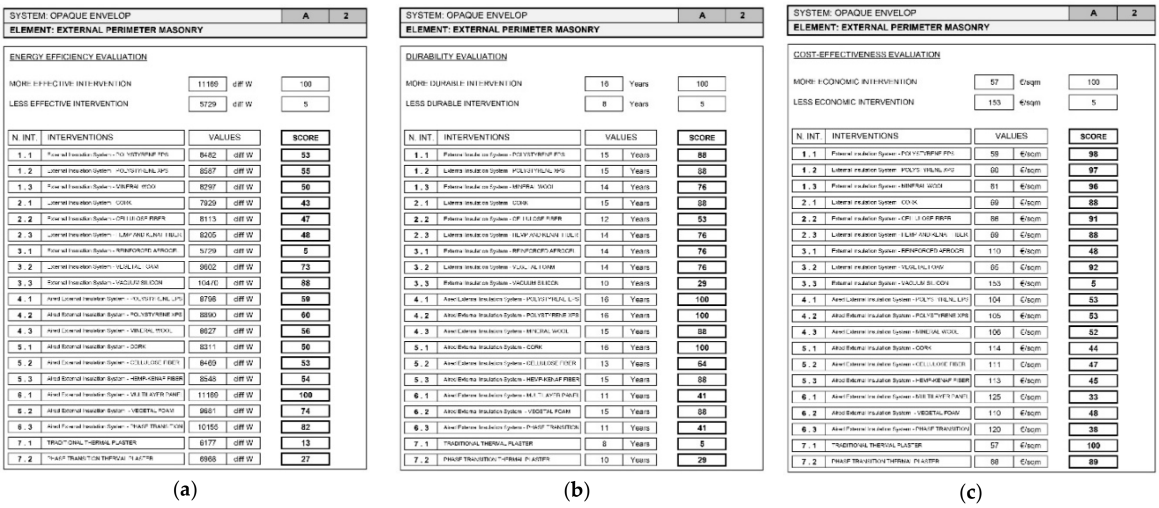


Figure 2. Evaluation forms for the intervention on the opaque envelope, external perimeter masonry: (**a**) energy efficiency; (**b**) durability; (**c**) cost-effectiveness.

The evaluations were calculated through a proportional ratio on a range from 5 to 100, thus returning a percentage value for each operation.

The energy efficiency score was calculated on the basis of the net decrease in the energy requirement for the winter load given by the intervention with the addition of insulating materials or recovery operations that limited the thermal loss of the involved architectural element. The value was then obtained by difference, comparing the dispersions determined on the current configuration of the building with the ones calculated after the application of each proposed energy improvement intervention. The durability score expresses the duration of the intervention over time and the cost effectiveness one indicates the maximization value of the economic resources.

Finally, the evaluation of compatibility expresses the value of conservation of the morphological, architectural, and material (not chemical–physical) characteristics of the intervention on the elements with historic and architectural characteristics. A total of 100 points are attributed to completely conservative interventions, which therefore respect all the identified restrictions that the single element presents, while 5 points are attributed to totally incompatible interventions, which do not respect any of these limitations. These must be assigned to each element referring to its characteristics (geometry, shape, material) and the score is modified according to the percentage of restrictions that the intervention respects. The constraints, in this case, represent a schematization and exemplification of the restrictions to which a historic building may be subject and are useful for the operators to understand which intervention can be considered most compatible in relation to the building.

To recap the evaluations, a table for each energy improvement intervention was organized (Figure 3) and a summary chart was designed to allow for easy and immediate comparison between the interventions that can be carried out on each construction element (Figure 4).

ELEMENT: EXTERNAL PERIMETER WALL	A	2	5 . 2
INTERVENTION: EXTERNAL INSULATION SYSTEM WITH VENTILATED CAVITY AND ECO-EFFICIENT INSULATION PANEL (CELLULOSE FIBER)			

ENERGY EFFICIENCY EVALUATION:			
More effective intervention	11169	diff W	100
Less effective intervention	5729	diff W	5
EVALUATION OF THE ENERGY EFFICIENCY	**8469**	diff W	**53**

DURABILITY EVALUATION:			
More durable intervention	16	years	100
Less durable intervention	8	years	5
EVALUATION OF THE DURABILITY	**13**	years	**64**

COST-EFFECTIVENESS EVALUATION			
More economic intervention	57	€/sqm	100
Less economic intervention	153	€/sqm	5
EVALUATION OF THE COST-EFFECTIVENESS	**111**	€/sqm	**47**

COMPATIBILITY EVALUATION			
Restrictions given by the element:			
• Conservation of geometries and shapes of the building,			
• Conservation of geometries and shapes of the openings,			
• Conservation of the architectonic ornaments,			
• Conservation of historic materials of the walls,	x		
• Conservation of historic materials of the finishes.			
5 **FULFILLED RESTRICTIONS**	**1**	**SCORE**	**20**

Figure 3. General evaluation table. Intervention on the opaque envelope, external perimeter wall: external insulation system with ventilated cavity and eco-efficient insulation panel.

The summary evaluation chart is one of the possible schematic representations of the analyzed and processed data, and is the result of the numerous comparative tables used for various purposes and connected with the interventions on the buildings. This table is a summary of the parametric assessments applied to the interventions on the same element or technological package capable of comparing the different options. Using a common unit of measurement and the same calculation methods allows the performance indicators of each intervention in relation to the four parameters to be evaluated at a glance and the most suitable solution to be selected based on the needs.

In this way, an end user (designer, operator, official in charge of the checks of the project proposed) could immediately select or evaluate an intervention according to the parameter to be privileged, which can be different in relation to the historic, morphological, and material characteristics of the building.

The summary chart also allows for the selection of which parameters to be considered representative from the design point of view, obtaining the result best suited to the needs of a defined element or category. Further data is given by the general evaluation of the intervention expressed on a scale from 5 to 100. The score is obtained through an unweighted average of the previous parameters and the result, even if scientifically partial, could provide additional orientation in the selection between the interventions. This choice was consciously simplified and established to evaluate or judge each intervention without giving a specific influence on one of the four categories, assuming that the parameters are basically the same at the time of the design choice.

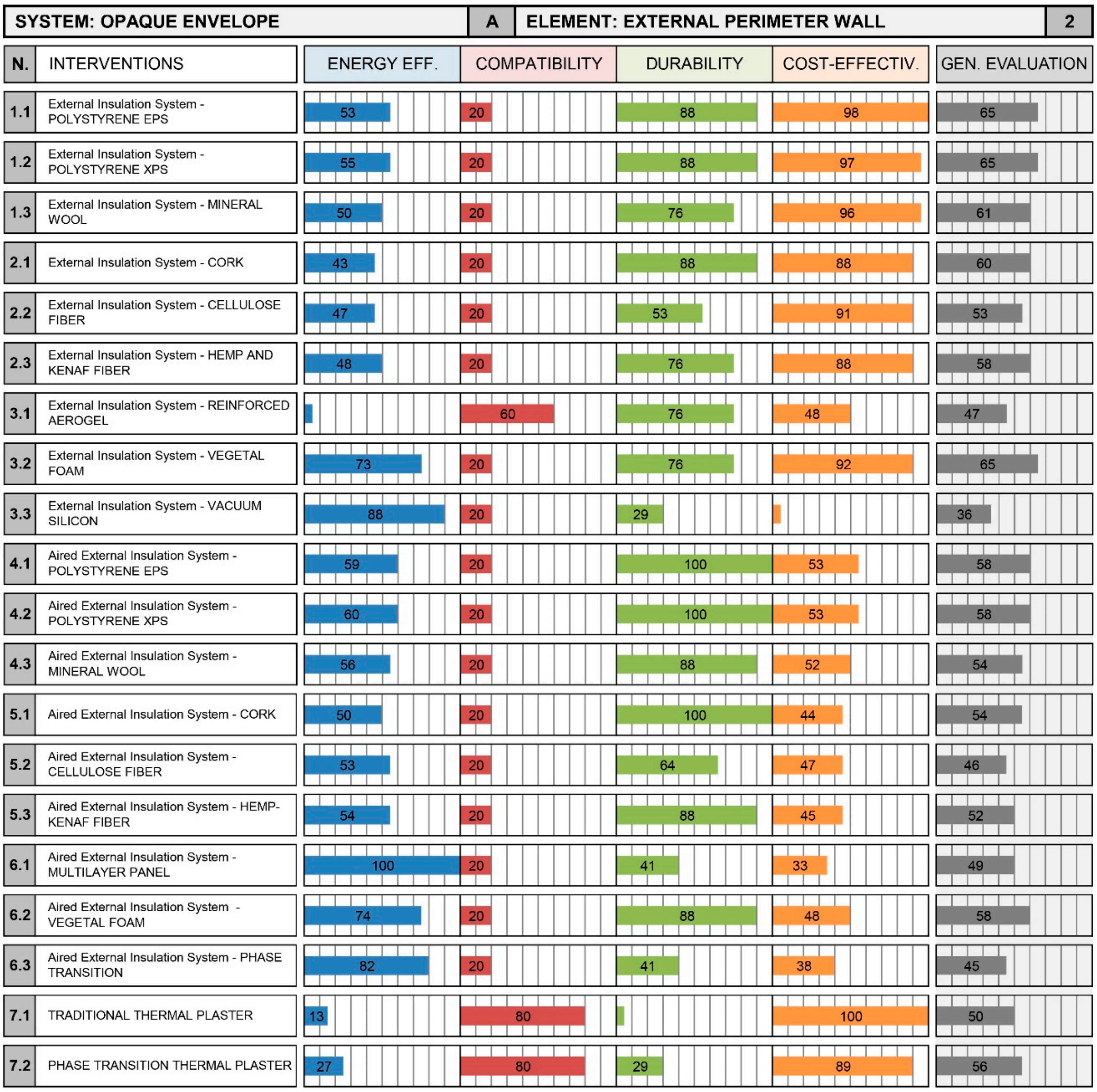


Figure 4. Summary evaluation chart, interventions on the opaque envelope, external perimeter wall.

The end user would have the possibility to select the intervention with the highest score in the category deemed primary for the building that is the object of the operation, in relation to detailed studies that have been carried out for general knowledge and the connected state of conservation of the element.

On the topic of the multi-criteria evaluation method, the interesting framework created for the interventions on the curtain walls of the Cité du Lignon in Geneva, Switzerland, should be noted.

The identified comparison parameters concerned the estimate of construction costs, the level of compatibility, durability, and the energy efficiency achieved by the interventions. These were studied at the level of the individual housing module and the data were reported in single summary forms, allowing the designers to immediately compare the different solutions determined: today's situation, ordinary maintenance of the structures, restoration of the existing façade, restoration of the elements, and new additions. The aim was to obtain a method for evaluating all the possibilities both globally and at the level of a single selected parameter to be directly delivered to the individual owners of the units [42].

3. The Validation of the System: Mulino del Cantone, Monza

To validate the system, the evaluation parameters, and the calculation methods and to avoid isolating the system from a possible context of application, it was necessary to consider a typical building, the Mulino del Cantone inside the Villa Reale Park of Monza, a paradigm of a vast series of historic buildings that has important architectural features. The structure is located north of the Royal Palace, near Villa Mirabello, and was built in the area called Cantone starting in 1840 for a project by Giacomo Tazzini [43].

The structure of the mill is made up of solid brick walls covered by plaster, partly cementitious and partly still in lime mortar. An acrylic paint covers most of the external surfaces of the building while the roof covering is of tile and supported by a wooden structure, as well as the floors. The windows, of different shapes and sizes, are of wood with single glass mirrors.

Although it belongs to the category of so-called monumental buildings due to its location and architectural features, the mill is a significant example of construction techniques commonly used on historic buildings, and therefore of much other construction done up to the post-war reconstruction era.

The characteristics of the façades, the elements in relief, and the traces of a decorated plaster constitute important restrictions to the interventions that can be carried out (Figure 5). While degradation phenomena are common to many buildings from the past, these characteristics make Mulino del Cantone an interesting example for the transferability and diffusion of the analysis reported here.

Figure 5. Detail of the main façade.

For these reasons, the building was used as an example to which to experimentally apply the selected energy improvement techniques, evaluate their effectiveness, calculate the energy improvement that can be obtained, hypothesize the intervention costs, and check their compatibility. The building was thus split into all its parts and analyzed from a constructive, technological, material, and geometric point of view in order to create a database of information that would allow for the full knowledge of the building, including its technical and energy characteristics. This initial basis was implemented with all the information and technical data derived from the specific analysis of the interventions, thus creating a series of additional indications that permitted the evaluation of each individual intervention.

Regarding the parameters of compatibility, durability, and cost effectiveness, the evaluation methods proved to be functional for the purpose by returning results that were mutually agreed upon and comparable. The calculation criterion adopted to evaluate the energy efficiency of the interventions, on the other hand, presented problems, as it had not fully taken into consideration the building in its entirety. It was therefore decided to modify this method using the net decrease in the energy requirement for the winter load as the evaluation variable.

On the Molino del Cantone, therefore, the application of the selected energy improvement interventions was hypothesized, inserting the current data concerning the dimensions, material composition, and thermal features of the dispersing surfaces in specific static calculation software in order to obtain the starting thermal dispersion values and transmittances. By changing the stratigraphy of the elements on the basis of the chosen interventions, the energy demand values varied. However, this approach also presented some critical issues for the calculation, so ad hoc worksheets were set up to simplify that process. The thermal resistance and the thermal transmittance were calculated on the basis of the EN ISO 6946/2017 with some modifications, using a simplified calculation method as per the table in Figure 6.

These have made it possible to analyze the insulating capacity of an element in relation to its surface and configuration (Figure 7), thus allowing for the insertion of exactly all the necessary characteristics.

By subsequently modifying the transmittance value of the stratigraphy, the net decrease was estimated and used as a yardstick to assess the energy efficiency of the operations. The scoring range, as for the other cases, is variable from 5 to 100. A value of 100 was attributed to the most efficient interventions among those examined and 5 to the less effective interventions. For the evaluation of this parameter, the data provided by the manufacturer's technical tables were taken into consideration, therefore without direct laboratory verification of the actual energy performance. However, a discrepancy was observed with respect to what was reported in the technical information from the analysis of some applications and research [3] (pp. 21–65). Given that this difference in values is mainly influenced by the different conditions of application of the material, the laying methodology, the material incompatibility, or the state of conservation of the structures, a 10% reduction was defined for all the transmittance values provided by the technical data sheets so as to obtain results closer to real applications.

ELEMENT STRATIGRAPHY		EXTERNAL PERIMETER WALL				
N°	LAYER DESCRIPTION (from inside to outside)	*d* [m]	*λ* [W/mK]	*C* [W/m²K]	*ρ* [kg/m³]	*R* [m²K / W]
1	Lime plaster	0.020	0.7000		1500.00	0.029
2	Full bricks	0.510	0.7000		1600.00	0.729
3	Lime plaster	0.020	0.8000		1600.00	0.025
4						
5						
6						
7						
8						
9						
10						
	internal surface resistance (Rsi)					0.130
	external surface resistance (Rse)					0.040

Thermal resistence (∑ R) (m²K / W)	0.952
Unitary trasmittance K (W / m²K)	1.050

ELEMENT STRATIGRAPHY		External perimeter wall - A 2 5,2 ventilated cavity and eco-efficient insulation panel				
N°	LAYER DESCRIPTION (from inside to outside)	*d* [m]	*λ* [W/mK]	*C* [W/m²K]	*ρ* [kg/m³]	*R* [m²K / W]
1	Lime plaster	0.020	0.7000		1500.00	0.029
2	Full bricks	0.510	0.7000		1600.00	0.729
3	CELLULOSE FIBER PANEL	0.050	0.0370		30.00	1.351
4	VENTILATED CAVITY	0.030		6.40		0.156
5	REINFORCED EXTERNAL PLASTER	0.030	0.8000		1600.00	0.038
6						
7						
8						
9						
10						
	internal surface resistance (Rsi)					0.130
	external surface resistance (Rse)					0.040

Thermal resistence (∑ R) (m²K / W)	2.472
Unitary trasmittance K (W / m²K)	0.404

Figure 6. Calculation table used to determine the transmittance value of each intervention. In gray are the current thermal characteristics of the element; in green are the thermal resistance and transmittance values after the application of the energy improvement: opaque envelope, external perimeter wall, external insulation system with a ventilated cavity, and eco-efficient insulation panel.

THERMAL DISPERSION				
	Mode of use	Room N°	iT°C)	eT(°C)
			20	-5

A- Dispersed power by air renewals (Pv)			
	N° Air renewals (vol/hour)	Volume (m³)	**Pv (W)**

B- Dispersed power by surfaces (Ps)							
N°	Description *Opaque and transparent envelop*	U (W/m²K)	S (m²)	Δt (°C)	Orient.	Increm. (%)	**Ps (W)**
1							
2							
3							
4							
5							
6							
7							
8							
					∑ Ps	**(W)**	

C- Dispersed power by thermal bridges (Ptb)							
N°	Description *Building corners and thermal bridges*	ψ (W/mK)	L (m)	Δt (°C)	Orient.	Increm. (%)	**Ptb (W)**
1							
2							
3							
4							
5							
6							
7							
8							
					∑ Ptb	**(W)**	

D- Dispersion summary and thermal power calculation							
		Pv	Ps	Ptb	$\Sigma P_{(v,s,tb)}$	Increm.	**total P**
		(W)	(W)	(W)	(W)	(%)	**(W)**

Figure 7. Calculation table used to determine the dispersion for air renewal across the surfaces and through thermal bridges of the building.

4. Discussion and Conclusions

The analysis completed and the experimental application phase of the system highlight two particularly significant sides of the research, the first concerning the energy improvement interventions and their effectiveness, and the second inherent to the proposed descriptive and evaluating system.

The effectiveness of energy improvement interventions is shown to be strongly influenced by the type of insulating materials selected. The higher the quality and performance level of the material used, the higher the energy efficiency of the intervention. This growth is often matched by a significant increase in the cost of the operations. In fact, the innovative insulating materials significantly affect the total amount of the individual interventions, considering the highly experimental nature and the complexities of the operations that involved them. Some innovative insulators, due to their fragility and the reduced thickness that frequently characterizes them, must be applied precisely through the creation of structures capable of protecting them from damages and through articulated laying structures [2]. The results of the summary evaluation chart, therefore, allow us to understand and demonstrate that the interventions differ slightly if we only consider the energy efficiency and cost-effectiveness evaluation because these two factors counterbalance each other. Hence the importance of the compatibility parameter emerges as a key element in selecting an intervention for historical built heritage.

The descriptive and evaluating system is the most important acquisition and the operational heart of this contribution. The data and concepts are arranged in such a way as to facilitate their examination and consultation. As has been said, it must always be emphasized that for each application, a detailed analysis of the individual building to which the intervention is aimed remains necessary. In fact, the forms and tables allow for the selection of an intervention in relation to the purposes that the project has and in relation to the characteristics of each historic building, allowing for the benefit of one or more criteria between energy efficiency, compatibility, durability, and economy, depending on the context of application. The provided system must be considered open: New acquisitions in terms of intervention techniques and methodologies, if included in the outlined layout, can be easily compared with others that already exist. The tables can also be adapted to the control of projects already completed, becoming a useful parameter not only for designers and operators but also for officials of the institutions responsible for approving interventions on historic buildings.

The methodology for assessing the effectiveness of energy improvement interventions is a highly debated and continuously advancing topic both in terms of scientific research and in terms of the creation of dedicated tools [44]. This is evidenced by numerous studies that have just concluded or are still in progress [45–48] that are capable of positively comparing the theoretical values obtained from complex calculation models with the actual measured transmittance values. Instead, the evaluation method proposed here is less refined and differs significantly from a methodological point of view. Using a prompt and immediate calculation method to provide values that are functional and easily comparable by any involved operator was preferred while giving back adequate results for the energy design process.

Significant outlooks for the research progress can be identified in the real application of the most appropriate techniques: The pilot site can constitute an important test bench for the energy improvement interventions that the system of tools defines most suitable, but above all for the descriptive and evaluating system, becoming an opportunity for a tangible verification [49]. It is also possible to proceed with the application of different solutions pertaining to each of the four key parameters, thus offering an opportunity to verify the effectiveness of the individual selected interventions, which would thus be tested on the same building, obtaining results objectively and immediately comparable. It could also be interesting to systematize the data and evaluations resulting from the energy improvement interventions applied to the opaque and transparent envelopes with the data coming from research, protocols, and regulations on the enhancement of the thermal systems. The purpose could be to combine all the information into a single database and perhaps into a simplified system in order to evaluate the total heat dispersion and energy input given by the whole system.

Finally, starting from the data collected, the organization of the descriptive and evaluating system gives the possibility of implementing the MiBACT guidelines [9] and the UNI EN 16883/2017 regulation [10] introducing common practices for the safeguarding of the historic, architectural, and material characteristics of the buildings able to guarantee effective energy improvement.

To facilitate professionals, technicians, officials of the institutions, and end users in the choice of the interventions and in the drafting of the projects according to standards of minimum quality and effectiveness, a checklist could be created in the awareness that the abbreviation of the procedures and the simplification of practices can benefit every field of application and research.

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