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A model for improving the energy efficiency of historic buildings with environmental and comfort considerations

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Abstract

The article presents issues related to the possibility of improving the energy efficiency of historic buildings. This group of buildings, in Poland, currently has no defined requirements for minimum energy demand values. However, taking into account the long-term strategy of decarbonization of Europe and the Long-Term Strategy for Renovation of Buildings adopted in Poland, it is necessary to develop models and procedures for thermal modernization activities of historic buildings. The group of historic buildings represents a very large potential for possible energy savings in the construction sector. The article presents proposals for a system approach to achieve the standard of a historic building with near-zero energy demand and climate neutrality. Developed algorithms of procedure are presented, which can support the decision-making process in the selection of optimal thermomodernization measures.

Keywords: historic buildings, temomodernization, thermal diagnostics, occupant comfort, energy efficiency

1 Introduction

Historic buildings are a unique group of objects. They are our cultural heritage and we should make every effort to keep their appearance intact. However, the deterioration of historic buildings should not be allowed by abandoning repair and modernization efforts. Many historic buildings that have not been repaired have fallen into disrepair, losing their historical value or have ceased to exist.

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Figure 1. *An example of a historic building in which the historic fabric has been destroyed as a result of the abandonment of modernization efforts (own source).*

According to the current law of July 23, 2003 on the protection and care of monuments, a monument is an immovable property or a movable thing, a part or a set of them, being a work of man or related to his activity and constituting a testimony of a bygone era or event, the preservation of which is in the public interest due to its historical, artistic or scientific value [1]. Immovable monuments that are, among other things, building complexes, departments of architecture, construction, objects of technology, industrial plants, etc., are subject to protection. Monuments constitute a significant group of objects in the national and international building stock. As of the end of 2020, about 80,000 historic buildings and areas were registered in the Register of Monuments in Poland. In addition to the Register of Monuments, municipal and provincial registers are kept, which include as many as ca. 700 thousand historic objects [2]. Figure 1 presents the number of immovable monuments in Poland by province as of 2020.

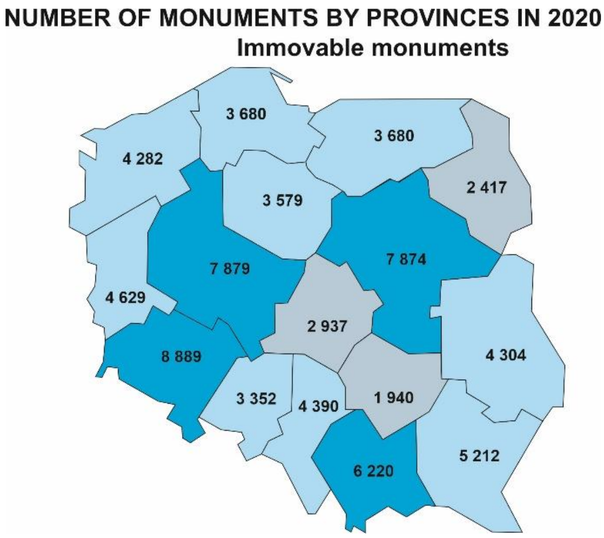

Figure 2. *Number of immovable monuments in Poland 2020* [2].

In most cases, historic buildings are under the care of conservators and are listed in the register of monuments. In the Polish national requirements [3] historic buildings are exempt from energy efficiency improvement measures. However, with such a large group of existing and very frequently used historic buildings, the potential for energy savings is very high [4]. [5]. Historic buildings, often intended for commercial purposes, are often in poor technical condition, thereby failing to provide comfort to users, which affects health and well-being as well as the quality of work performed. The scientific goal of the article is to identify opportunities to improve the energy and utility standard of historic buildings, in accordance with the idea of sustainable development in construction. In accordance with this idea, the policies of the European Union member states in the area of the construction sector, set trends aimed at increasing the energy efficiency of new and existing buildings. In the area of thermal protection requirements for new and thermo-modernized buildings, a standard for "near-zero energy consumption (nZEB)" buildings has been introduced [3] [6]

European Union member states have committed to implementing the standard for buildings from 2021 (from 2019 for buildings occupied by government authorities). In Poland, the nZEB standard is defined by two parameters: the thermal insulation coefficient U [W/(m^2K)] and the index of non-renewable primary energy EP [kWh/(m^2rok)]. The minimum values of these parameters are written in the Technical and Construction Conditions [7]. Newly designed buildings must meet the conditions of not exceeding both indicators, thermo-modernized buildings have restrictions imposed only on the thermal insulation of the partitions, while historic buildings are exempt from the requirements. This is summarized in Table 1.

Table 1. *Parameters that buildings must meet from 2021 in Poland*

Building:	Coefficient U [W/(m^2K)]	Coefficient EP [kWh/(m^2rok)]
newly-designed	obligatory	obligatory
existing, undergoing extensive thermal upgrades	obligatory	not required
Historic, under conservation care	not required	not required

As shown in the table, historic buildings and those under the protection of the conservator are exempt from any requirements for energy efficiency improvements. The provisions of Article 5 of the Construction Law [8]- exempt from the obligation to establish energy performance for buildings subject to protection under the regulations on the protection and care of historical monuments. All buildings listed in the register of monuments are subject to a complete exemption from the obligation to establish their energy performance in the form of an energy certificate. In addition, carrying out construction work on a building listed in the register of monuments requires, prior to the issuance of a construction permit decision, obtaining a permit to carry out such work, issued by the competent provincial conservator of monuments. The legal basis for the protection of objects under conservation protection is an act of local law in the form of a local zoning plan. In a situation where compliance with thermal insulation requirements is not possible due to the welfare of the protected object, as well as it is not possible to meet the aforementioned requirements, using alternative methods of insulating the building, acceptable in the opinion of the conservator and in accordance with the local zoning plan, it is possible not to meet the thermal insulation requirements of the partitions of historic buildings. Of course, all possibilities permitted by the conservator should be used to improve the energy performance of the historic building, thus protecting the historic asset, primarily due to:

- improving the technical condition of the historic building;
- minimizing energy consumption
- minimizing the carbon footprint;
- improving the comfort of users of historic buildings.

Additional arguments for developing optimal methods of improving the energy efficiency of historic buildings while preserving their historic qualities include provisions in the 2018 Energy Performance of Buildings Directive. For the first time, the EPDE Directive introduced a provision for historic buildings and under preservation "Scientific research on new solutions to improve the energy performance of historic buildings and structures, as well as the testing of such solutions, should be supported, and at the same time the protection and preservation of cultural heritage should be ensured." [9]**.** Under the directive, member countries have begun to implement its provisions in national legislation. In 2022, Poland published a "Long-term strategy for the renovation of buildings"[10] . According to the strategy, buildings should be modernized by 2050 in a manner consistent with the transition to a climate-neutral economy. Also in the Lisbon Treaty [11]one can find many references on the relationship between the idea of sustainable development and cultural heritage. Thus, immovable monuments, as one of the resources of cultural heritage, are one of the elements of sustainable development of civilization and play an important role in the strategy of sustainable development, which is highlighted, for example, in the publication of the Polish Committee for UNESCO Affairs [12]. Monuments as part of the national heritage, being a testimony of history, documenting the past, should be protected and stimulate the national identity of society and be the basis of its continuance and development. Implementation of the idea of sustainable development in the process of protecting monuments, emphasizes their important role and significance as objects of cultural heritage [13]. A system of administrative measures, EU subsidies, and various tax breaks, encourage preservation activities for historic buildings, which promotes both heritage protection and sustainable development.

In summary, historic buildings, due to their nature and historical functions, should have energy efficiency improvement guidelines that take into account many aspects, other than for non-historic buildings. These requirements should, depending on the use, take into account, among other things, the parameters of the internal environment, adaptation to the function performed, technological possibilities for improving thermal protection, or the financial aspect. Many of these buildings are currently used for residential or public functions, or are used in other ways. Owners and users of historic buildings, often face the dilemma of how to carry out the modernization of a historic building. There is a lack of guidelines on how to improve the technical condition with special attention to thermal protection. There is also a lack of tools that allow the user to select the optimal function for a particular building, given the technical possibilities, historical, social or financial aspects. The article presents a method for improving the energy efficiency of historic buildings, improving occupant comfort and a method for achieving climate neutrality. The methodology takes into account the change of the utility function of a historic building in whole or in part. In the case of historic buildings, a common case is the restoration of a non-functioning historic building to a functional form in whole or in part. It is also often the case that a monument needs to be adapted to a different function than the current one, while it is not known what function from the point of view of the nature of the monument would be the best In such cases, procedures and methods are needed to select the new optimal use function of the historic building.

2 Criteria adopted to analyze the possibility of improving the technical condition of historic buildings in terms of sustainable development

Figure 1 defines the basic criteria for improving the technical condition of historic buildings in accordance with the proposed methodology.

The main and overriding criterion for historic buildings is the protection of national heritage. All thermomodernization measures are subordinated to this criterion. Therefore, according to the study [14] proposed steps prior to thermorenovation of historic buildings should include:

Develop a strategic plan for the protection of the monument. In this document, on the basis of preliminary studies, the essential role of the monument, the function of the object should be determined (this applies to monuments that are being restored to use or there is a change of use function). The strategic plan should include a preliminary conservation design, along with an indication of the types of research and expertise needed for a full diagnostic of the monument. The strategic plan should set directions for action and form the basis for conservation decisions.

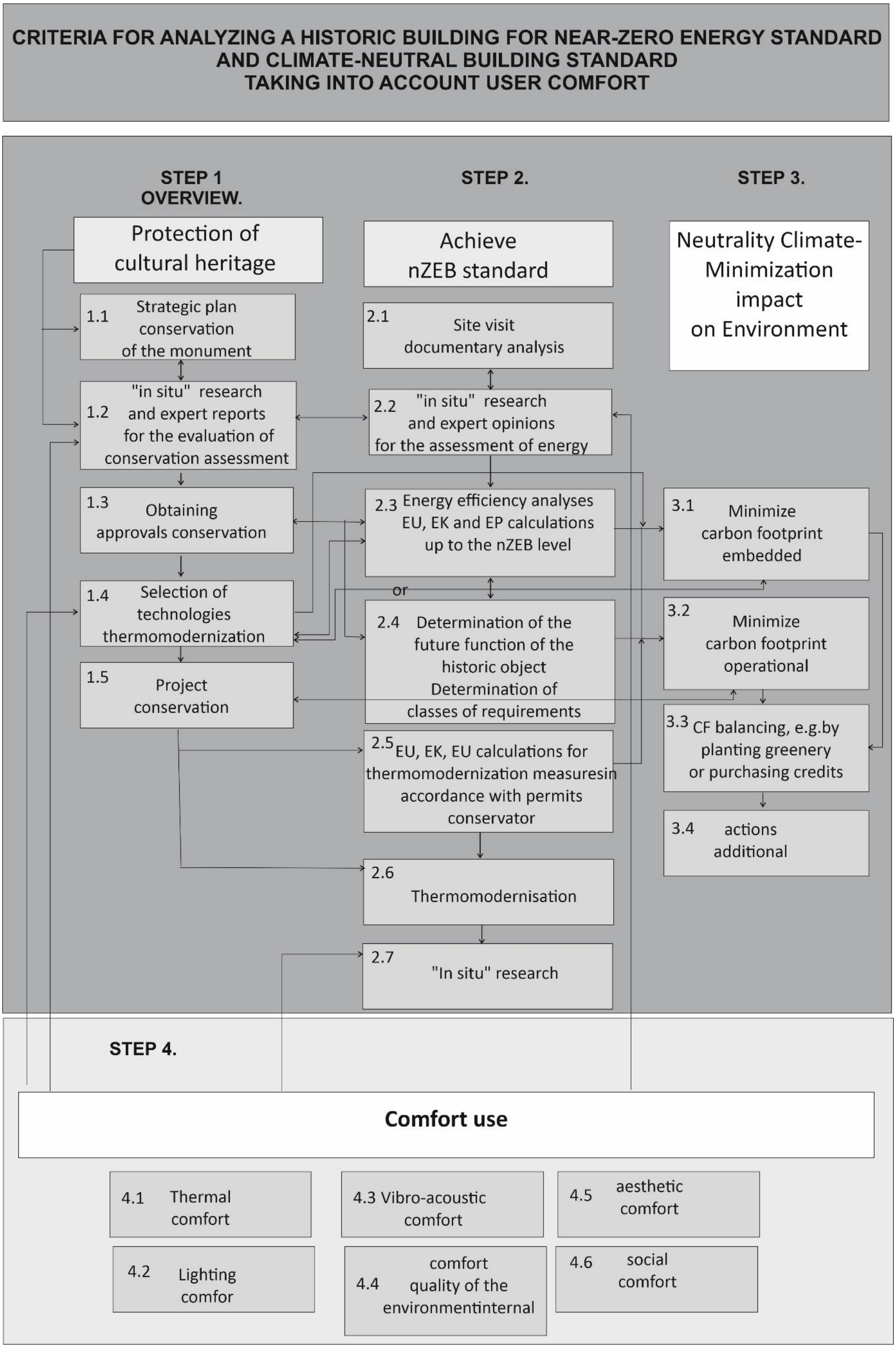

Figure 1. *Criteria for improving the energy efficiency of historic buildings, adopted in the developed methodology (own source).*

Development of the conservation project. The conservation project should be developed on the basis of multidisciplinary research performed in accordance with the strategic plan. Based on the results of the research, after defining the conservation diagnosis, the scope of conservation and restoration activities can be determined, without compromising the historical heritage. The conservation project should include a program and schedule of activities, along with an indication of construction methods and materials. The conservation and restoration tasks should also refer to the building's surroundings and furnishings. Branch projects are part of the conservation project. Among the "in situ" studies diagnosing the technical condition of a historic building, we can mention thermal imaging studies, testing the air permeability of the building envelope, if necessary, mycological, stratigraphic and other studies depending on the condition of the building.

Step 2. Achieve the standard of a building with almost zero energy demand

As shown in Table 1, historic and conservation buildings are exempt from any energy efficiency improvement requirements. The provisions of Article 5 of the Construction Law [15]- exempt buildings subject to protection under the provisions of the Law on the Protection and Care of Historic Buildings from the obligation to determine energy performance. In the methodology presented here, the assumption is that a historic public building should only meet the requirements for the EP indicator in order to be described as a building with almost zero energy demand. However, despite the fact that it will be impossible in most cases to improve the thermal insulation of the elements of the historic building envelope to the values specified in the Technical Conditions, it is necessary to take advantage of all opportunities to improve the thermal insulation of the building envelope, while ensuring airtightness. The nZEB standard for historic buildings does not have to meet the minimum requirements for Final Energy Demand. However, in the case of a planned change of use function, the proposed methodology introduces into the energy efficiency assessment of a historic building both an improvement in the thermal insulation of the building envelope and (alternatively) a reduction in the Final Energy rating. An additional requirement for thermo-modernization of historic buildings should be the recommendation to conduct "in situ" studies diagnosing the building's vulnerabilities. Even at the pre-renovation stage, it is possible to reduce energy consumption to improve comfort, for example, by sealing leaky windows or doors. Possibilities for achieving a near-zero energy consumption building standard have been developed in the form of a list identifying feasible measures. The value of energy savings depends on the current state of the building and the feasibility of improvements in consultation with the building conservator. We are able to estimate the exact and actual value of savings only after conducting an individual energy audit.

Step 3. climate-neutrality analysis.

Climate neutrality is a recently introduced concept. It denotes measures aimed at reducing the environmental impact of energy-intensive sectors. An indicator that illustrates climate neutrality is the carbon footprint index. The carbon footprint is defined by the total sum of greenhouse gas emissions caused directly or indirectly by a person, organization, event, product or building. It is a type of environmental footprint. The carbon footprint includes emissions of carbon dioxide, methane, nitrous oxide and other greenhouse gases expressed in CO_2 equivalent. In order to consider a climate-neutral building, it is necessary to calculate the building's heating and electricity demand, assume a calculation period of, for example, 30 years, and for such a period calculate how much the analyzed building will emit environmentally harmful gases due to energy consumption during this period. After determining the amount of CO_2 emissions, assuming the current state of the building, first consider the possibility of reducing the energy intensity of the building and then perform recalculations for the building where thermal upgrading measures have been determined. The amount of CO2 emissions should be balanced by "green" measures, for example, buying credits issued on the basis in the form of planting new trees. Other forms of greenery can also be considered, such as green walls, green roofs and others. The origin of greenhouse gases in construction-retrofit analyses can be divided into two categories: operational and built in. Most attempts to create building-retrofit green solutions boil down to reducing operational emissions, i.e. those related to heating, cooling and lighting, throughout the building's life cycle. The methodology presented in the article follows the latest trends. Specific solutions affecting the reduction of operational emissions are indicated. In addition, an attempt has been made to carefully reduce the embedded emissions of the facility, with respect to building materials and construction processes associated with thermal upgrading activities. Analyses of the embedded footprint highlight the complexity of emissions generated through: acquisition of mineral resources, transportation of raw materials, production of building materials (i.e., emissions from coking plants, steel mills, cement plants, brickyards, etc.), storage, transportation of materials to the site, construction, maintenance, demolition/recycling or disposal. Table 2 shows all phases of a building's life from the raw material acquisition phase to the recycling phase. In the case of existing structures and even more so in the case of historic buildings, it is almost impossible to obtain information on the carbon footprint of the materials and technologies from which the building is made. It would be necessary to have knowledge about the production of historic materials, the way they are transported or the technology of erecting historic buildings. Therefore, only phases B5 and B6 are included in the analysis presented here. Phase B5 refers to the CO_2 emissions for the building materials that were used for thermal upgrading. Here, it was limited to the materials used for thermal insulation, windows and doors. No new installations, automation systems or lighting were analyzed. No CO_2 emission databases are available for these technical systems.

Table 2. *Phases in the life cycle of a building and building product.*

The product phase			Phase process construction		Use phase							End of life phase				
Mining and supply of raw materials	Transport	Production of the product	Transport	Construction process	Usage	Conservation	Repair	Exchange	Renovation	Energy consumption	Water consumption	Demolition/Demolition	Transport for disposal	Recycing	Disposal	Retrieved
A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D
Embedded Carbon Footprint										Operational CF		Embedded Carbon Footprint				

Phase B5 considers phases A1-A4 according to the building life cycle stages according to EN 15804. The other phases have been omitted due to the lack of national carbon footprints from construction processes, as well as the lack of key inventory data needed to determine the use and end-of-life phases.

Step 4 is the selection of balancing activities for the calculated carbon footprint. The methodology assumes balancing the carbon footprint over a 30-year period. Such a period was adopted due to the fact that the European Union countries have committed to achieving climate neutrality by 2050, so the 30-year calculation period coincides with the deadline for the transition of European countries including Poland to zero emissions. The methodology adopted balancing CO_2 emissions with plantings of new trees and other forms of greenery.

The last criterion adopted by the authors is building occupant comfort. The multi-faceted comfort of buildings has been a topic repeatedly addressed by the author in publications [16–19].

3 Expert system of evaluation and classification of historic buildings to be upgraded with a change of function

For the purpose of the analyses presented in the article, an expert system was developed for evaluating and classifying historic buildings for modernization, taking into account the aspect of changes in the utility function of part or all of the modernized building. The procedure of the system is shown in Figure 5. The activities are divided into three sub-procedures (A, B and C). Procedure A applies to historic buildings that will not undergo a change in use function after retrofitting, procedure B applies to historic buildings for which a partial change in use function is planned, procedure C applies to historic buildings for which a complete change in use function is planned.

In the proposed procedure, step 1 is to assess the possibility of improving the thermal insulation of the building envelope or reducing the level of Final Energy Consumption (EK). This depends on the consent of the conservation officer to carry out certain measures to improve the thermal insulation of the building envelope or other measures, for example, changing technical installations, introducing building automation, etc. Typically, of the measures for insulating the envelope of historic buildings, it is possible to insulate the attic ceiling and the ceiling above the basement, to dry and insulate the basement walls, to make screens in the form of laid heat-protective plaster in radiator niches, if any. Sometimes the conservator agrees to insulate the partitions from the inside, if this will not lead to degradation of the historic fabric. However, it should be borne in mind that the technology of insulating from the inside of the building is problematic from the point of view of the possibility of dampness of the partition. Often it is not possible to use modern energy-efficient joinery, so the renovation of the existing joinery with the replacement of single glazing with special glazing packages, renovation of windows with sealing is used. The installation package may include the use of a new energy-efficient heating system, the use of recuperation in mechanical ventilation systems, or the replacement of lighting and the use of control and energy management systems. If the conservator agrees to replace the old heating system with a heat pump, the final energy savings could exceed 60%.

Step 3 is to assess the potential for reducing the carbon footprint. As mentioned earlier in the proposed assessment methodology, the operational carbon footprint over a 30-year period and the embedded carbon footprint of the materials used for insulation, window and door replacement should be considered. Due to shortcomings in Polish databases, the methodology does not currently provide for the evaluation of installation components, automation systems or lighting replacement.

Step 4 concerns ensuring the multi-faceted comfort of the historic building. Activities in this area are based on the selection of appropriate thermal insulation technologies that take into account guidelines for optimizing occupant comfort (for example, the use of sunshades, anti-vibration inserts, or soundproofing screens). "In situ" testing, is an important aspect in the proposed methodology. Only through research can design assumptions be confirmed. Proposed "in situ" testing may include: air tightness testing of the building envelope combined with thermal imaging, interior microclimate testing, mycological testing, and dampness of the envelope. Each historic building should be considered individually for the choice of "in situ" surveys. The author's suggestion is to conduct surveys before the thermo-modernization process and, by diagnosing the building's weak spots already in use prior to thermo-modernization measures, make improvements in the form of sealing, introducing sunshades, greenery and other comfort-improving measures. The second stage of the study is "in situ" research after the thermal upgrading measures. Their effect is to verify that the renovation measures were carried out with due care towards the project.

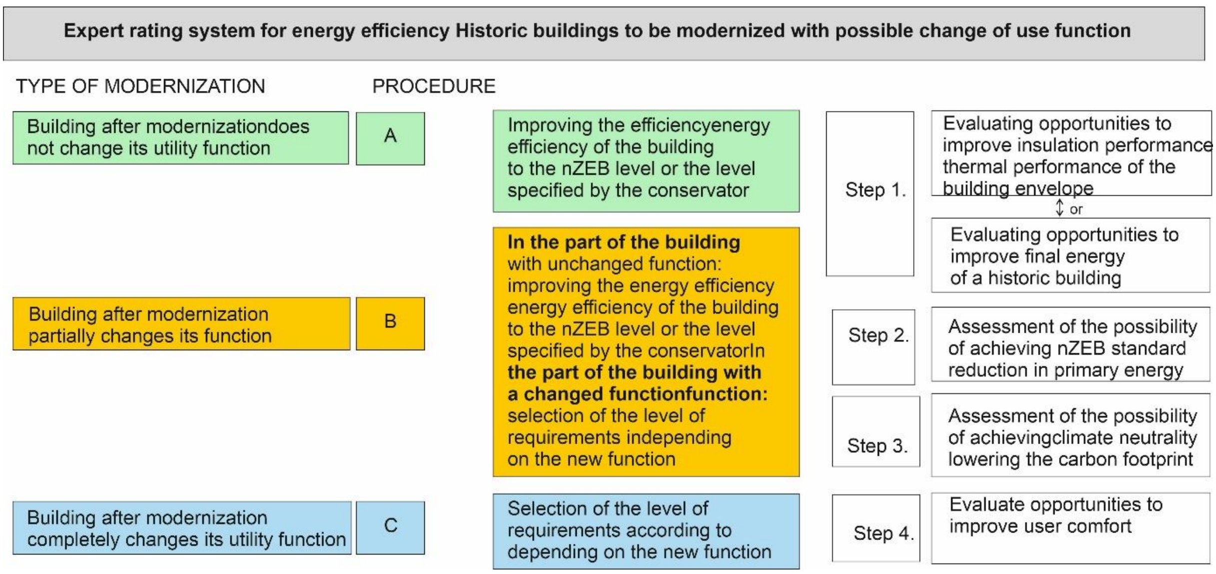

Figure 5. *General scheme of the expert rating system for energy efficiency of historic buildings.*

The following figures present a proposal for the scoring of activities related to Step 1 - insulating the exterior envelope elements (external walls) of historic buildings. The authors of the article [20] show that the application of thermal insulation plaster (5 cm thick) on the uninsulated walls of a building under conservation protection reduced its energy intensity by more than 20%. On this basis, a classification was adopted for evaluating the improvement of thermal insulation of exterior walls in historic buildings, assuming a change in the function of use. Figure 6 shows the procedure for historic buildings for which no change of use function is planned. Figure 7 is the procedure for buildings where a change of use function is partially planned. The last figure 8 is the procedure for buildings where a complete change of utility function is planned.

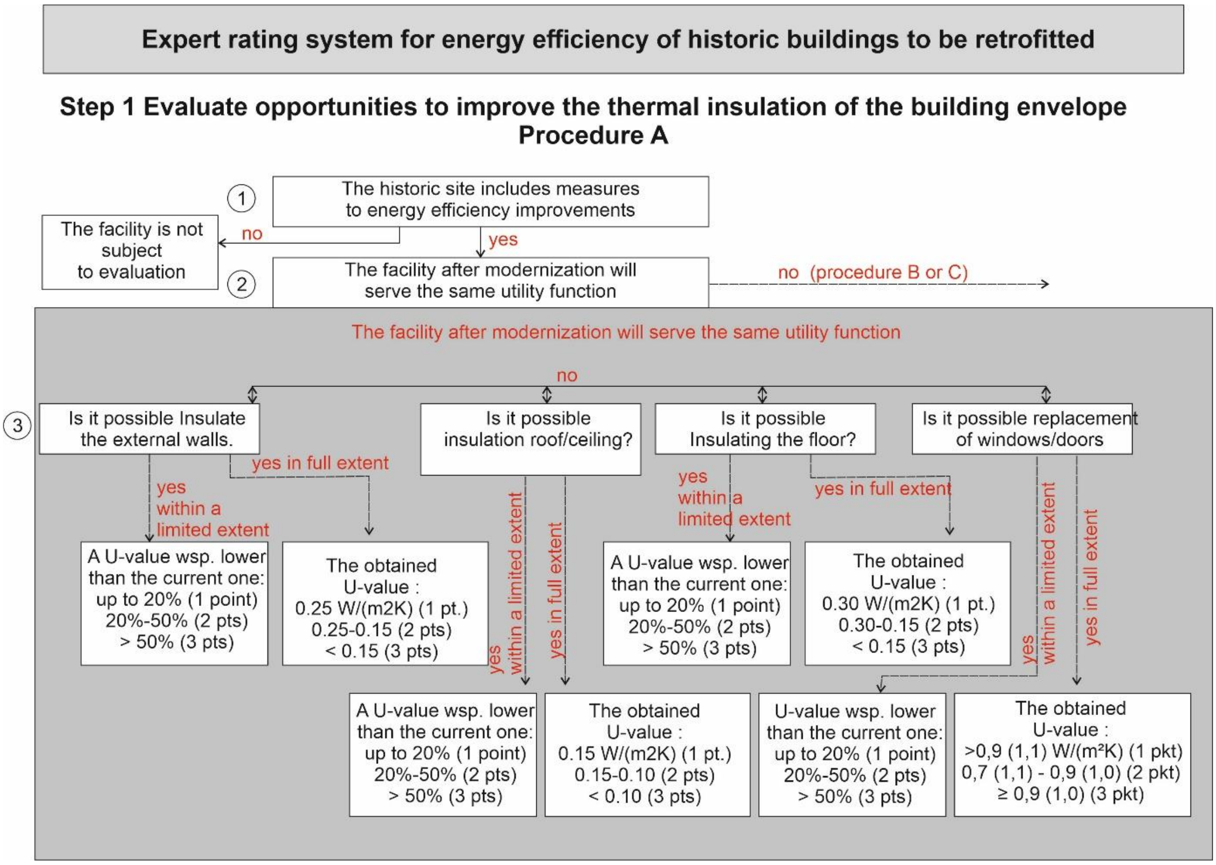

Figure 6. *Procedure A for step : "assessment of the possibility of improving the thermal insulation of the building envelope"*

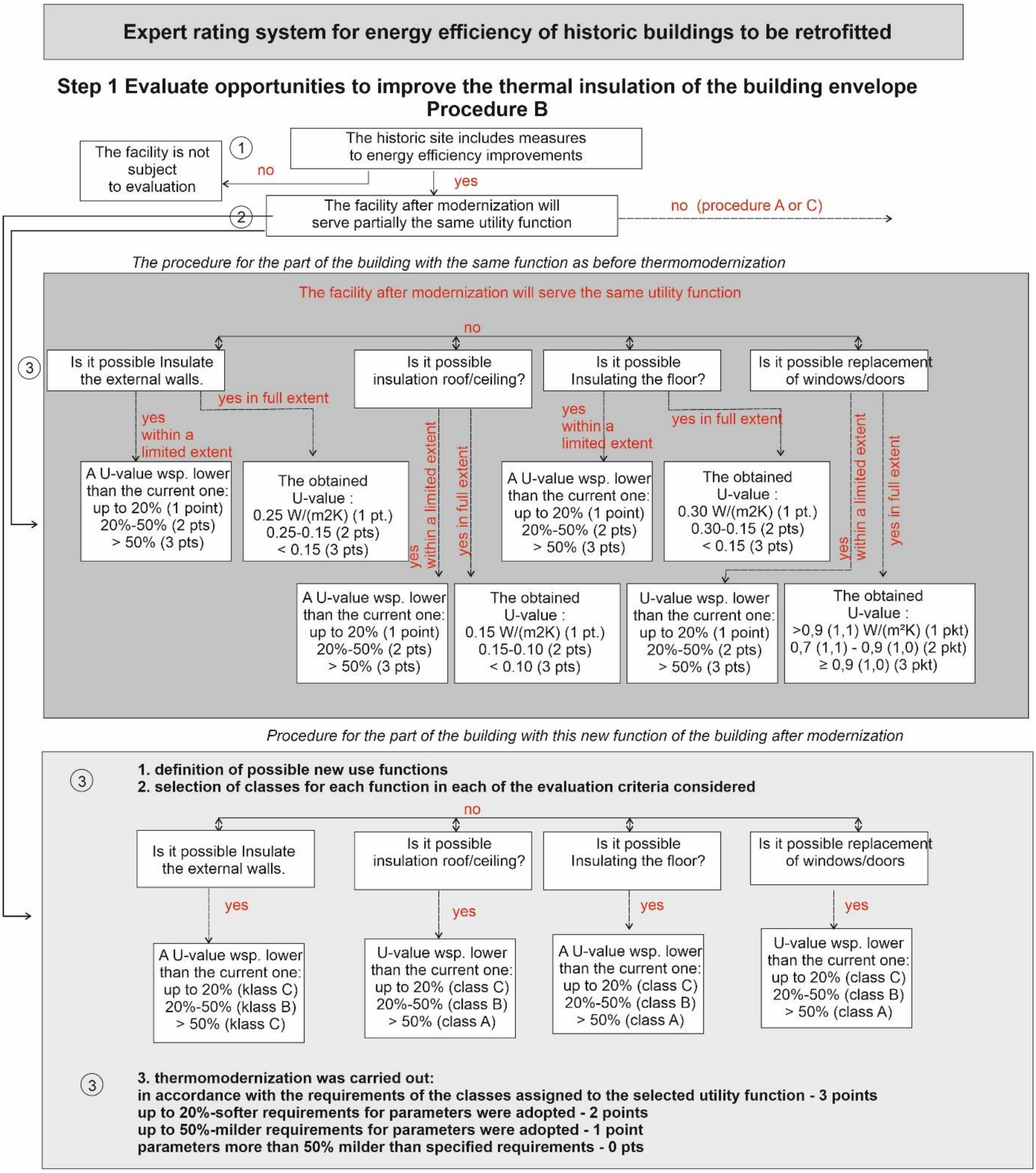

Figure 7. *Procedure B for step : "assessment of the possibility of improving the thermal insulation of the building envelope"*

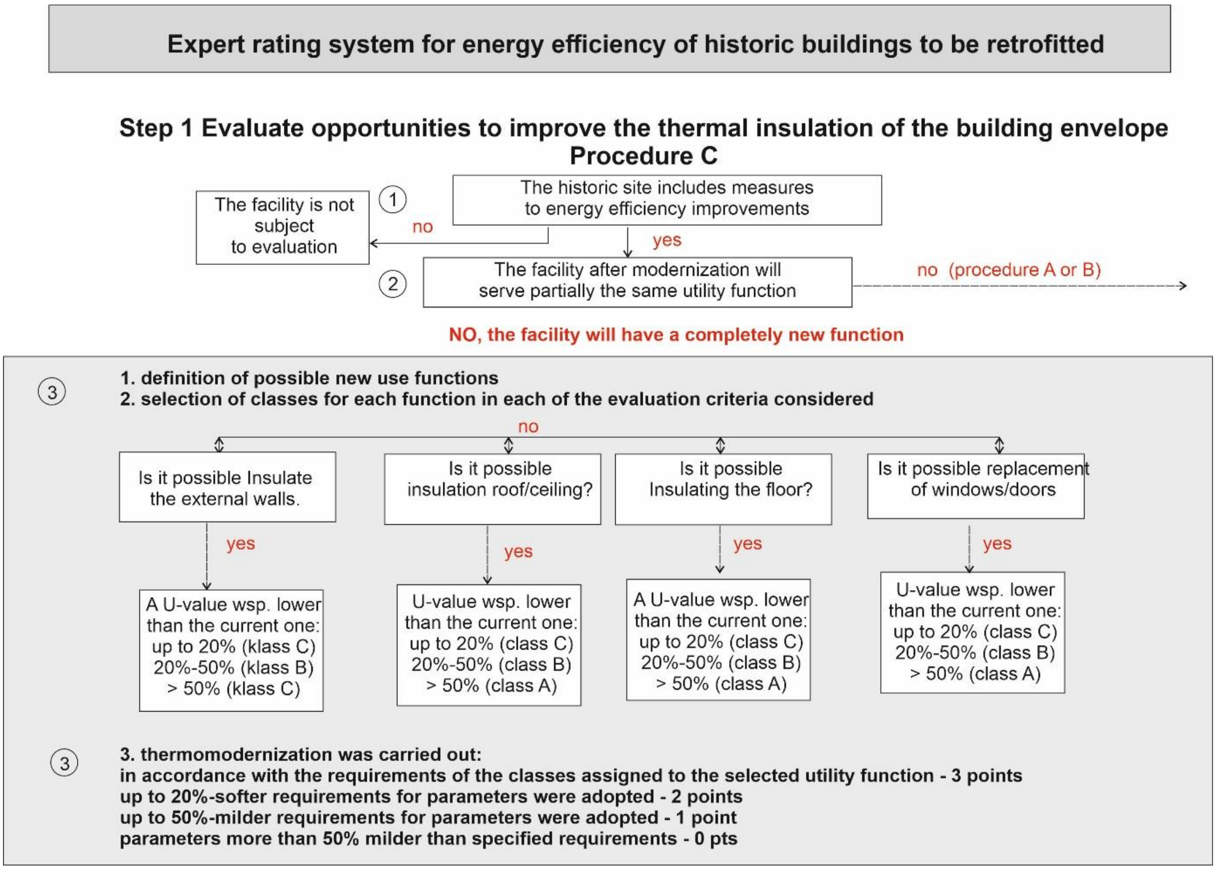

Figure 8. *Procedure C for step : "assessment of the possibility of improving the thermal insulation of the building envelope"*

Similarly, procedures related to the evaluation for reducing the Final Energy Index, Primary Energy, carbon footprint level and achieving occupancy comfort have been proposed. The following classes, defined by EK, EP, CF and thermal comfort parameters, have been adopted for historic buildings for which a change of use function is being considered. Other classes of parameters are described in the articles [16,21–23]

Parameter	Class A	Class B	Class C
	Reduction from the original version		
EK [kWh/(m^{2}rok)]	> 40%	20% ÷ 40%	< 20%
EP [kWh/(m^{2}rok)]	> 60%	20% ÷ 60%	< 20%
Carbon Footprint [kgCO_2e/m^2]	> 60%	20% ÷ 60%	< 20%
Thermal comfort PMV [-]	-0,2 ≤PMV≤ +0,2	-0,5 ≤PMV≤ +0,5	-0,7 ≤PMV≤ +0,7
Leakage test n_{50} [1/h]	≤ 1,5	1,5 < n_{50} < 3,0	≥ 3,0

"In situ" studies are a very important part of the methodology presented. They should be carried out in 2 stages. Stage 1 before modernization measures, conducted to diagnose the historic building, locate "weak points", determine the scope of thermal modernization measures. At this stage, it is possible to diagnose "hidden" defects in the building, such as energy carrier ducts, moisture in the walls, etc. One of the proposed tests is the study of wall moisture. In historic buildings where the walls are prone to dampness before thermal upgrading and determining their thermal quality, it is worth determining the effect of wall dampness on the thermal diffusivity coefficient. This is an extremely important parameter affecting the subsequent thermal comfort of building users [24].

This stage of "in situ" research should delineate possible measures to improve energy efficiency and comfort, even before thermal upgrading measures are taken. A sample set of surveys, selected individually for each historic building, is shown in Figure 11.

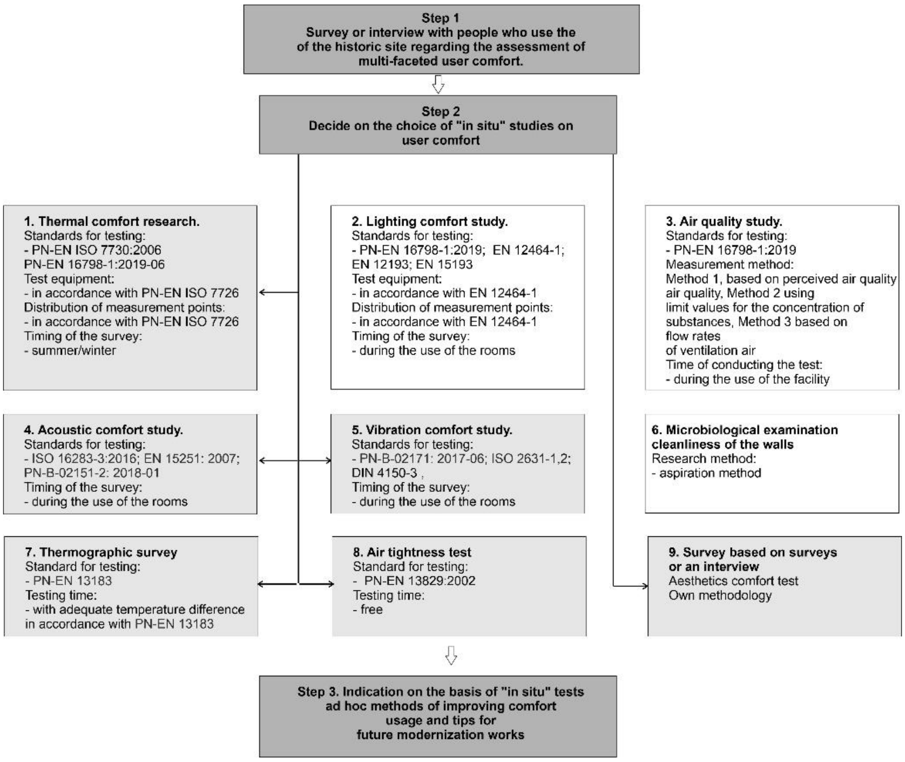

Figure 11. *Examples of "in situ" tests proposed for the diagnosis of the building, before the start of thermal upgrading work.*

Supporting activities are additional activities that have an impact on improving the energy efficiency of the historic site and the possibility of achieving climate neutrality. These are activities in the field of blue-green architecture, such as shaping greenery around the facility and managing rainwater, gray water through retention measures, among others.

The expert system developed allows for the scoring of activities at the historic site. The scoring takes into account the overriding decisions of the monument conservator.

The expert system is linked to the procedures described in the articles [22,25,26] regarding the assignment of different levels of requirements depending on the intended use of the building's future function. The same requirements should not always be defined for the different functions of a historic building-for example, a high-end hotel should meet different requirements than a gallery or conference rooms. Both procedures, the one presented in the article and the procedures described in the articles [22,25,26] are an innovative tool for making decisions related to improving the energy efficiency of historic buildings taking into account the protection of historical heritage.

4 Conclusions

Changing the use of a historic building by adapting it to new functions is an effective way to extend its life cycle. This multi-faceted process forces the decision-maker to use a multi-criteria approach in deciding on a new use function for a historic building. A good concept in this type of decision-making process is to try to synthesize the problem in the form of a decision-making model, the analysis of which will allow the decision-maker to make the best choice in relation to the adopted criteria. The article proposes a new innovative way of approaching the issues of improving energy efficiency, climate neutrality and comfort of historic buildings. In addition, the aspect of changing the utility function of part or all of the building is included in the method. The developed method will allow optimal decision-making in the process of thermal modernization of historic buildings.

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