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Existing tools enabling the implementation of EN 16883:2017 Standard to integrate conservation-compatible retrofit solutions in historic buildings

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Abstract: The heterogeneity of historic buildings and environmental conditions, as well as the variety of possible technical solutions, introduce great challenges to the decision-making process for the definition and implementation of energy retrofit projects. The variety of stakeholders involved in the process, each bringing specific skills and goals, further add to this complexity. How can the decision be finalised when multiple and often conflicting objectives and different stakeholders are involved?

In this context, the European Standard EN 16883:2017 provides guidelines to improve the energy performance of historic buildings while respecting their heritage significance. It presents a normative working procedure to select conservation-compatible retrofit solutions, which is based on a step-by-step investigation, analysis and documentation of the building. However, the recommendations provided in the Standard remain at a general level and it is the task for the stakeholders to tailor the intervention to the specific case.

This paper investigates how the implementation of the EN 16883:2017 can be enabled by adopting a selection of existing computer-based tools to support the identification, assessment, and selection of retrofit solutions in historic buildings. To this end, a number of tools were analysed, highlighting their advantages, input data, outcomes and main limitations, in relation to their possible use in support of the implementation of the Standard procedure (or steps of it).

Keywords: historic building, built heritage conservation, heritage retrofitting, energy efficiency, EN 16883:2017, tool

1. Introduction

According to the “EU 2030 Climate Plan” [1], although impressive progress has been achieved in the EU to meet sustainability targets, more effort will be needed to double the energy retrofit of the existing building stock in the next ten years [2-5]. In this context, an important role is played by historic buildings [6], which are defined as architecturally and culturally valuable constructions not directly listed, representing up to 40% of the EU building stock [7].

The main challenge in retrofitting an historic building lies in reconciling conservation needs and indoor comfort, with the necessary energy saving retrofit solutions [8, 9]. Usually, retrofit solutions include the improvement of the building fabric [10] (e.g., addition of thermal insulation and/or exploitation of the thermal mass, improvement of air tightness of windows), the optimization of building systems (e.g., heat generation, addition and/or exploitation of ventilation systems, use of energy-efficient artificial lighting) [11], and the integration of renewable energy sources - if feasible [12]. However, the complexity of historic buildings poses a challenge to the choice of appropriate conservation-compatible retrofit solutions [8, 9, 13], which must encompass a holistic whole-building approach. Indeed, the selection of retrofit solutions will differ on the building characteristics, the scope of the retrofit and the criteria defined by the stakeholders [14-16]. Furthermore, other factors, such as building restrictions, use of the building, user behaviour, and financial resources, may influence the choice of the most appropriate combination of solutions [8, 9].

The need for a more structured decision-making process for the retrofit of historic buildings [17] has been regulated for the first time by the European Standard EN 16883:2017 "Conservation of cultural heritage. Guidelines for improving the energy performance of historic buildings" [18]. The scope of this Standard is to facilitate an iterative and interdisciplinary planning process, adaptable to different contexts, through a step-by-step planning procedure. However, as underlined in recent research literature [19-21], the application of this Standard might place higher demands on the end user in terms of resources and competences [20, 21]. Indeed, the Standard does not provide a prescriptive procedure but rather suggests informative elements to be tailored to the individual case study. Moreover, the proposed full iterative planning process cannot be easily applied even for small projects [21].

1.1. The EN 16883:2017 decision-making process in historic buildings towards the definition of conservation-compatible retrofit solutions

The EN 16883 has been published in 2017 [18], offering a guideline for building owners, practitioners, and public sector to select appropriate retrofit solutions in the planning stage in historic buildings. This Standard is meant to be applied "to a wide range of buildings where special considerations are needed in order to find a sustainable balance between the use of the building, its energy performance and its conservation".

It presents a normative working procedure for selecting retrofit solutions to improve the energy performance of historic buildings, based on an investigation, analysis and documentation of the building including its heritage significance. The procedure includes an assessment of the impact of retrofit solutions from several points of view, including energy, technical compatibility, and conservation.

The planning procedure in the Standard recognises seven steps (numbered in parenthesis according to the number of the reference section in the document) in the overall decision-making process. More specifically, it can be synthetized as:

- **Initiating the planning process (6)**: before starting the retrofit planning, it is fundamental to identify the project team and define the scope of the project, considering the stakeholders' expectations.
- **Collection of relevant information (7)**: relevant and accurate information is needed for building characterisation and energy evaluation. The building survey shall describe: i) heritage significance and conservation opportunities and constraints; ii) past and present uses; iii) structural system; iv) energy performance assessment; and v) indoor environmental assessment.
- **Identification of objectives (8)**: to decide if a building retrofit is needed, it is important first to identify the problem to be solved or the question to be answered for the specific case study. The choice of objectives must be carried out in a multidisciplinary way, considering both qualitative and quantitative aspects raised by the project team. The areas where objectives should be specified, according to the *Baukultur concept* on sustainability [22, 23], are: *Culture* – i) technical compatibility with the existing structural, constructional and technical systems (i.e. damage risks and reversibility); ii) heritage significance (i.e. physical, spatial and visual integrity); *Economy* - iii) economic viability; *Environment* - iv) energy (i.e. operational energy demand and embodied energy), v) indoor environmental quality; vi) impact on the outdoor environment; and *Society* - vii) aspects of use.
- **Deciding if a building retrofit is needed (9)**: in this stage of the process, it can be decided if an energy performance improvement is needed or not. The need for an intervention shall be defined comparing the retrofit objectives and the building conditions. Indeed, the condition of both the building envelope and the technical building systems shall be assessed before considering improving energy performance, to avoid possible physical damage to the building because of the further interventions.
- **Identification of the retrofit solutions (10.3-10.4)**: possible solutions to the problem investigated have to be defined (concerning the building envelope, the technical systems and user behaviour). It starts by compiling a long list of solutions (10.3) to exclude those considered inappropriate for the case study (10.4).
- **Assessment and selection of solutions (10.5-10.7)**: once solutions are identified, it is necessary to weight the evidence for or against them through a risk-benefit analysis. The single solutions are considered

(10.5), as well as their combination in packages (10.6-10.7). The interdisciplinary project team will assess the packages of solutions (i.e. scenarios) in relation to the targets defined in Clause 8.

- **Implementation of solutions (11.2)**: this is the part of the decision-making process where the best scenario is chosen, and the most suitable retrofit solutions are implemented.
- **Post-occupancy evaluation (11.4)**: after a predetermined amount of time, it is necessary to reassess the decision made to ensure that the objectives have been met and the desired effects have been achieved.

A previous study collected practical experiences on the usability of the procedure in EN 16883:2017 [21] and reported a shared lack of understanding among the users on how the different steps were supposed to be carried out, due to their generic approach. Although the process is thought to be carried out by a multidisciplinary team, the appropriate balance of the team is not always verified. This leads to a series of difficulties in following in the planning process.

At the beginning of the planning process (6), it is not always easy to define goals shared by everyone and to have a clear project team: multiple actors with sometimes conflicting objectives have a role in the decision arena, such as public government representatives, architects, conservators, engineers, energy experts, architectural historians, developers, and owners. Afterwards, in step (7), the identification of retrofit solutions cannot be separated from the analysis of the building and its users' needs. Special attention has to be paid in analysing peculiar features of the historic environment, understanding the changes of its use, of its constructive characteristics and its material restrictions. This step implies an adequate knowledge of historic buildings, building physics, restoration and therefore can be complex to carry out without any planning support from specialists. In step (8), the choice of objectives can be very complex because this requires knowledge of how to identify the priorities for planning an intervention. This step is often considered more difficult to do in the presence of multiple actors involved.

In step (10.3-10.4), there is usually more than one option to consider when trying to meet a goal. This balance requires a comprehensive understanding of historical architecture and technical know-how. Similarly, in step (10.5-10.7), the specific choices made among the available retrofit solutions depend on the initial goal setting: in addition to the capacity of 'reading' the building, the different possible solutions must be carefully weighted in a multidisciplinary and integrated way, with the support of evaluation tools, energy simulation, financial assessment, risk assessment, etc. The multicriteria approach required by the Standard makes it possible to balance qualitative and quantitative aspects, so that the importance of preserving the values underlying the historical construction is not overlooked. In this sense, the general intention is to achieve the best possible energy performance while retaining the heritage significance of the building. However, this operation is for expert users to perform. Finally, steps (11.2) and (11.4) imply verifying if all objectives are met and the problems solved, by means of post-intervention monitoring, an assessment of end-user satisfaction, a cost-benefit assessment, etc.

Practitioners found the identification and assessment of retrofit solutions particularly challenging due to the lack of practical support in the whole procedure [21].

2. Research aim

The aim of this paper is to examine how to support and accompany the application of the EN 16883:2017 and the decision-making process towards the implementation of conservation-compatible retrofit solutions. The paper investigates the possibility of combining the Standard with the use of computer-based tools developed in recent years to support designers in choosing retrofit solutions for historic buildings. While a one-for-all tool capable of supporting the whole implementation of the Standard would be desirable, no such tool is currently available. However, there are several tools that can be used (either directly or after informed adaptation) in support of the decision-making process required to implement some of the seven steps listed in the Standard.

The paper is the result of a multidisciplinary research carried out by an international network of experts in the fields of sustainability and heritage within the IEA-SHC Task 59/ECB Annex 76 project on "Deep renovation of historic buildings towards lowest possible energy demand and CO_2 emission (nearly Zero Energy Buildings—nZEB)" [24]. In particular, the objective of the working group was to assess a selection of tools, considering which step in the decision-making procedure of the EN 16883:2017 each tool supported, which data is required, how the corresponding data sets are processed, and which results are delivered by the respective tool. The task was to compare the tools, and to clarify where there is a need for action for further development.

According to the research aim, the following part of this document introduces the methodology for the selection of the analysed tools (section 3), followed by an overview of their possible use in support of the implementation of the Standard procedure, with a brief description of their contents and structure (section 4). Lastly, inputs, outputs and main limitations of the tools are compared, offering to practitioners an overview on the topic (section 5).

3. Material and methods

3.1. Decision-making process: computer-based tools to support the identification, assessment and choice of solutions

The heterogeneity of historic buildings, the large variety of technical solutions and the complex interconnections between technical, conservation, economic and legislative factors represent a great challenge implementing energy retrofit projects [8, 9, 25]. To manage the complexity of taking a decision in this context, several computer-based tools allowing quick comparisons of multiple alternatives have been developed to support the stakeholders [26-28]; the scope of computer-based tools is to facilitate a transparent discussion and a better understanding of different valuing processes, providing a framework that unifies different stakeholders' perspectives in strategic decision-making [29]. The literature review on computer-based decision-making tools for sustainable retrofit by [30] categorised tools for energy retrofit as based on energy consumption and CO_2 reduction methods, and on purely economic analysis. The authors of [28] proposed three additional categories for historic buildings: energy and heritage value appraisal methods; hygrothermal assessment approaches; and holistic methods. Tools developed adopting a holistic approach are more targeted for a wider perspective on the retrofit of historic buildings, where multiple factors are used as decision-making criteria [31].

In [32] the authors reviewed several existing decision-making tools developed for improving historic buildings with a holistic approach. Some tools are structured as real information repositories (here defined as "Repository Web Tools"): they contain a set of retrofit solutions where pros and cons, references, useful links are explained. In some of them it is sometimes even possible to download technical sheets with examples of the use of certain technical solutions. These tools are mainly dedicated to the investigation of possible retrofit solutions, according to predefined initial criteria. They are not necessarily directed to experts in retrofit planning and contribute to highlight possible interferences among different solutions in combination.

The other main category of tools for supporting the planning of improvements in historic buildings in [32] was the Decision Support System (DSS). A DSS is described as "a system under the control of one or more decision makers that assists in the activity of decision making by providing an organized set of tools intended to impose a structure on portions of the decision-making situation and improve the ultimate effectiveness of the decision outcome" [33]. This type of tools has the advantage of supporting people in making more deliberate, thoughtful decisions by organising relevant information and defining alternatives, reducing the working and decisional process time [34]. The use of DSSs is quite varied within the context of cultural heritage [32, 35]. The majority of DSSs on historic buildings have been used for identifying restoration priorities and selecting the best reuse strategy [36, 37]. In the set of existing DSSs there is also a certain number of tools dedicated to support the retrofit of historic buildings [28, 32].

3.2. Methodology for collecting decision-making tools

As a collaborative research project, the IEA-SHC Task 59 relied heavily on knowledge exchange and task sharing, thanks to the large international group of multidisciplinary experts involved [9]. Collaboration between scientists facilitates "knowledge co-creation" [38] and enables to obtain more effective research results in solving complex tasks [39].

Thus, the identification of decision-making tools to support the implementation of EN 16883:2017 was carried out following a collaborative information search methodology [40]. Project members worked in collaboration on the shared task of collecting and assessing tools that aim to select and evaluate retrofit solutions in historical contexts [9]. They were asked to investigate how existing decision-making tools can support the user in implementing the EN 16883:2017 procedure to select solutions that balance out building restrictions, environmental conditions, context, and conservation goals.

Criteria for the selection of tools were:

- Tools which support the implementation of one or more steps defined in EN 16883:2017;
- Tools targeted for the planning of energy efficiency retrofit of historic buildings and/or districts.

The IEA-SHC Task 59 partners focused on tools that were developed in research projects, where sufficient information is documented, and which were developed and/or used by them. For each tool identified, the following characteristics were analysed: i) the level of action (i.e. single building component, entire building, district level, mix); ii) the structure and the single steps that constitute decisional procedure of the tool; iii) the data needed to run the tool; iv) how the selection of solutions was connected with the context and the building knowledge; v) the existence and organisation of a repository of solutions (if a repository was present, additional information was collected, like how many solutions are included; if there is a mechanism in the tool to support the creation of retrofit solutions scenarios; etc.); vi) the existence of a weighting system for assessing the solution/ criteria adopted; vii) if the tool includes extra information on how to select solutions (e.g., a database with best practices/documents/examples/links/others?). In the following the collected tools are presented in detail.

4. Results

4.1. Identified tools

In a first phase of the research, 18 tools were collected and reviewed; but only 8 reflected all the selection criteria listed in section 3.2 (Table 1). Among the many types of existing tools [32], those collected belong to the Repository Web tool and Decision Support System (DSS) categories, mentioned previously.

Table 1 - *Overview of the identified tools*

Acronym / Name	**Context**	**Language**	**Authors**	**Date of publication** (update)	**Connection to the EN 16883:2017** (limited support)	**Scale of the retrofit planning**	**Link[1]**
Repository Web Tools							
Responsible retrofit guidance wheel	UK	English	Sustainable Traditional Buildings Alliance (STBA)	2013 (2020)	Identification of the retrofit solutions (10.3-10.4); Selection and assessment of packages in relation to targets (10.6-10.7)	Building	http://responsible-retrofit.org/greenwheel/ [41]
French version of the responsible retrofit guidance wheel	France	French	STBA; Centre Rehabilitation du Bâti Ancien (CREBA)	2018	Identification of the retrofit solutions (10.3-10.4); Selection and assessment of packages in relation to targets (10.6-10.7)	Building	http://www.rehabilitation-bati-ancien.fr/fr/outils/guidance-wheel [42]
HiBERTool – Historic Building Energy Retrofit Tool (Atlas)	Alpine space	English	Interreg AS ATLAS / IEA-SHC TASK 59	2021	Identification of the retrofit solutions (10.3-10.4); Assessment of remaining solutions (10.5)	Building component	https://www.tool.hiberatlas.com [43]
Decision Support Systems (DSSs)							
exDSS – Climate for Culture	Europe	English	Climate for Culture project	2014	From Collect on relevant information (7) to Identification of the retrofit solutions (10.3-10.4)	Building	http://cfc.exdss.org/dss/riskcon [44]
Effesus DSS/RE2H	Europe	English, Spanish, Basque	TECNALIA	2015 (2020)	From Initiating the planning process (6) to	Urban district level	http://proyectos.hei-

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[1] Accessed on the 12th February 2022.

					Identification of the retrofit solutions (10.3-10.4)		tecnalia.com/RE2H/ [45]
PETRA – Platform for Energetic and Technical Retrofit in Architecture	Switzerland	English, German, French, Italian	Scuola Universitaria Professionale della Svizzera Italiana (SUPSI)	2013	From Initiating the planning process (6) to Assessment and selection of solutions (10.5-10.7); Implementation of solution (11.2)	Building	http://www.petraweb.ch/ [46]
DEMI MORE – Demi More Integrated Description of the Conservation Process Visual Decision Tool	Central Europe	French, Dutch	Interreg V-N DEMI MORE	2019	From Initiating the planning process (6) to Check of the decision (11.4)	Building	https://maakmonumentenduurzaam.eu/wp-content/uploads/2019/12/DEMI-MORE.BWF_.41.outil-visuel.pdf [47]
RIBuild tool – Robust Internal Thermal Insulation of Historic Buildings	Europe (esp. Belgium, Denmark, Germany, Italy, Latvia, Sweden, Switzerland)	English (videos referring to guidelines are in more languages)	Aalborg University (AAU); Technical University of Denmark (DTU)	2020	Collection of relevant information (7); Identification of objectives (8); Identification of the retrofit solutions (10.3-10.4); Assessment of remaining solutions (10.5)	Building component	https://www.ribuild.eu [48]

Differences can be seen in the tools characteristics as well as the possible connection with the planning procedure of the Standard (Figure 1). Both the selected Repository Web Tools (the Guidance Wheel – UK and French versions – and the HiBERtool) provide information on the risks associated with a retrofit solution. These tools are mainly linked to the steps (10.3-10.4) and (10.5-10.7) of the Standard and aim at suggesting alternative retrofit solutions in case of generic data. However, they present differences in their structure, in the categories of solutions included in their repositories and in the context of reference. The Guidance Wheel [41, 42] provides a systemic approach to consider interactions and interdependencies present among interventions to fabric, building services, and behaviour change, and it was developed specifically to fit the historic building stock and its context in the UK and France. Conversely, the HiBERtool [43] supports the decision on building component solutions by means of fuzzy decision-trees [49] on the topics of walls, windows, solar and HVAC.

DSS tools are mainly structured as complex computerized decisional processes, where a sequence of questions is asked, and context parameters are defined, before assessing the selected solutions through mathematical calculations/simulations. As indicated in (Figure 1), only the DEMI MORE tool [47] provides an offline step-by-step methodology to guide the user towards the selection of solutions that are appropriate for the entire building.

Most of the DSSs refer to the entire retrofit process suggested by the Standard, but the tools differ in their methodologies. In Effesus DSS/RE2H [45], the implementation of a retrofit strategy is facilitated by a categorisation tool linked to GIS-3D technologies, created to support the identification of the energy potential of urban historic districts. The PETRA tool [46] is structured in a step-by-step process gathering relevant information on the building, with the aim of evaluating the necessity of a retrofit intervention (from both an energy, heritage and economic perspective).

Two of the DSS tools (i.e. the exDSS and the RIBuild tool) are directed to support the identification of solutions (10.3-10.4), considering more specifically the hygrothermal risk of implementing retrofit solutions in a historic building. However, their scope differs: in the exDSS [44] the automated system receives inputs on the type of building, building function, collections housed in the building, indoor climate, and it gives suggestions on good practices and possible solutions to minimise hygrothermal risks. The RIBuild tool [48] was developed to explore if the external walls of a building are suitable for internal insulation and, based on the information provided on the walls and on the selected retrofit planning priorities (e.g. lowering the wall U-value, reducing the risk of mould growth, etc.), what kind of insulation system should be considered and what remedial solutions are needed.

More detail on each mentioned tool is given in the following section.

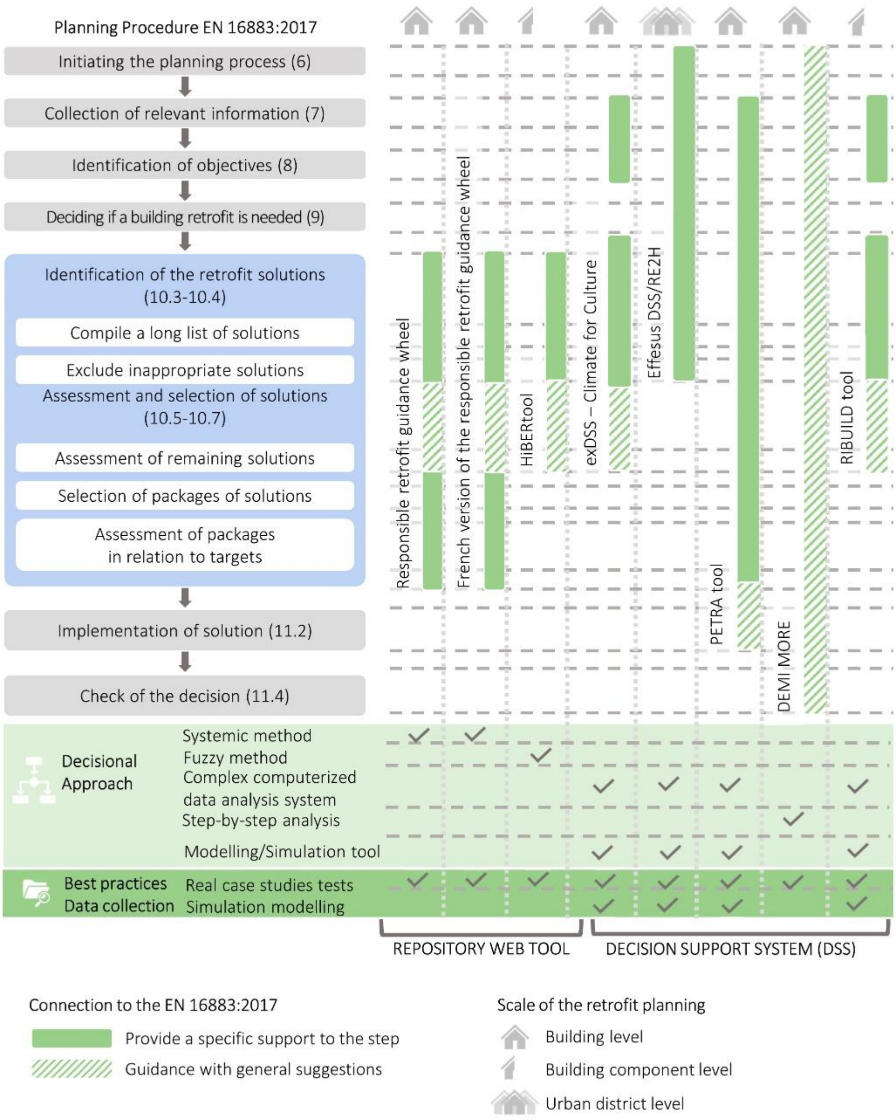


Figure 1 – *Synthetic representation of the possible connection between the EN 16883:2017 and the analysed tools. A green solid pattern indicates if a tool provides a specific support for getting through a step; a striped pattern indicates instead if a tool provides general guidance on the process by suggesting references or illustrative material. For each tool the method underlying the decision-making system is indicated; it is also specified whether the retrofit solutions derive from real examples or from simulation modelling. The retrofit scale supported by the tool (building, building component, urban district) is also indicated. (Source: Authors' elaboration based on [18]).*

4.2. *Repository Web Tool*

- **Responsible retrofit guidance wheel** (both UK and French version)

The Responsible Retrofit Guidance Wheel is a repository web decision-making tool for retrofitting traditional buildings. It was developed by the Sustainable Traditional Buildings Alliance (STBA) in the United Kingdom in 2013 [50] and by CREBA in a French version in 2018 [51].

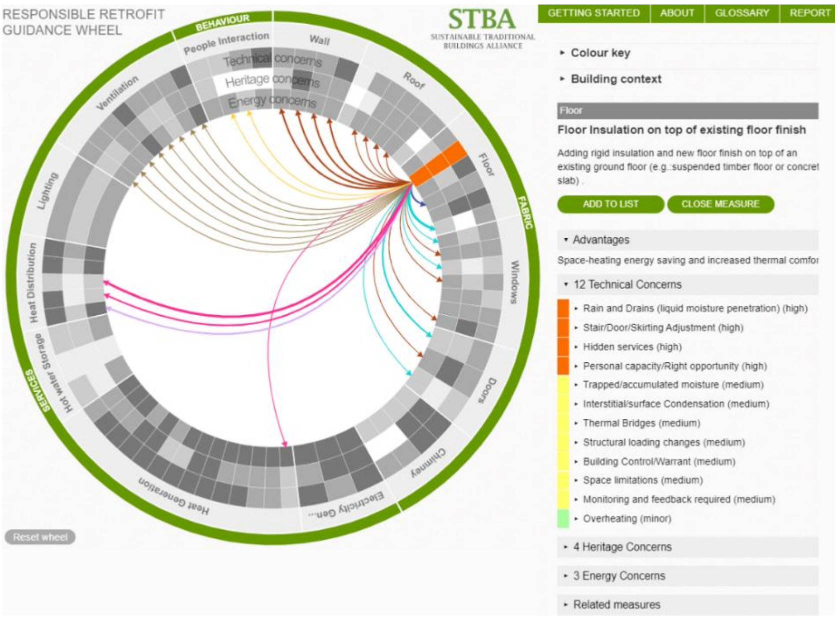
The Guidance Wheel aims to identify the advantages of retrofit solutions, providing the risks associated and the level and type of technical, heritage and energy concerns, while considering the interconnections in a package of different solutions. It can be used to inform the development of a retrofit plan, which may consider a step-by-step refurbishment or a deep renovation.

The structure of the tool is that of a wheel (which justifies its name), where each segment corresponds to a specific retrofit solution that the user can explore. In particular, the tool considers interventions to fabric and services and behaviour change (Figure 2). As input data, the Guidance Wheel requires information on the context of the building, namely the heritage value of the building, its condition, the level of exposure to wind-driven rain, the number of exposed sides (for ventilation), the occupant's energy use and interest in the building. After entering these data, it is possible to explore technical benefits and consequences for each potential retrofit solution, as well as its energy saving and heritage issues, with the related risk level (i.e. minor, medium, high, or major). This information can be used for comparing different possible solutions, singularly or as a package.

At the end of this exploration, it is possible to download a report which presents the list of selected solutions with the associated level and type of concerns, as well as a list of suggested actions to minimise and mitigate the risks – associated with the identified concerns – before, during and after installation. All the information provided by the tool on retrofit solutions derives from real cases and laboratory tests developed in the local context (UK and France) [41, 42].

Considering the procedure of the EN 16883:2017, the Guidance Wheel can be useful to address the steps referred to identify solutions (10.3-10.4) and to assess the selected package of solutions (10.7). Indeed, it offers information on the risks associated with a retrofit scenario, considering the individual solutions and their interaction with other current or planned solutions. It is not a prescriptive tool but gives the designer the relevant information for the development of a retrofit scenario within a wider risk-management process.

The main limitation is that this tool is tailored to the traditional historic building stock in the UK (UK version) and France (French version). Hence, it requires an informed adaptation to other contexts before being applied more widely. There are no dedicated publications on the use of this tool, except for some case studies reported on the UK website [52] and an in-depth analysis in [51] for the French version, where the tool was applied on 13 case studies.



- Colour key
- Building context

Floor

Floor Insulation on top of existing floor finish

Adding rigid insulation and new floor finish on top of an existing ground floor (e.g.:suspended timber floor or concret slab) .

- Advantages

Space-heating energy saving and increased thermal comfor

- 12 Technical Concerns
  - 🟧 Rain and Drains (liquid moisture penetration) (high)
  - 🟧 Stair/Door/Skirting Adjustment (high)
  - 🟧 Hidden services (high)
  - 🟧 Personal capacity/Right opportunity (high)
  - 🟨 Trapped/accumulated moisture (medium)
  - 🟨 Interstitial/surface Condensation (medium)
  - 🟨 Thermal Bridges (medium)
  - 🟨 Structural loading changes (medium)
  - 🟨 Building Control/Warrant (medium)
  - 🟨 Space limitations (medium)
  - 🟨 Monitoring and feedback required (medium)
  - 🟩 Overheating (minor)
- 4 Heritage Concerns
- 3 Energy Concerns
- Related measures

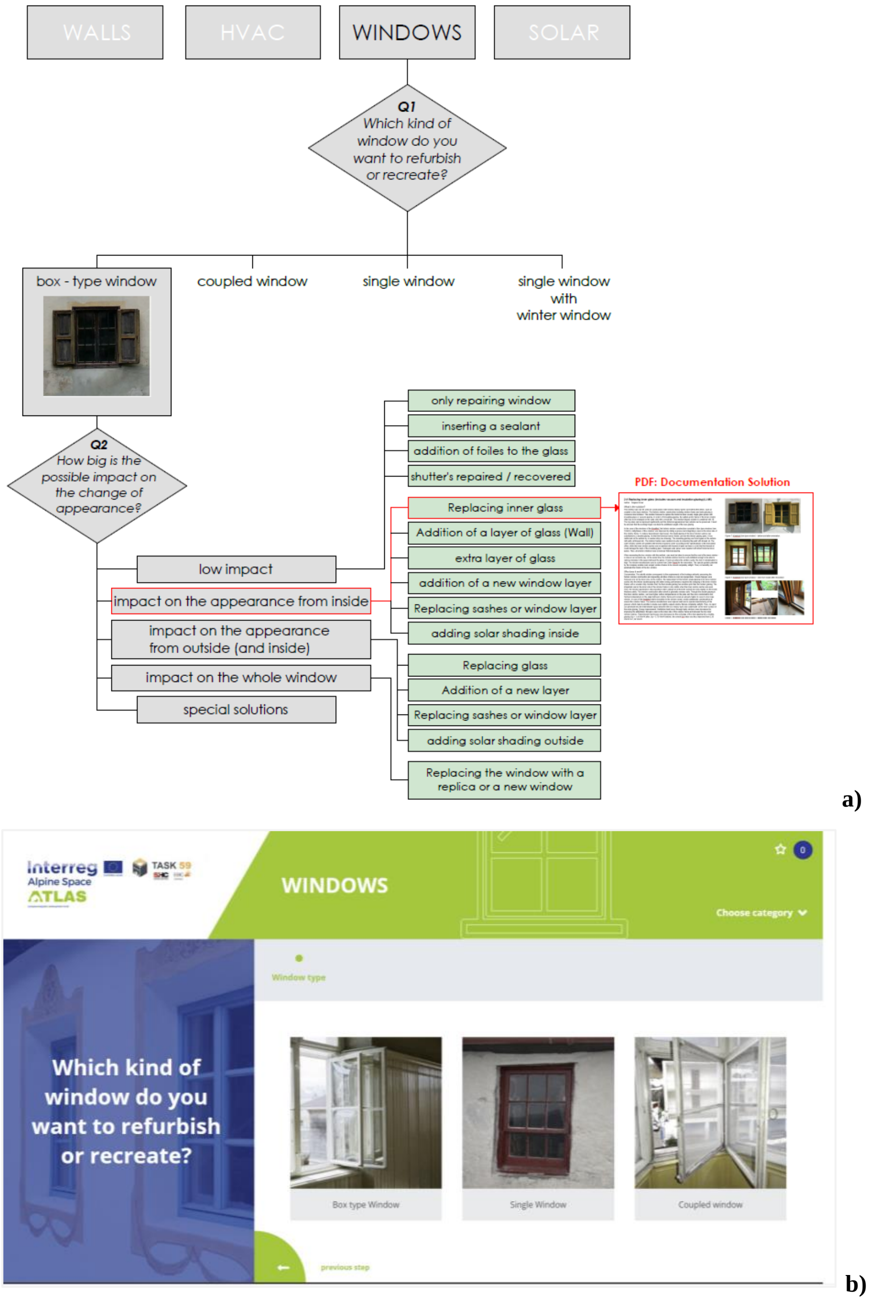
Figure 2 – *Guidance Wheel [41, 42]. Typical user interface: it is possible to select intervention solutions and check for possible concerns in the Technical, Heritage and Energy fields.*

- **HiBERtool** – Historic Building Energy Retrofit Tool (Atlas)

The HiBERtool is a database for energy retrofit of historic buildings that has been developed within the framework of the ATLAS Interreg [49] and the IEA SHC Task 59 [24] projects. It intends to provide access to well-established but also innovative solutions that the experts involved in the aforementioned projects have compiled and evaluated. So far, the tool is based on a stock of 130 documented retrofit solutions for historic buildings. Solutions are partly derived from the knowledge exchange of the contributing partners, but to a large extent based on best practice examples of the HiBERatlas, a database for historic building energy retrofit develop within the ATLAS Interreg project [53].

The set of solutions is structured in four groups: wall insulation, window solutions, solar systems, and HVAC. For each category, the user is guided through a query with easy-to-answer questions on the technical and heritage conservation framework conditions that ultimately leads to a selection of sample solutions (Figure 3a). A typical view of the HiBERtool user interface is shown in Figure 3b. The query is different for each solution category; for example, while in the windows category it is asked about the type of the existing windows and the parts that should be preserved, in the walls category the rainwater protection level is of interest among others. In order to support the user at best in answering the questions, infographics are included. A selection of the solutions in the HiBERtool is therefore not realised by an automated data processing but by using the query process to narrow down a long list of possible solutions, according to fuzzy decision-trees [49]. From the displayed list of possible solutions, the relevant ones can be selected. At the end, the documentation is available as a PDF data sheet, describing the selected technical solution (including the risks that can occur with the implementation), with technical specifications and links to case studies where these solutions are installed.

The HiBERtool can be mainly used to address steps (10.3) and (10.4) of the EN 16883:2017, respectively for the identification of a long list of possible retrofit solutions and for the assessment of the listed solutions. With the detailed assessment of each single solution in the data sheets, the HiBERtool also paves the way towards step (10.5) for the selection of a short list of solutions. All participants in the process can get comprehensive information of the long list of solutions in a very short time and be therefore prepared for the evaluation towards the short list. The main limitation is that the tool is very much dependent on the restricted number of the documented solutions. It will therefore improve as more solutions will be added over time. Furthermore, although the tool is in English and offers solution from all over Europe, there are several references to traditional regional alpine architecture. To date, the tool has been used only in practical case studies within the Interreg IT-AU Project Shelter [54], the results of which will be published this autumn.



Which kind of window do you want to refurbish or recreate?

Figure 3 – *HiBERtool [43].* **a)** *Exemplar underlying decision-tree for a window retrofit to select a solution from a collection of examples from real case studies; b) Typical user interface.*

4.3. Decision Support Systems (DSSs)

- **exDSS** – Climate for Culture

The exDSS tool is part of the Climate for Culture project (2009-2014) outputs, and it aims at assessing the hygrothermal risk of retrofit solutions in historic buildings [44]. The tool is developed as an open-source software [55], and it is divided in three parts: Future Outlook, Risk Assessment, and Indoor climate control methods (Figure 4a). The automated system requires input information on the type of building (size, use, location, etc.), artwork collection, historic indoor climate pre-retrofit. This system provides the end user with valuable advice on hygrothermal risks, using standard or fuzzy logic based on the answers provided. An extensive analysis of indoor climate control methods was performed in the Climate for Culture project, by using modelling tools and the data collected in 74 case studies [56]. The information resulting from this analysis was used as basis for the tool development.
Input information is provided by means of a predefined questionnaire following the three parts of the tool. First, the "Future outlook" part indicates how the indoor climate and risks related to the indoor climate might change in

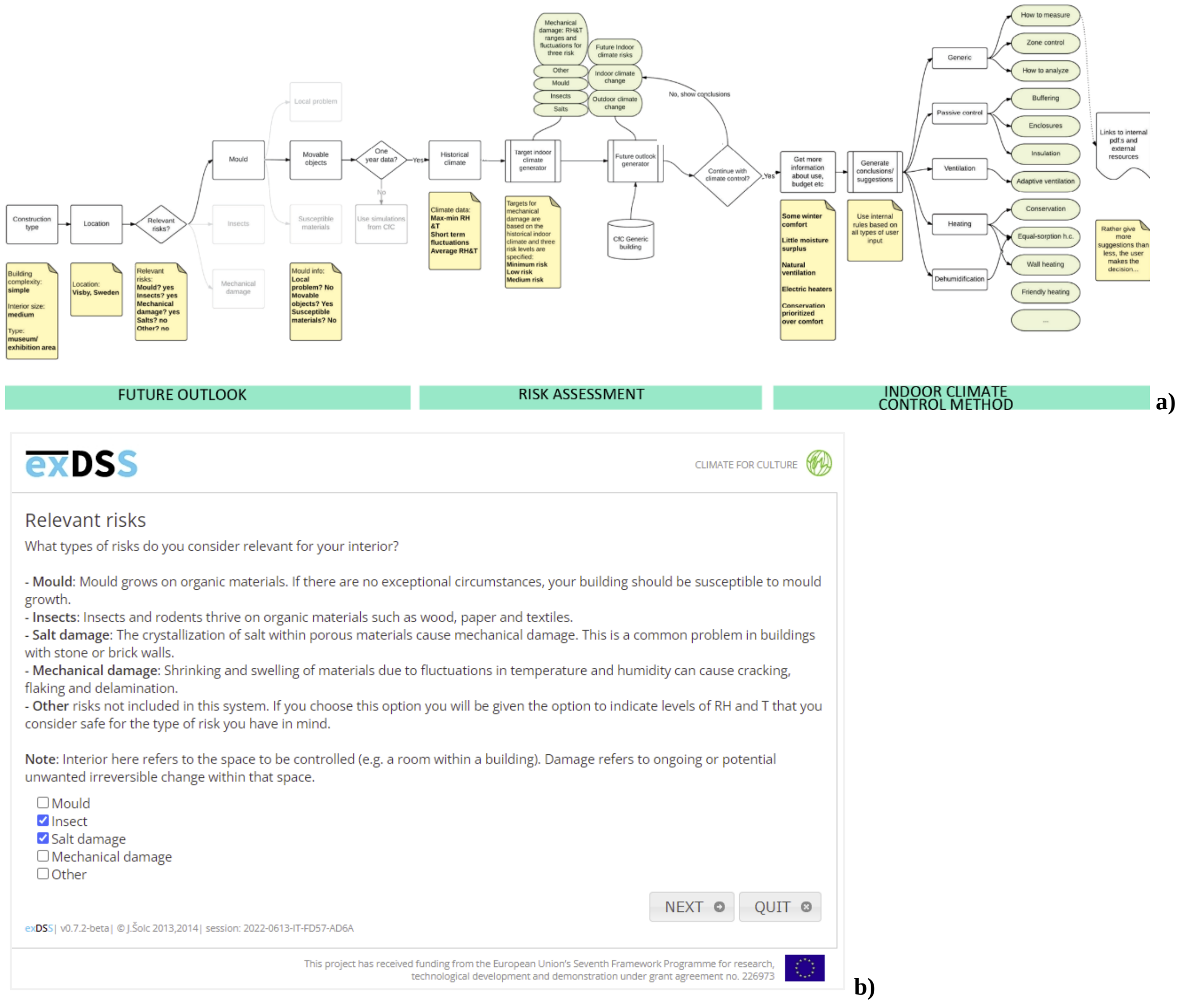
the near and far future for the assessed building, from the wide set of maps provided as one of the results of the Climate for Culture project [57].

The “Risk Assessment” part investigates which climate-induced risks are relevant to the building and the artefacts collected in it. It gives suggestions for target specifications for temperature and relative humidity (Figure 4b).

Lastly, the “Indoor climate control methods” part investigates which indoor climate control methods are suitable for the assessed building, based on the type of building, type of collection, historic indoor climate and more. As final outcome, an information document is provided to support the technical analysis of single retrofit solutions, according to heritage, economy, energy, maintenance and invasiveness priorities. The document includes references to the case studies assessed in the Climate for Culture project, where HAMBase and WUFI$^{®}$Plus software were used for hygrothermal building simulation considering the indoor climate change effects [57].

This tool is considered useful to follow and support the implementation of the EN 16883:2017 procedure from the Collection of relevant Information (7) to the identification of retrofit solutions (10.3-10.4), considering only the hygrothermal risk analysis included in the DSS. The main limitations of this tool are firstly the fact that it has not been updated since 2015 and, secondly, the limited number of solutions, references and best practices included.

The only publications dedicated to the use of the exDSS in case study applications are those reporting the results of the Climate for Culture project [58, 59].



Relevant risks

What types of risks do you consider relevant for your interior?

- **Mould**: Mould grows on organic materials. If there are no exceptional circumstances, your building should be susceptible to mould growth.
- **Insects**: Insects and rodents thrive on organic materials such as wood, paper and textiles.
- **Salt damage**: The crystallization of salt within porous materials cause mechanical damage. This is a common problem in buildings with stone or brick walls.
- **Mechanical damage**: Shrinking and swelling of materials due to fluctuations in temperature and humidity can cause cracking, flaking and delamination.
- **Other** risks not included in this system. If you choose this option you will be given the option to indicate levels of RH and T that you consider safe for the type of risk you have in mind.

Note: Interior here refers to the space to be controlled (e.g. a room within a building). Damage refers to ongoing or potential unwanted irreversible change within that space.

☐ Mould
☑ Insect
☑ Salt damage
☐ Mechanical damage
☐ Other

exDSS| v0.7.2-beta| © J.Šolc 2013,2014| session: 2022-0613-IT-FD57-AD6A

This project has received funding from the European Union's Seventh Framework Programme for research, technological development and demonstration under grant agreement no. 226973

Figure 4 – *Climate for Culture exDSS [44].* **a)** *Illustration of the underlying decision tree for indoor climate risk assessment implemented in the exDSS software;* **b)** *Typical user interface of the online tool.*

- **Effesus DSS/RE2H**

Effesus DSS/RE2H [45] is an ecosystem of tools and methodologies to support energy planning and renovation of historic buildings at urban scale. It was developed within the EFFESUS project [60] in 2015 by TECNALIA. It includes a 3D urban data model based in cityGML [61], a solutions repository and two DSS tools that support the different assessments required.

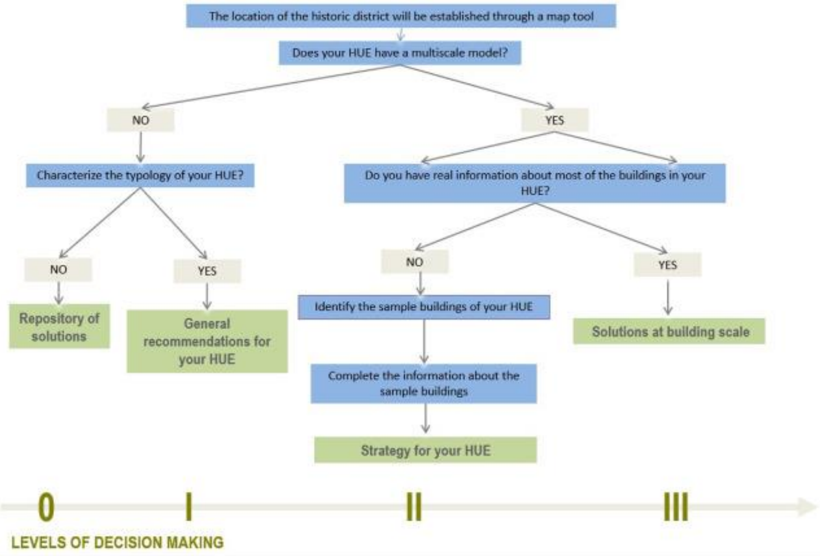
The first DSS tool is the "Categorisation tool" [62], a web application that categorizes the building stock for the identification of representative building typologies in a Historic Urban Environment (HUE) (some key parameters are materials, thermal characteristics, level of protection, etc.), using the information from the 3D urban data model. The second DSS tool is an "Expert system" that implements the decision-making process, guiding the decision-makers in the selection of the best retrofit solutions for the historic district.

The two DSS tools can be combined to address different levels of actions through an incremental decision-making approach where four different levels of decision making (LoDM) are proposed (Figure 5a). These LoDMs range from low levels (LoDM 0 and I), which require only general information regarding the city and provide generic strategies at urban scale, to medium-high levels (LoDM II and III), where a 3D urban data model is necessary to provide tailored retrofit solutions to the historic district at building scale.

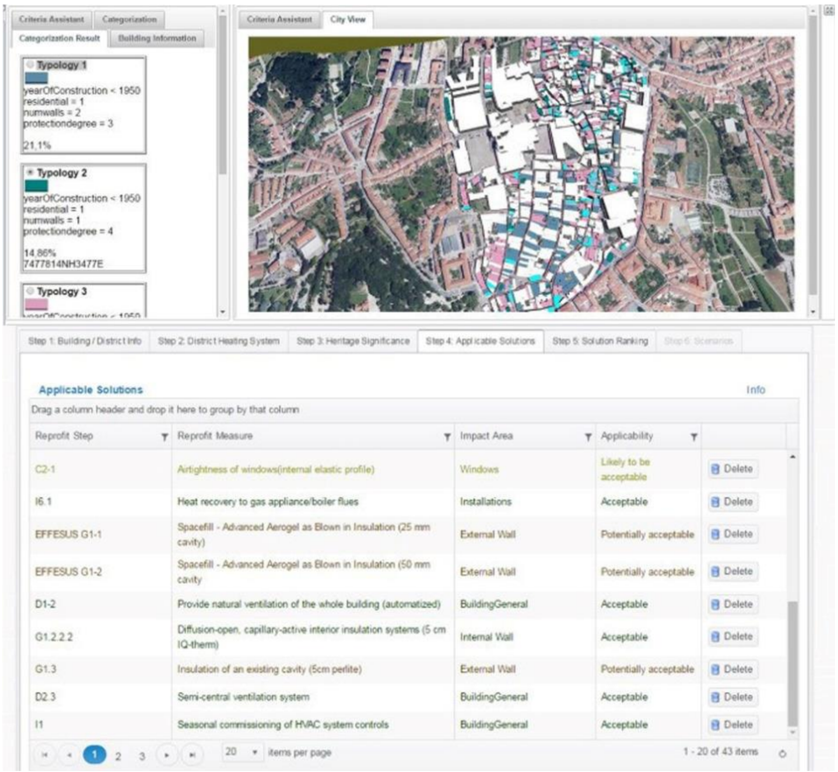
The Expert System DSS take the inputs provided by the user and query the solutions repository using a data-driven decision approach to retrieve the results for the decision-makers. The collection of solutions includes examples to improve the building and energy management, passive solutions to reduce the energy demand and active solutions that pursue the improvement of the efficiency of the technical installations.

In order to prioritise the retrofit solutions according to specific case study, a 0-4 scale is used to characterise each solution regarding: Indoor Environmental Quality (i.e. thermal comfort, acoustic comfort, visual comfort, and indoor air quality); Energy saving (calculated by means of a quasi-steady-state monthly method based on the EN ISO 13790:2008); Economic feasibility (estimated crossing data on the geometry of the building, solution and energy costs); and Impact on heritage significance (i.e. visual, physical and spatial qualitative impact). At the end of the process, the most suitable energy strategies are provided together with their impact at the historic district scale [63]. A typical view of the Effesus DSS/RE2H user interface is shown in Figure 5b.

The DSS/RE2H tool can be used to support the EN 16883:2017 from the beginning of the decision-making process (6) to the identification of retrofit solutions (10.3-10.4). However, there are two limitations to consider: first, a specific 3D urban model is needed to obtain specific retrofit solutions; second, the tool may be complex for a non-technical user. To date, the use of the tool in case study applications has only been documented in publications resulting from the Effesus project [44].



a)



○ Typology 1
yearOfConstruction < 1950
residential = 1
numwalls = 2
protectiondegree = 3

21,1%

● Typology 2
yearOfConstruction < 1950
residential = 1
numwalls = 1
protectiondegree = 4

14,86%
7477814NH3477E

○ Typology 3

Applicable Solutions

Drag a column header and drop it here to group by that column

Reprofit Step	Reprofit Measure	Impact Area	Applicability
C2-1	Airtightness of windows(internal elastic profile)	Windows	Likely to be acceptable
I6.1	Heat recovery to gas appliance/boiler flues	Installations	Acceptable
EFFESUS G1-1	Spacefill - Advanced Aerogel as Blown in Insulation (25 mm cavity)	External Wall	Potentially acceptable
EFFESUS G1-2	Spacefill - Advanced Aerogel as Blown in Insulation (50 mm cavity	External Wall	Potentially acceptable
D1-2	Provide natural ventilation of the whole building (automatized)	BuildingGeneral	Acceptable
G1.2.2.2	Diffusion-open, capillary-active interior insulation systems (5 cm IQ-therm)	Internal Wall	Acceptable
G1.3	Insulation of an existing cavity (5cm perlite)	External Wall	Potentially acceptable
D2.3	Semi-central ventilation system	BuildingGeneral	Acceptable
I1	Seasonal commissioning of HVAC system controls	BuildingGeneral	Acceptable

20 items per page

1 - 20 of 43 items

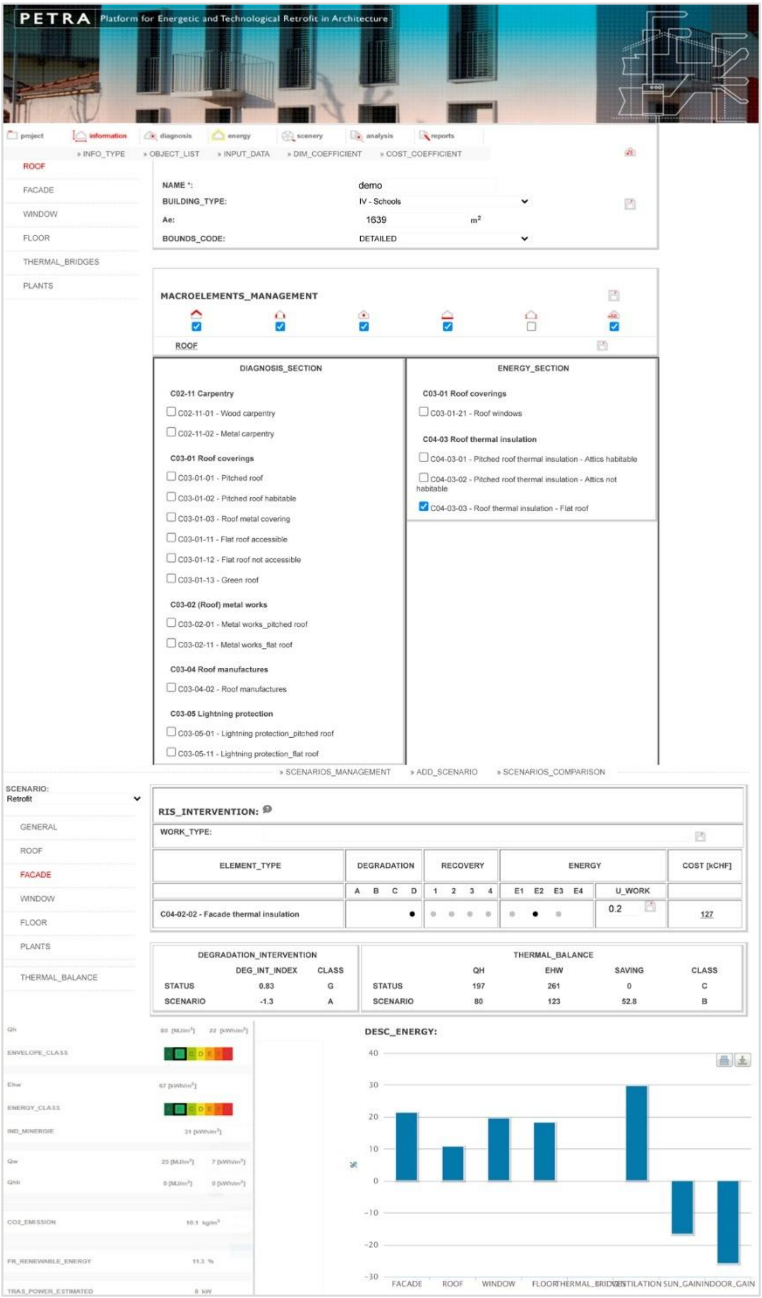
b)

Figure 5 – *Effesus DSS/RE2H Tool [45].* **a)** *Illustration of the underlying decision tree. Four levels of decision making (LoDM) are provided;* **b)** *Typical user interface, showing building categorization results and applicable solutions for a selected building category of the 3D urban model.*

- **PETRA** – Platform for Energetic and Technical Retrofit in Architecture

The PETRA web platform was conceived in 2013 by the University of Applied Sciences and Arts of Southern Switzerland (SUPSI) with the participation of the Swiss Federal Institute of Technology in Lausanne and three private companies [64]. In the PETRA tool, renovation solutions are proposed for individual building elements. Upon registration on the website, it offers a DSS tool for the implementation of building retrofit solutions in compliance with Swiss regulations [65]. The DSS tool uses a database on sustainable building renovation, and it is structured as a step-by-step process. It gathers relevant information of the building (1. Information) to check the necessity of intervention (2. Diagnosis) which serves for the immediate calculation of the energy balance according to current regulations (3. Energy), so scenarios with targeted interventions for upgrade and efficiency improvement are rapidly created (4. Scenarios) and a cost estimation is generated to enable the comparison of scenarios and their economic return (5. Analysis).
Accurate information of the building is required at the beginning by entering energy data collected from an on-site inspection, building plans, photographs or 3D models, information on building services, construction materials, user behaviour, etc. For the analysis, evaluation and protection of the historic buildings, the tool allows to enter descriptive comments and to define a building heritage class, according to the Swiss heritage protection regulation in force (from A to G, based on seven criteria: i. Architectural value; ii. Authenticity; iii. Integration on the site; iv. Uniqueness; v. Representativeness; vi. Historical value- cultural; vii. Affective value). Furthermore, it is possible to indicate the level of decay of every single element of the building and to implement an initial planning of the interventions by choosing the priorities at the time of diagnosis [66]. The solutions are displayed by the tool on a decision grid, and it allows the comparison between the current state of the property and the selected solutions, highlighting heritage, economic, energy and environmental aspects (Figure 6).
PETRA is based on the inductive analysis method, namely EPIQR+ software (Energy Performance Indoor Environment Quality Retrofit) [67, 68], which is a predictive cost/benefit analysis evaluation method with a focus on energy saving and a lower environmental impact. PETRA also supports the economic evaluation of retrofit solutions using the concepts and coefficients developed from the INVESTIMMO [69] model for all building types. As final outcome, the tool provides digital reports presenting the alternative solutions and a further step about the future management and maintenance of the building.

PETRA can be considered a useful tool to support the entire retrofit process of the EN 16883:2017 as it covers all the steps of the planning process, including a partial support to check the implementation of solutions (11.2, 11.4). However, one limitation of the tool is that the calculation of the thermal balance and the estimation of intervention costs it provides are not specifically targeted to historic buildings. Moreover, PETRA is very locally focused and mainly considers the Swiss market and regulations; the tool was last updated in 2013. Although the tool is in use by both professionals and governments, there are no publications that attest to its functionality, except [70].



NAME *: demo
BUILDING_TYPE: IV - Schools
Ae: 1639 m²
BOUNDS_CODE: DETAILED

MACROELEMENTS_MANAGEMENT

☑ ☑ ☑ ☑ ☐ ☑

ROOF

DIAGNOSIS_SECTION	ENERGY_SECTION
C02-11 Carpentry	**C03-01 Roof coverings**
☐ C02-11-01 - Wood carpentry	☐ C03-01-21 - Roof windows
☐ C02-11-02 - Metal carpentry	**C04-03 Roof thermal insulation**
C03-01 Roof coverings	☐ C04-03-01 - Pitched roof thermal insulation - Attics habitable
☐ C03-01-01 - Pitched roof	☐ C04-03-02 - Pitched roof thermal insulation - Attics not habitable
☐ C03-01-02 - Pitched roof habitable	☑ C04-03-03 - Roof thermal insulation - Flat roof
☐ C03-01-03 - Roof metal covering	
☐ C03-01-11 - Flat roof accessible	
☐ C03-01-12 - Flat roof not accessible	
☐ C03-01-13 - Green roof	
C03-02 (Roof) metal works	
☐ C03-02-01 - Metal works_pitched roof	
☐ C03-02-11 - Metal works_flat roof	
C03-04 Roof manufactures	
☐ C03-04-02 - Roof manufactures	
C03-05 Lightning protection	
☐ C03-05-01 - Lightning protection_pitched roof	
☐ C03-05-11 - Lightning protection_flat roof	

SCENARIO: Retrofit

RIS_INTERVENTION:

WORK_TYPE:

ELEMENT_TYPE	DEGRADATION				RECOVERY				ENERGY					COST [kCHF]
	A	B	C	D	1	2	3	4	E1	E2	E3	E4	U_WORK	
C04-02-02 - Facade thermal insulation				●	○	○	○	○	○	●	○		0.2	127

DEGRADATION_INTERVENTION	DEG_INT_INDEX	CLASS
STATUS	0.83	G
SCENARIO	-1.3	A

THERMAL_BALANCE	QH	EHW	SAVING	CLASS
STATUS	197	261	0	C
SCENARIO	80	123	52.8	B

Qh	80 [MJ/m²]	22 [kWh/m²]
ENVELOPE_CLASS	A B C D E F G	
Ehw	67 [kWh/m²]	
ENERGY_CLASS	A B C D E F G	
IND_MINERGIE	31 [kWh/m²]	
Qw	25 [MJ/m²]	7 [kWh/m²]
Qhli	0 [MJ/m²]	0 [kWh/m²]
CO2_EMISSION	10.1 kg/m²	
FR_RENEWABLE_ENERGY	11.3 %	
TRAS_POWER_ESTIMATED	8 kW	

DESC_ENERGY:

Figure 6 – *PETRA tool [46]. After filling in the building information required (including heritage value, building component characteristics and thermal zones parameters), retrofit solutions can be selected and ranked according to advantages in energy, heritage protection and cost.*

- **DEMI MORE** – Integrated Description of the Conservation Process Visual Decision Tool

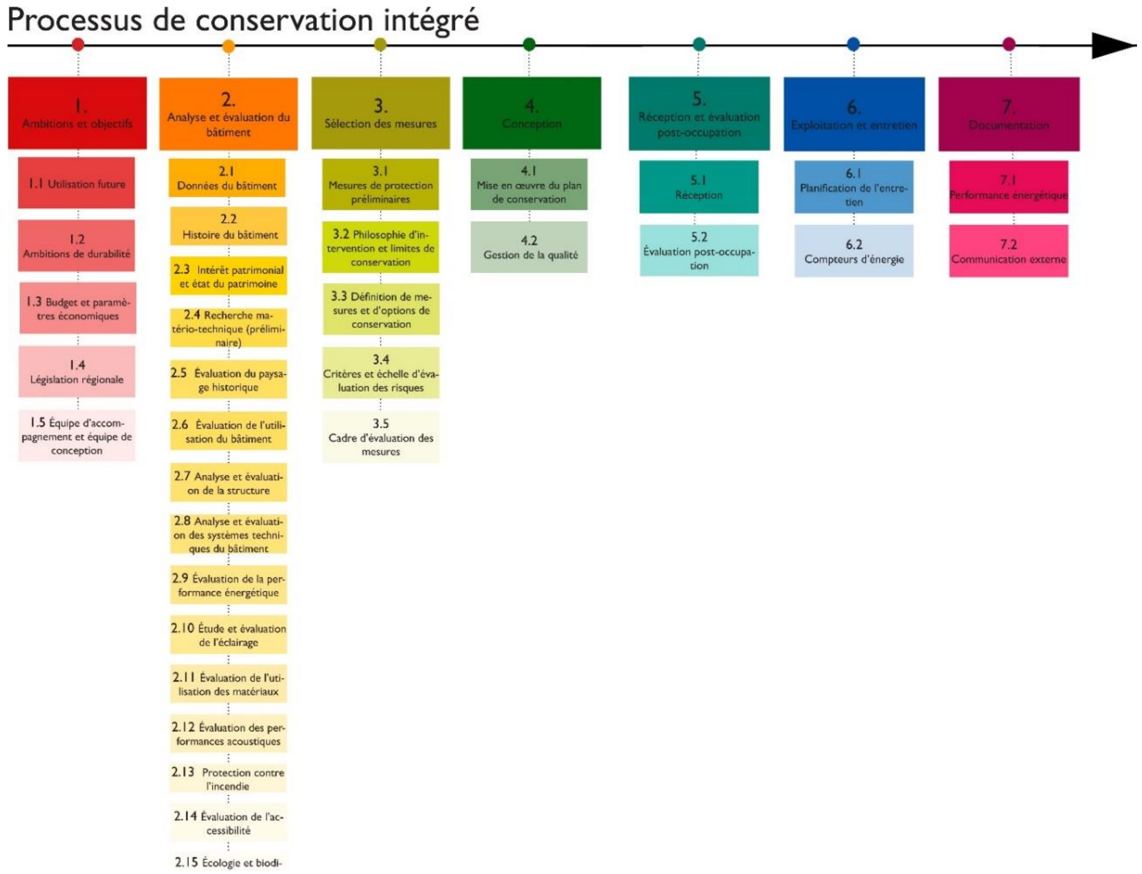
The DEMI MORE tools consist of a visual DSS tool [47] (available in French and Dutch) and an "integrated description of the conservation process" [71, 72]. Both complementary instruments were developed in the DEMI

MORE (Demonstration of Energy efficiency by Measurement and Innovation gives MORE) INTERREG-project Flanders- Netherlands.

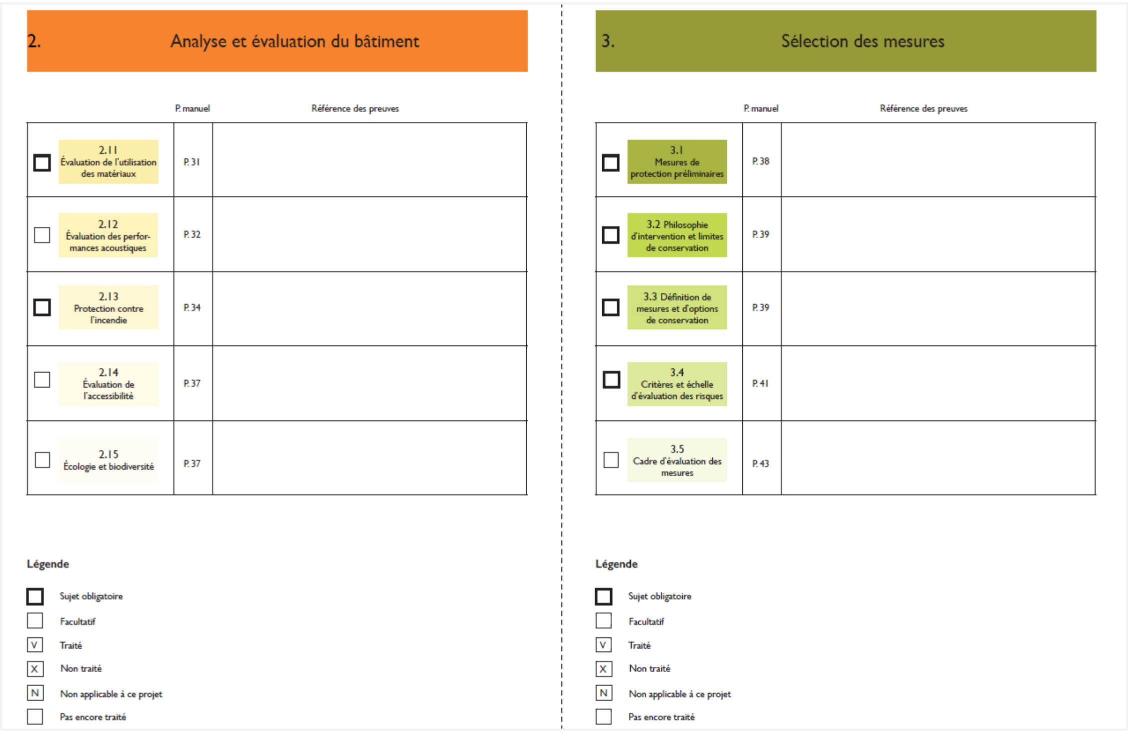
The structure and content of the DEMI MORE visual decision tool follow all steps defined in the EN 16883:2017 as a decision-tree for the overall conservation process; for each step the tool provides checklists at building level (Figure 7a). It starts with questions on the project ambitions and objectives (future use, budget, sustainability ambitions, regional legislation, research and design team), followed by building survey (heritage value, building conditions, context), selection and assessment of solutions (intervention philosophy, risk evaluation), design implementation (conservation plan, quality assurance), completion and post occupancy evaluation, operation and maintenance (maintenance plan). For all steps it is mentioned if it is mandatory or optional, applicable or not, depending on the aim of the project and on heritage restrictions (Figure 7b).

The focus is guiding the user (public administrations, professionals and owners) through the process, as a checklist and reference tool to existing guidelines and standards used in Belgium and the Netherlands, rather than suggesting or defining retrofit solutions. Links to appropriate tools to support the selection of solutions are provided in the document ‘integrated description’, downloadable on the tool website [73].

Despite this tool fits perfectly the EN 16883:2017 planning procedure, the main limitation of the DEMI MORE visual decision tool is that it is not an all-in-one tool that guides the user directly to the concrete solutions that are possible in a certain case. Indeed, the user needs to consult it together with other documents. Another limitation is that it exists only in French and Dutch, which makes its use restricted to those who master one of the two languages. The tool was used and tested on cases in the INTERREG project it was developed in [47]; thanks to the local Heritage Board activity of sponsorship, this tool is used in practice in Flanders, but there are no publications available.



a)



2. Analyse et évaluation du bâtiment

	P. manuel	Référence des preuves
☐ 2.11 Évaluation de l'utilisation des matériaux	P. 31	
☐ 2.12 Évaluation des performances acoustiques	P. 32	
☐ 2.13 Protection contre l'incendie	P. 34	
☐ 2.14 Évaluation de l'accessibilité	P. 37	
☐ 2.15 Écologie et biodiversité	P. 37	

Légende

☐	Sujet obligatoire
☐	Facultatif
V	Traité
X	Non traité
N	Non applicable à ce projet
☐	Pas encore traité

3. Sélection des mesures

	P. manuel	Référence des preuves
☐ 3.1 Mesures de protection préliminaires	P. 38	
☐ 3.2 Philosophie d'intervention et limites de conservation	P. 39	
☐ 3.3 Définition de mesures et d'options de conservation	P. 39	
☐ 3.4 Critères et échelle d'évaluation des risques	P. 41	
☐ 3.5 Cadre d'évaluation des mesures	P. 43	

Légende

☐	Sujet obligatoire
☐	Facultatif
V	Traité
X	Non traité
N	Non applicable à ce projet
☐	Pas encore traité

b)

Figure 7 – *DEMI MORE visual decision tool [47].* **a)** *Step-by-step structure of the tool;* **b)** *Typical pages of the offline tool; the compilation of the forms must comply with the accompanying documentation on the project website.*

- **RIBuild guidelines and tool** – Robust Internal Thermal Insulation of Historic Buildings

Internal insulation is often the only possible solution when improving the thermal performance of solid walls of historic buildings. However, internal wall insulation may be considered risky from a moisture perspective and practitioners may need guidance on that. For this reason, the H2020 research project RIBuild (Robust Internal Thermal Insulation of Historic Buildings) (2015-2020) has developed a set of guidelines in the project website to support the decision-making process, combining written guidelines and a web-based assessment tool [48].

The RIBuild guidelines contain information at different levels of detail, and are targeted at building owners, professionals and researchers. They use a computer-based data analysis approach starting with setting the goal for the renovation (step 1), followed by a description of how a visual assessment is to be carried out and what to look for (e.g., mould growth or rising damp) to decide whether the building is suited for internal insulation (step 2). This includes a description of possible remedial solutions to be implemented before deciding to install internal insulation. Step 3 is about deciding what kind of insulation system to choose based on a description of their characteristics, and finally step 4 presents how to evaluate the environmental impact and life cycle cost of the solutions.

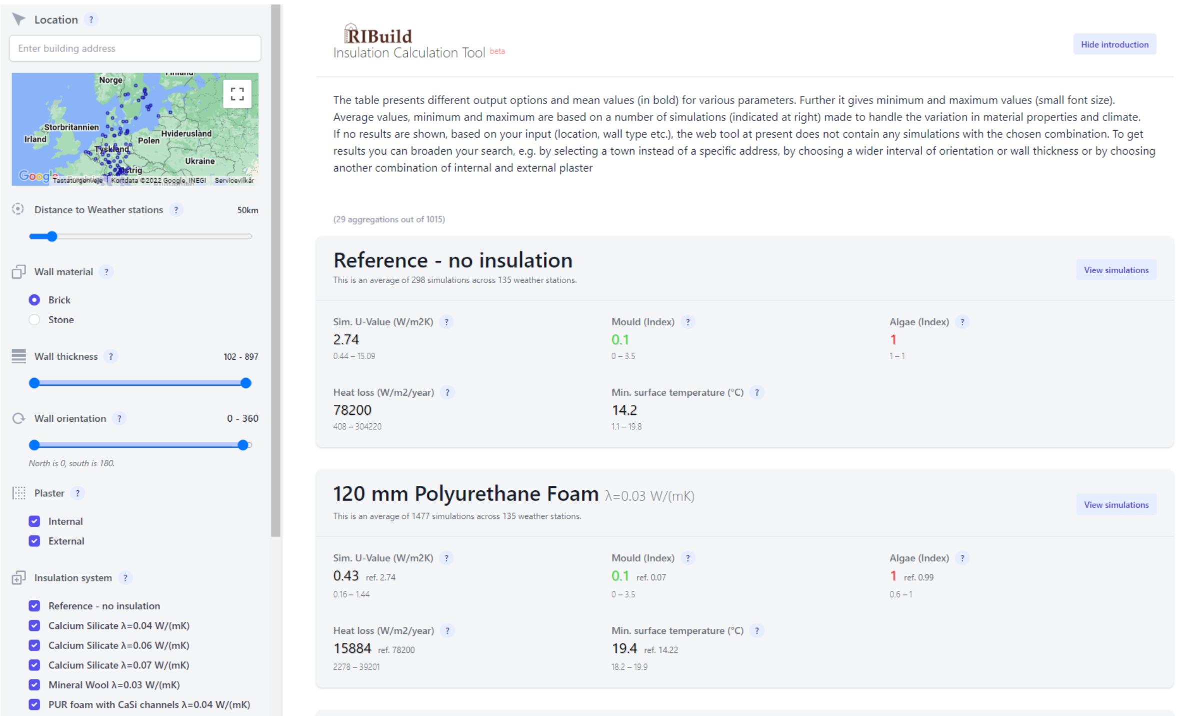
The RIBuild online tool (beta version) provides several internal insulation solutions to be considered for the specific building, based on a limited number of inputs. It can be used by different target groups as the requested inputs are quite simple; however, it is not fully developed to be used as a stand-alone tool. It is based on a probabilistic approach to represent the variation in e.g., material properties and outdoor climate, thereby indicating the risk of applying a certain solution. The inputs for the simulations were selected by the RIBuild partners based on the research performed in the project and on their previous experience. Measurement data from both laboratory experiments on components with internal insulation products and on-site monitoring of test buildings have supported the tool development. The probabilistic damage model calculation has been based on a huge amount of precalculated simulations for four failure modes in brick masonry or natural stone wall sections (i.e. external surface: algae growth; 5 mm from the external surface: frost damage; etc.) and of the internal surface temperature (i.e. 0.5 mm from it) [74]. The probabilistic model involves a combination of locations, orientations, wall type and thickness, etc., covering the seven countries that took part in RIBuild (Belgium, Denmark, Germany, Italy, Latvia, Sweden, and Switzerland). The simulations are based on the tool DELPHIN, considering future weather forecasts covering years 2020-2050 to reflect the fact that the buildings are to be used for several years ahead after being renovated.

Required inputs for the RIBuild tool consist of location of the specific building, orientation of the wall, the wall type and thickness, and the presence of internal or external rendering. The more detailed the inputs are, the shorter is the list of solutions returned. The solutions can be ranked, based on whether the user prioritises a low U-value or heat loss, a high internal surface temperature, or a low risk of either mould growth or algae growth [74] (Figure 8).

While the RIBuild guidelines can cover the entire building retrofit process in the EN 16883:2017, the RIBuild tool mainly covers the building survey (7) and the identification of planning objectives (8), towards the identification of wall insulation retrofit solutions (10.3-10.4).

The main limitation of the present version of the RIBuild tool is that it does not cover all failure modes for moisture-related damages. It includes mould growth and algae growth, but not frost damage or rot (wood decay) due to the absence of reliable models suitable for simulation of degradation. The web tool is based on limited weather data, not covering all locations, orientations, wall design and insulation systems relevant for the specified countries. Therefore, depending on the user's input it might happen that no solutions are suggested. This is explained in the disclaimer of the tool [48].

There are currently no publications attesting the use of the RIBuild tool, apart from the case studies included in the project on-site monitoring activities [75].



Distance to Weather stations ? 50km

Wall material ?

● Brick
○ Stone

Wall thickness ? 102 - 897

Wall orientation ? 0 - 360

North is 0, south is 180.

Plaster ?

☑ Internal
☑ External

Insulation system ?

☑ Reference - no insulation
☑ Calcium Silicate λ=0.04 W/(mK)
☑ Calcium Silicate λ=0.06 W/(mK)
☑ Calcium Silicate λ=0.07 W/(mK)
☑ Mineral Wool λ=0.03 W/(mK)
☑ PUR foam with CaSi channels λ=0.04 W/(mK)

The table presents different output options and mean values (in bold) for various parameters. Further it gives minimum and maximum values (small font size). Average values, minimum and maximum are based on a number of simulations (indicated at right) made to handle the variation in material properties and climate. If no results are shown, based on your input (location, wall type etc.), the web tool at present does not contain any simulations with the chosen combination. To get results you can broaden your search, e.g. by selecting a town instead of a specific address, by choosing a wider interval of orientation or wall thickness or by choosing another combination of internal and external plaster

(29 aggregations out of 1015)

Reference - no insulation

This is an average of 298 simulations across 135 weather stations.

Sim. U-Value (W/m2K) ?
2.74
0.44 – 15.09

Mould (Index) ?
0.1
0 – 3.5

Algae (Index) ?
1
1 – 1

Heat loss (W/m2/year) ?
78200
408 – 304220

Min. surface temperature (°C) ?
14.2
1.1 – 19.8

120 mm Polyurethane Foam λ=0.03 W/(mK)

This is an average of 1477 simulations across 135 weather stations.

Sim. U-Value (W/m2K) ?
0.43 ref. 2.74
0.16 – 1.44

Mould (Index) ?
0.1 ref. 0.07
0 – 3.5

Algae (Index) ?
1 ref. 0.99
0.6 – 1

Heat loss (W/m2/year) ?
15884 ref. 78200
2278 – 39201

Min. surface temperature (°C) ?
19.4 ref. 14.22
18.2 – 19.9

Figure 8 – *RIBuild tool user interface [48]. The inputs required to filter out the relevant simulations and rank them for the specific case study are selected on the left; simulations results based on the user's input data are shown at the centre.*

5. Discussion

5.1. Review of identified tools

As shown in the descriptions of the different tools, there is a wide variety in the amount and complexity of input data, in relation to their structure and purpose, including the target audience to which they refer (Table 2).

Most of the tools are structured to work at the building scale [41, 42, 44, 46, 47], a few works at the building components level [43, 48], and just one at the urban district scale [45].

All tools require initial information about the case study (e.g., heritage value, characteristics of the building components, exposed sides, energy consumptions, driving-rain protection, etc.) and its context (e.g., location, climate, surroundings). However, some tools [41-44] have been developed to help stakeholders prioritise retrofit solutions according to indicated targets and boundary conditions; this type of tools is directed to support only the *identification of the retrofit solutions* (10.3-10.4) and the *assessment and selection of solutions* (10.5-10.7) steps of the EN 16883:2017 planning procedure. Other tools [45-48] aim instead to guide the user during the entire building retrofit process; this type of tools, aimed at directing the whole planning process, enabling the user to proceed step-by-step in the Standard procedure. In some cases [41-44, 48], the decisions are supported also with references to external documents and examples that can facilitate both the *exclusion of inappropriate solutions* (10.4) and the *assessment and selection of solutions* (10.5-10.7).

The level of action in the tools changes as well: while some focus on suggesting suitable solutions providing an overview among different possible alternatives [41, 42, 43, 47], others must be handled by an expert professional when making decisions on how to best intervene and suggesting various scenarios based on technical and more detailed data [44, 46, 48].

Most of the analysed tools are the result of international research projects related to this topic [44, 45, 47, 48]. The advantage of tools developed within large groups of experts in the field is that most retrofit solutions are tested on real case studies of historic buildings. Moreover, the international nature of these research projects has the advantage that the solutions are collected in different countries, therefore with a greater geographical extension and on different types of historic buildings. In other cases, dedicated tools are used at local and regional level to support stakeholders involved in the process of specifying solutions when facing building renovation [41-43, 46]. They are aimed at considering issues that are specific to the traditional buildings of interest, so they present a limitation in the possibility of being used in countries with different climatic conditions, building materials and constructive typologies. However, as reported in [27], while location-specific data allow the consideration of local climate aspects, tools that are not site-specific can result in a lesser consideration of specific cultural and constructive aspects.

Some tools are thought to be implemented and updated over time. However, some of them remained stationary at the time of online publication, with the risk of not being updated to new regulations [44, 46].

Finally, almost all tools provide an output report collecting information of possible retrofit solutions for the specific case study. In each report, information is differently structured and could be more or less detailed on a certain topic (e.g., including a special appendix on the economic evaluation [46], or a collection of actions to reduce possible risks for the historic building [41, 42]). Conversely, some provide only a collection of information and references to deepen the analysis and selection of the solutions [44, 47, 48].

Table 2 presents a brief synthesis of the selected tools, expressed as input data needed, output data provided and main limitations.

Table 2– *Input data needed, output data provided and main limitations of selected tools*.

Acronym / Name	**Input Data needed**	**Output data provided**	**Main Limitations**	**Level of detail /** ***Main user***
Repository Web tool				
Responsible retrofit guidance wheel	Building context (heritage value, building condition, exposure to wind-driven rain, exposed sides), occupant's energy use, and interest in the building.	Report for a selected package of solutions presenting a list of concerns, as well as a list of suggested actions to minimise/mitigate the risks before, during and after installation.	It is very locally focused (UK) and mainly considers traditional buildings.	Preliminary general overview on possible retrofit solutions for the single building, including possible interactions between solutions. *Non-energy-expert users (e.g., homeowner), professionals, heritage officers.*
French version of the responsible retrofit guidance wheel			It is very locally focused (France) and mainly considers traditional buildings.	
HiBERTool – Historic Building Energy Retrofit Tool	The user has to answer different questions to explore a category of solutions (e.g., window, wall). Questions are mostly generic and do not require any specific pre-survey (e.g., preservation of the appearance of the façade, availability of driving rain protection, etc.).	Information and further links on the solution in the form of a PDF sheet. Reports include information on technical and energy performance, interaction with building conservation, and further links.	The repository has a limited number of exemplar solutions, which can be extended over time. Many of the examples belong to Alpine architecture.	Preliminary general overview on possible retrofit solutions for the single building. *Non-energy-expert users (e.g., homeowner), professionals, heritage officers.*

Decision Support Systems (DSS)				
exDSS – Climate for Culture	Information about the building (size, use, location, etc.) compiling a predefined questionnaire developed in three steps (1: future outlook, 2: risk assessment, 3: indoor climate control methods).	Information to support the technical analysis of single retrofit solutions is provided. It includes also further links to more detailed publications.	The tool has not been updated since 2015 and it contains a limited number of solutions, references and best practices, provided at the project time.	Detailed hygrothermal risk assessment and climate change impact at building level. *Professionals, building owners/estates managers and researchers.*
Effesus DSS/RE2H	All the information required is structured in a 3D model based in CityGML. Besides the geometry, the model requires information at urban level regarding heritage significance, thermal characteristics of the buildings and their use.	A report on the current state of the district, a list of possible solutions classified by their applicability, and a priority list of strategies likely to be suitable in the specific historic district.	The tool needs a specific 3D model to get specific retrofit solutions. It could be complex to be used by non-technical users.	Selection of solutions at the urban/district scale with an overview on building typologies. *Public administrations and urban planners.*
PETRA – Platform for Energetic and Technical Retrofit in Architecture	Accurate information of the building from on-site inspection, building plans, photographs or 3D models, information on plants, constructive materials, user behaviour, etc.	Digital reports with information on: (i) Technical and energy buildings analysis; (ii) Estimation refurbishment costs of alternative retrofit scenarios; (iii) Information for future management and maintenance.	It is very locally focused and mainly considers the Swiss market; it is based on macro elements that depend on the allocation and the complexity of the buildings. Updating funds stopped in 2013.	Selection of solutions at the building scale, also accounting for the costs and savings of the intervention. *Building professionals and operators of public administrations.*
DEMI MORE – Demi More integrated description of the conservation process	Requires compiling a checklist, answering questions on the building and its context. Some info is mandatory, other not.	Integrated description of the solution, with a link to legislation, guidelines, and tools developed by the regional authority.	No direct link in the tool to the possible solutions for a certain case. Limited to users who master French and Dutch.	General support for the discussion of planning solutions. *Planning group with different expertise.*
RIBuild Guidelines and tool – Robust Internal Thermal Insulation of Historic Buildings	Location and orientation of the building, wall thickness, presence of plaster internally or externally.	List of relevant solutions for internal insulation.	It does not cover all relevant failure modes, locations and orientations of buildings, wall designs, insulation systems. Weather data are limited to seven European countries.	Detailed hygrothermal risk assessment for wall internal insulation. *Professionals, building owners/estates managers and researchers.*

5.2. *Critical analysis of results for future research insights*

According to the review undertaken in this work, no tool fits every step of the Standard procedure. Most of the tools available were developed within European projects for specific purposes, far from the idea of supporting the use of the design procedure indicated in the EN 16883:2017. The DEMI MORE tool is the only one covering the whole procedure (cf. Figure 1), although it only offers suggestions on a general level.

The idea of having a one-for-all tool that supports all steps of the EN 16883:2017 procedure was discussed by the sustainability and heritage experts involved in the TASK 59 project [20, 21]. However, considering the complexity of working with historic buildings in different climate zones and contexts, involving multidisciplinary teams, this goal was deemed to be mainly useful for the research community and possibly not so much for practitioners [20-21]. Conversely, the possibility for the user to make use of more than one tool to address the different steps of the Standard has been suggested by the TASK 59 working group as a possible – and more straightforward – approach to really support the implementation of the EN 16883:2017 use and facilitate the conversation among different teams.

From what emerged, the tools reviewed can be divided in relation to the level of experience of the user who wants to follow the Standard and their main role in a retrofit planning (Table 2). The Guidance Wheel or the HiBERtool are particularly suitable for non-expert users (e.g., homeowners), due to their ease of use to get a preliminary overview on possible retrofit solutions for the single building. In both cases it is possible to have a reference to real case studies, although the main strength of the Retrofit Wheel is the possibility to explore the advantages associated to each measure, concerns about their performance and possible interactions between different solutions. The PETRA tool is particularly useful for building professionals and operators of public administrations who may want to evaluate a selection of solutions at the building scale, also accounting for the costs and savings of the intervention. For analysis at urban scale (e.g., public administrations which aim to retrofit a historic district) it is recommended the use of the Effesus tool with the support of an urban planner. The DEMI MORE is recommended for a planning group with different expertise, as it can support a multidisciplinary team in the discussion of the Standard procedure steps. Finally, the RIBuild and the exDSS tools are respectively recommended to professionals, building owners and researchers who look for more information about internal insulation retrofit solutions and for possible hygrothermal risk of retrofit solutions more in general.

If networked, the tools reported here could cover the needs that arise when addressing the challenge of energy renovation of a historic building. It was made clear that – in some of the required steps of the Standard – specific tools are necessary for the evaluation, energy simulation, financial assessment, risk assessment, etc. of single solutions or combinations of retrofit scenarios. That would eventually lead to a more robust decision-making process where complementary tools could be connected for the identification of the most suitable retrofit scenario [76].

6. Conclusions

Decision-making is a complex process of identifying, evaluating, and choosing among alternatives based on the values, preferences, and beliefs of the decision-maker. In the context of retrofit projects in historic buildings, this complexity is amplified. Indeed, the decision makers must consider achieving a sustainable balance between the use of a building, its energy performance and its preservation when selecting the most appropriate energy efficiency solutions [27]. In this vision, the different aspects of energy performance and conservation need to be considered in the broader context of the sustainable management of buildings.

The choices made in a specific case, among all available options, depend heavily on the initial goal setting: each goal might be directly linked to one or more criteria, possibly quantifiable by indicators, to support the evaluation of alternatives [77]. The complex nature of the problem is linked to the variety of stakeholders involved in the process, as well as to other factors influencing the choice of the ‘optimal’ combination of solutions (i.e. the ‘package’ or the ‘scenario’). To reach decisions that balance all aspects of sustainability, a more structured decision-making process is needed that bridges the gap between rigorous, universal standards and ad hoc decision-making processes [20].

To fill the gap between theory and practice, the EN 16883:2017 provides a systematic procedure to facilitate the decision-making in the retrofit of each individual case. It pushes towards a holistic vision of the planning and to a whole building approach, considering different variables and goals. The proposed planning procedure shall be used to identify the need for energy performance improvements and appropriate improvement solutions that match the requirements for the historic building in question. The Standard suggests a series of general steps for the planning process of energy retrofitting for cultural heritage buildings; quoting its text, “this method should not be seen as a mechanical tool that provides an answer” (chapter 10.2), but it is meant to allow a transparent dialogue to decide on retrofit interventions. Thus, the Standard procedure represents a possible basis of work to discuss different retrofit solutions with the project team, that can be supported with additional tools and resources [19]. For this reason, several computer-based tools were reviewed and compared, to identify how they can enable the implementation of the EN 16883:2017 procedure to integrate conservation-compatible retrofit solutions in historic buildings.

In the Standard, seven steps have been identified as priority aspects to make an informed and holistic decision on any energy performance improvement solutions in historic buildings. This paper highlighted that the tools reviewed cover different parts of the process, also showing a different level of action and usability in the different steps considered.

This research has also shown that in the future it would be useful to have a general approach to support the Standard process in the selection of retrofit solutions. This approach could be supported by networking (some of) the tools reviewed in this paper and it should consider aspects linked to the holistic view on sustainability currently included in the European *Baukultur* concept [22, 23], such as: 1) cultural sustainability, to ensure that the built heritage significance is retained for present and future generations, 2) economic sustainability, to increase the market value of historic buildings, their revenues and operating costs; 3) environmental sustainability, to reduce the impact on the planet by considering the building life cycle (e.g., use of renewable resources, use of local materials, etc.); and 4) social sustainability, to contribute to the local context in terms of building use, as well as conservation of the building integrity and social involvement.

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