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Organisation name of lead contractor for this deliverable:	**Università Politecnica delle Marche (UNIVPM)**
Author(s):	**Elisa Di Giuseppe, Marco D'Orazio, Claudio Favi, Marta Rossi (UNIVPM); Sébastien Lasvaux, Pierryves Padey, Didier Favre (HES-SO); Kim Wittchen, Guangli Du, Anker Nielsen (AAU); Andra Blumberga, Edite Kamendere (RTU).**
Participants(s):	**UNIVPM, HES-SO, AAU, RTU, DTU**
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Internal reviewers:	**Andra Blumberga (RTU), Ernst Jan de Place Hansen (AAU), Hans Janssen (KUL), Morten Birkved (DTU)**
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Abstract:

This report presents the results of the work performed within WP5, Task 5.2 "Probabilistic Life Cycle Impact Assessment of the environmental impact of internal insulation solutions" (Part 1 of the report) and Task 5.1 "Evaluation of the energy saving potential of internal insulation solutions depending on building practice" (Part 2). The report accompanies the WP5 software tool, key part of Deliverable 5.1 that puts into practice the LCA probabilistic methodology developed as part of the RIBuild project and paves the way for further developments of the RIBuild project, i.e. the environmental assessment of internal insulation solutions for historic buildings included into the RIBuild web tool.

Keyword list: Internal Insulation, LCA, Energy Saving, Probabilistic Methodology, Monte-Carlo method, Uncertainty Analysis, Sensitivity Analysis.

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Executive Summary

This report presents the first of two deliverables related to RIBuild Work Package 5 ”Development of cost/benefit and environmental impact assessment”. The main aim of WP5 is to develop a probabilistic methodology for assessing the environmental impacts and global costs of internal insulation solutions based on a life cycle perspective.

The work can be seen in parallel with the probabilistic methodology developed within RIBuild WP4 in the field of the hygrothermal assessment of interior insulation solutions. ”*The focus in the probabilistic methods developed in WP4 and WP5 is on setting up the methodology for the assessment of the thermal envelope of historic buildings and the improvement of it in the context of hygrothermal performance (WP4) and in the context of environmental impact and life cycle economy (WP5).*”[1] WP6 will take the next step in this assessment and has the aim of combining the methodologies developed in WP4 and WP5 to a common methodology and a set of guidelines on internal insulation of historic buildings usable for building designers, owners etc.

This deliverable 5.1 reports the outcome of the work performed within Task 5.2 “Probabilistic Life Cycle Impact Assessment of the environmental impact of internal insulation solutions” (Part 1 of the report) and Task 5.1 “Evaluation of the energy saving potential of internal insulation solutions depending on building practice” (Part 2).

The ***Part 1*** (*Probability based Life Cycle Impact Assessment of internal insulation measures)* contains four sections dealing with the approaches to Life Cycle Assessment (LCA) in the building context, the probabilistic LCA methodology developed within RIBuild, example cases of applying the methodology, and the software tool developed to apply the probabilistic methodology in the field of internal insulation - and of building retrofit measures in general-. Further it contains four appendices in which LCA input data and calculation procedures are deepened.

Section 1 provides a brief overview of Life Cycle Assessment approaches in the context of buildings. The section presents the existing standards, the guidelines and the main research projects conducted in the field of building LCA (section 1.1). As demonstrated, several specific LCA methodologies have been developed for buildings and building components and the European context now has a basis for the building LCA methodological rules based on EN 15804 and EN 15978.

Section 1.2 then focuses on more specific aspects, e.g. system boundaries, databases, indicators, that should be taken into account when performing an LCA in the building field. From the review analysis performed by Task 5.2 partners, some general considerations were drawn and used in the following discussion on the specific RIBuild LCA approach, especially concerning the limitations in terms of the life cycle stages covered in the assessments and the selection of LCIA indicators. Furthermore, the review was carried out in parallel with the development of preliminary national “deterministic” case LCA studies of internal insulation solutions in historic buildings, during the initial stages of the Task. The review was done to provide a picture on the environmental hotspots, the building impact share represented by materials, the energy saving potential, the impact of

[1] RIBuild ANNEX 1 (Part A).

different phases in the case of LCA of insulation interventions in historic buildings, in view of the following LCA “probabilistic approach” development.. The results of these preliminary assessments are reported in *Appendix 4*.

Section 1.3 focuses on the relationship between building LCA and components service life, a key parameter in building renovation projects, impacting the maintenance cycles and renovation plans for a building. In particular, the potential of the probabilistic factorial method in the field of building components service life characterisation is presented, paving the way for its application into the probabilistic building renovation LCA.

Finally, section 1.4 presents a brief summary of the already conducted works on probabilistic approaches to LCA, particularly focusing on the state-of-art in the building sector. The section includes an overview on the essential concepts related to the definition, identification and characterisation of uncertainties in LCA; and the main methods for their propagation and for the interpretation of the results. This section shows that the definition of uncertainty and variability in LCA is confusingly non-standardized. Furthermore, a probabilistic approach to LCA is still rarely used, especially in practice, in the building sector. Existing building LCA studies or building LCA tools rarely consider systematic uncertainties and sensitivity analysis methods for improving the credibility of results. Hence, there appears to be a need for tackling this issue more comprehensively by developing a robust probabilistic LCA methodology where the users could be made aware of and try to “quantify” the uncertainties related to the results.

Extending the aim from section 1, *Section 2* presents the specific probabilistic LCA methodology developed for application within the field of internal insulation solution of historic buildings within Task 5.2, following the main problems that are commonly encountered when dealing with “uncertainty” in a specific model, calculation or process: its characterisation, propagation and analysis.

The probabilistic LCA methodology developed is useful for providing decision support during the design phase, giving insight into design robustness and possible ranges of the environmental impacts of a specific design option (the insulation solution) or to investigate and compare different design options. Moreover, it provides, through a comprehensive sensitivity analysis, an idea of the significance of input parameters’ uncertainties and their impact on the result.

The goal and scope and main assumptions of the probabilistic LCA performed at “component level” are presented in sections 2.1 and 2.2. The developed methodology couples the calculation of environmental indicators to Monte Carlo simulation methods, which are effective ways to build the entire output probability distribution and to assess global uncertainty and sensitivity (section 2.3). The probabilistic method developed consists in four main steps summarized below.

1. Explicit Life Cycle Inventory reference model: Establishing the specific procedure for the LCA of internal insulation solutions. The main input parameters are identified; the output parameters and a suitable model to simulate them are selected (section 2.4);
2. Uncertainty characterization: Selection and characterization of the uncertainties that are considered in the assessment (section 2.5);
3. Uncertainty propagation: Performing Monte Carlo methods with specific sampling procedures (section 2.6);
4. Uncertainty and sensitivity analysis: Representing the output distribution and calculating the sensitivity indices which allow the identification of the most influential parameters in terms of output variance (section 2.6).

The methodology is based on a flexible approach, tailored to the user's needs. It comprises three alternative methods, with increasing difficulty and accuracy level, to assess the heat transmission losses through the building wall before and after the renovation measure, necessary to assess the operational energy use and determine the environmental burden savings before performing the actual LCA. The methodology can be coupled to accurate HAM tools even based on probabilistic approaches as that developed within RIBuild WP4, to monthly steady-state calculation, or to a simplified annual HDD method.

Furthermore, the probabilistic LCA, as implemented in the WP5 software tool, can be adjusted to the user's level of knowledge and information on input data related to the design options and possible assessment scenarios. In case no specific information is provided by the user, then background probabilistic density functions for the input parameters are proposed for the assessment. If the user would like to reduce the level of uncertainty by taking time to refine the input characterisation or if the user wants to assess a specific case study, the background distributions proposed can be replaced by other distribution types or deterministic values. This allows the user to switch from screening uncertainty assessment to a more detailed assessment.

Even if specific assumptions are made for the probabilistic LCA of internal insulations, the methodology developed is a robust example of a probabilistic LCA approach that could find other relevant applications in the building refurbishment sector.

Exemplary cases of the methodology application, performed by Task 5.2 partners, are reported in *Section 3*, to illustrate its potential and its possible uses also in view of future progress of RIBuild guidelines or, in general, in building renovation projects. Four different applications are presented:

1. Influence of the users' LCA inputs knowledge level on the results (from screening to detailed assessment) (section 3.1);
2. Comparison of the environmental performance of several design options (section 3.2);
3. Assessment of results robustness under different scenarios for energy sources and building reference study periods (sections 0 and 3.4);
4. Identification of influential parameters on the outcome uncertainty (section 3.5).

The exemplary cases highlight how the methodology can be applied to assess the environmental performance of design options (internal insulation solutions) across various possible scenarios (original wall applications, climatic contexts, energy sources, reference study periods).

Finally, *Section 4* presents the WP5 software tool, key part of Deliverable 5.1, that implements the probabilistic LCA methodology developed. The tool includes both the Life Cycle Assessment and Life Cycle Costing Monte-Carlo based methodologies developed within, respectively, WP5 tasks 5.2 and 5.3 and allows the real-time calculation of the distributions of environmental and economic impacts of insulation systems applied to the wall case studies under possible scenarios with a small calculation time[2].

The software has been implemented using *R*, an open source programming language and software environment for statistical computing and graphics, and *Shiny*, an *R* package which facilitates the building of interactive and user-friendly web apps straight from *R*. The LCA calculation

[2] The LCC section of the software is almost ready at this stage, but will be further developed within WP5 task 5.3 "Probabilistic Life Cycle Cost (LCC) analysis and Cost-Optimal (CO) levels of minimum energy performance of interior insulation solutions", as part of D5.2, by June 2018.

assumptions behind the software architecture are extensively reported in section 4.1, while section 4.2 includes the software user guide.

The main idea behind the software is to allow for a flexible use of it: the tool already includes a database of input data covering the exemplary national case studies performed within RIBuild Task 5.2, also reported in *Appendix 3*. This database can be edited and/or expanded according to user preferences. Furthermore, the software tool can be used to assess other possible renovation measures than internal insulation, which maximises the impact of the tool and methodology in the field of building renovation.

The ***Part 2*** (*Energy saving potential of internal insulation measures*) contains four sections, each representing a partner country, reporting the results of the analyses on the potential energy savings in historic buildings when considering internal facade insulation. Energy performance improvements due to installation of internal facade insulation in historic buildings has been calculated for selected case buildings in four countries participating in Task 5.1, i.e. Denmark (*section 5*), Latvia (*section 6*), Italy (*section 7*) and Switzerland (*section 8*). Calculations included energy savings from facade insulation separately and energy savings from facade insulation in combination with other energy saving measures applied to the building envelope that have been or normally will be implemented at renovation.

Results of building energy assessments are key inputs for the LCA of internal insulation solution of historic buildings that includes the operational energy use phase. However, internal facade insulation is normally not the single solution when dealing with energy savings in existing buildings, but it often comes in combination with other energy saving measures. To be able to evaluate the life cycle environmental impact and energy consumption of facade insulation solution it is therefore important to evaluate this measure isolated from other measures in the renovated building. Calculation of energy savings in the case buildings is then based on a number of scenarios depending on the degree of renovation before implementing internal insulation.

Part 1: Probability based Life Cycle Impact Assessment of internal insulation measures

Introduction

Building energy renovation is today a strategy gaining increasing attention within the building sector. The intentions with the strategy are basically to achieve effective energy savings, hence a substantial reduction of greenhouse gas emissions and finally a real improvement of peoples' health and lifestyle.

Considering that in today's Europe 30% of all buildings are historic buildings that are expected to last for decades, there is great potential for energy savings and consequently exploitable emission reductions in existing and historic buildings. More attention should then be given to the renovation strategies and technologies aiming at existing buildings in different climates and conditions. This however implies facing the inherent risks and constraints relating to the life cycle of the building and insulation component anon the least from and environmental performance quantification perspective.

Energy saving is the principal tool promoted by the EU commission to limit environmental impacts related to the use of buildings. Nevertheless, the buildings' environmental performance needs to be evaluated through a consolidated, comprehensive, systemic method. The assessment of the environmental impacts should rely on a life-cycle perspective, including e.g. building components' embedded energy, replacement of these component, maintenance needs, and clear the altered energy consumption induced by renovations across the entire building service life.

Unfortunately, Life Cycle Assessment (LCA) procedures applied to energy renovation measures on historic buildings most often suffer from several intrinsic uncertainties. These uncertainties relates to the long-term perspective of the building interventions as the presence of several constraints (architectural, cultural, social, structural, etc.), that forces the renovation measure to follow specific narrow paths in terms of integrity, authenticity and compatibility between the old and the new materials and building techniques.

For this reason, taking into account uncertainty and variability in LCA has been identified as one of the key challenges to improve the reliability of LCA based decision making. While in some fields of engineering and computing sciences uncertainty assessments are part of standard framework. In LCA, only little has been done in terms of uncertainty and sensitivity analysis and international standards are not exhaustive regarding these aspects. Building LCAs are usually performed considering deterministic data inputs only for practical reasons e.g., the lack of simulation tools supporting a probabilistic LCA in practise, the challenges in terms of vast amounts of data needed for probabilistic calculations, the absence of guidance from existing standards and/or insufficient data samples to perform the uncertainty modelling. As a result, the inherent uncertainties are rarely considered and even more rarely quantified. Nonetheless, the use of deterministic values and assumptions on various life cycle parameters may yield biased results and thus misled decisions.

This part of D5.1 report addresses these issues, by describing the probabilistic LCA methodology developed within RIBuild WP5, Task 5.2 "*Probabilistic Life Cycle Impact Assessment of the environmental impact of internal insulation solutions*".

The probabilistic LCA methodology can be effectively applied to offer decision support during the building renovation phase, providing possible ranges of the environmental impacts of insulation solutions under alternative scenarios. Furthermore, it offers an idea of the significance of input parameters' uncertainties and their impacts on the results, through a detailed sensitivity analyses, going broadly beyond the state of the art within the field of building LCA. The probabilistic approach presented here considerably improves the reliability of LCA based decision making and allows for overcoming the evident limitations of traditional deterministic LCA approaches.

The methodology developed within Task 5.2 has been illustrated through exemplary case studies and implemented in a software tool, for the probabilistic Life Cycle Assessment of internal insulation solutions in historic buildings.

The *WP5 software* is the key part of Deliverable 5.1, as it translates into practice the developed LCA methodology and paves the way for further developments of RIBuild in WP6, which aims to create "*comprehensive guidelines for comparative assessment of internal insulation solutions based on life cycle cost, combining the probabilistic assessment of hygrothermal performance developed in WP4 with the quantification of life cycle costs of internal insulation's benefits and damages formulated in WP5*"[3]. In WP6, this can be done by assessing the "probabilistic" hygrothermal performance and environmental and economic impacts of selected case studies of internal insulations using the simulation approaches and software tools developed respectively in WP4 and WP5. The software will be further updated, including the Life Cycle Costing (LCC) section, within WP5 task 5.3 activities, as part of D5.2[4]. Furthermore, the software developed within WP5 has been conceived to be applied also to other possible renovation measures than internal insulation, in order to maximise the impact of the tool within the field of building renovation.

[3] RIBuild ANNEX 1 (Part A).
[4] The LCC section of the software is almost ready at this stage, but will be further developed within WP5 task 5.3 activities, as part of D5.2, by June 2018.

1 Overview on the approaches to Life Cycle Assessment (LCA) in the building context

The concept of Life Cycle Assessment (LCA) was conceived in the 70s in the industrial sector mainly due to the energy crisis. Since the 90s, LCA has been recognized as an important tool for environmental performance quantification and thus widely applied also in the building sector [1].

LCA is the environmental method used to address the potential environmental impacts of product, goods and services. It assesses a product's or rather a services technical life cycle, quantifying energy and material flows entering or leaving the product system, and characterizes the associated environmental burdens. The method has for decades been standardised according to the ISO 14040 and ISO 14044 standards developed by the International Organization for Standardization (ISO) [2,3].

It comprises fives steps including:

- Goal and scope definition (definition of the goal of the study, functional unit used to compare the product systems, choice of boundaries e.g., cradle-to-gate, cradle-to-grave etc., allocation rules of the flows e.g., allocation of the impact of the kWh consumed in a factory plant with different production lines of products);
- Inventory analysis (quantification of energy and mineral resources consumption and release of pollutants into the air, water and soil compartment);
- Life Cycle Impact Assessment (choice of life cycle impact categories and indicators e.g. global warming potential, acidification etc.);
- Interpretation (analysis of LCIA results, uncertainty analysis, sensitivity analyses, etc.);
- Reporting (LCA documentation and possible critical review).

An LCA is always conducted for specific applications e.g., internal use in companies (for product development, R&D innovative product comparison etc.) or external use (reporting of environmental impact, compliance with regulations, comparative assertions disclosed to public etc.). Most frequently an LCA is conducted in order to compare different variants allowing for determination of which alternative is the performing best seen from the environmental point of view.

Following the definition of the LCA framework in the early 1990ies, some institutions took the lead in the LCA database development, e.g. in Switzerland, and released the first life cycle inventory databases mainly covering energy systems [4]. Following the general development of LCA with background data covering mainly energy systems, many sectors have by now started using the methodology and adapted it to their own requirements.

The following paragraphs briefly provide an overview of LCA applied to building context. At first (section 1.1), the specific standards, guidelines and research projects in the field of building LCA are reviewed. Then section 0 presents specific aspects including system boundaries, databases, indicators, that should be taken into account when performing an LCA within the building field, also providing a brief state-of-art review on exemplary "deterministic" approaches. Section 1.3 especially focusing on the relationship between building LCA and components' Service Life, a key parameter in building renovation projects, impacting the maintenance cycles and renovation plans for a building. Finally, section 1.4 presents a brief summary of the already conducted works on probabilistic approaches in LCA, particularly focusing on the research within the building sector.

1.1 European context in buildings LCA: standards, guidelines and main research projects

A wide range of standards, guidelines and research projects has been established for building LCA at EU-level.

The two generalized international LCA standards – ISO 14040 and ISO 14044 - streamlined the principles, framework, requirements and guidelines for LCA implementation. However, these standards are only general frameworks for LCA, thus further detailed specification are required to avoid the biases in sector-specific and application-specific practical situations.

Due to these considerations, under the coordination of the European Commission's Joint Research Centre (JRC) through the Institute for Environment and Sustainability (IES), the International Reference Life Cycle Data System (ILCD) handbook has been developed in line with the existing LCA standards ISO 14040/44 and the EU policy on sustainability assessment [5]. The ILCD handbook consists of a series of technical documents, which further provides governments and businesses with more specific rules for the LCA implementation regarding life cycle data, methods and assessments. However, these documents are still too general and generic to be used in specific sectors e.g., the construction sector.

Two European standards, EN 15804 and EN 15978 [6,7], were developed providing specific calculation rules for LCAs of construction products and buildings. Both standards illustrate various life cycle scenarios of a building via modular information: product stage (module A1-A3), construction process stage (module A4-A5), use stage (module B1-B7), end of life stage (module C1-C4). In building LCAs, modules A4 to C4 are analysed based on the product information from the module A1-A3; while a wide range of life cycle scenarios from the modules A4 to C4 are either analysed through default scenarios, or by the actual information on the operational input.

The ISO standard 15686 series established the general principles for service life prediction and a systematic framework for undertaking service life planning of buildings throughout their life cycle [8]. The standard is composed of the following parts [9,10].

- ISO 15686-1: 2011 (General principles and framework);
- ISO 15686-2: 2012 (Service life prediction procedures);
- ISO 15686-3: 2002 (Performance audits and reviews);
- ISO 15686-4 (Data requirements/data formats);
- ISO 15686-5:2008 (Life cycle costing);
- ISO 15686-6: 2004 (Procedure for considering environmental impacts);
- ISO 15686-7:2006 (Performance evaluation for feedback of service life data from practice);
- ISO 15686-8: 2008 (Reference service life and service life estimation);
- ISO 15686-9: 2008 (Service life declarations);
- ISO 15686-10: 2010 (Using requirements for functionality and ratings of serviceability during the service life);
- ISO 15686-11 (Terminology).

Over the last two decades, many International or European projects were funded in the field of building LCA. The overall goal of these projects is to promote the LCA implementation in the building sector thus reducing the resources consumption from applying life cycle thinking. Several of these projects developed and harmonized operational guidelines based on the existing ISO 14040/44, EN 15804 and EN 15978 standards.

IEA EBC Annex 31, Energy Related Environmental Impact of Buildings (1996-99) [11], is a project established under the auspices of the International Energy Agency's (IEA) Energy Conservation in Buildings and Community Systems Program, with fourteen participating countries. The project examined how LCA tools and methods could be developed and used to improve the energy-related induced impacts from buildings on interior, local and global environments. The project provided an international directory of current tools, a description of tool theory and methods, research reports on how the individual tools preform along with case studies.

IEA EBC Annex 56, Cost-Effective Energy and Carbon Emission Optimisation in Building Renovation (2011-2015) [12], developed a new methodology for a cost-optimal building renovation towards both the nearly zero energy and nearly zero emissions objective. To develop and support the methodology, generic buildings in each project country have been selected and parametric studies have been performed on them.

It should also be mentioned that a new *IEA EBC Annex 72*, Assessing life cycle related environmental impacts caused by buildings, has been launched in 2016-2017 [13].

Among the EU project, the *REGENER* project (end 90s) [14] defined a common methodology on the LCA applications for buildings and designed a tool box with illustration of case studies. The *PRESCO* project (2004) [15] compared and benchmarked the LCA-based environmental assessment and design tools. The project included two items: the realization of a set of guidelines for sustainable constructions and the definition of recommendations for a more harmonized approach to environmental assessment tools for buildings.

The *IMPRO-Building* project, Environmental Improvement Potentials of Residential Buildings (2008) [16] presented a systematic overview of the environmental life cycle impacts of residential buildings in EU-25, proposed several potential technical improvement options focusing on the energy use for space heating, also assessing the environmental benefits and the costs associated with these improvement options.

The *ENSLIC project,* Energy Saving through promotion of Life Cycle Assessment of buildings (2011) [17,18], promoted the use of LCA in design of new buildings and for refurbishment, thus to achieve an energy saving in the construction and operation of buildings. This action draws on the existing information generated from previous research projects regarding: design for low energy consumption, integrated planning, environmental performance evaluation of buildings, and design for sustainability and LCA techniques applied to buildings. The output, compiled with the collaboration of key target groups, is a set of guidelines along with a methodology which clarifies the various aspects of the LCA, e.g. purpose, benefits, requirements, flexibility and different techniques.

The *LoRe-LCA Project,* Low Resource consumption buildings and constructions by use of LCA in design and decision making (2011) [19,20], aimed to increase the use of LCA for buildings to gather, analyse, valuate and document comprehensive information, by providing a guideline for the practitioners and the decision makers. The project also collected the previous LCA initiatives and compared the use of LCA of buildings in (some) EU countries.

More recently, the project *EeBGuide,* Operational guidance for Life Cycle Assessment Studies of the Energy-Efficient Buildings Initiative (2011-2012) [18,21], developed guidance documents through an online InfoHub on all aspects of building LCAs including the proposal for different calculation rules for screening, simplified and complete LCAs. The guidance document provides recommendations on how to handle specific LCA aspects for buildings classified according to the LCA stages in accordance with ISO 14040 and ISO 14044 and also according to EN 15804 and EN 15978 life cycle stages for buildings.

1.2 LCA methodologies in the building context

As mentioned in section 1.1, several specific LCA methodologies have been developed for buildings and building components and the European context now has a basis for the building LCA methodological rules based on EN 15804 and EN 15978. Other countries have also developed their own rules e.g. Switzerland with the fact sheet SIA 2032 on embodied energy for buildings and SIA 2040 on the Energy Efficiency Path for building LCAs including materials, operational energy consumption and users' mobility [22,23]. This section briefly presents different LCA specific aspects including system boundaries, databases, indicators, that should be taken into account when performing an LCA in the building field.

Concerning the *system boundaries*, depending on the scope of the LCA, the elements to take into account can be drastically different. For instance, in the IEA EBC Annex 56 a specific LCA methodology was defined to compare different renovation scenarios. The LCA methodology only includes the materials and the building integrated technical systems that influence the operational energy consumption i.e., to simplify the LCA approach only the insulation materials and heating and domestic hot water technical systems were included.

LCA of building components generally comprises, next to the inventory of construction materials, their influence on the heating energy demand. Component LCAs are generally simplified approaches adapted to the scale of the analysis (the building component) compared to a full building LCA.

In several studies, authors investigated the relevance of simplifying the calculations by neglecting elements of various life cycle stages. For instance, Kellenberger et Althaus [24] have assessed the relevance of simplification in the LCA of building components based on ecoinvent LCI data. The authors found that the transportation to the building site and the ancillary materials are of relevance while the building process and the cutting waste can be neglected. In addition, they found that the heavier the used materials and the longer the transport distances the bigger is the influence of transports on the LCA results.

More recently, Hoxha et al [25] conducted an LCA study taking into account the mass of each material used for the construction of the building, the environmental impact of each material and the number of times each material has to be replaced during the building lifetime (determine through the material's service life). It revealed that the most influential parameters for the building LCA results are the service lives of materials and their related environmental impacts.

A comparison between three different LCA methodologies for building energy refurbishment has been conducted by Oregi et al. [26], taking into account a decreasing number of stages, in order to determine which methodology is more accurate and time effective for decision making. The full LCA included all the stages defined within EN 15978 (A1-5, B1-7 and C); the Simplified LCA focused only on the evaluation of the product (A1-3), replacement (B4) and operation energy use phase (B6); and finally an Operational Stage Assessment focused only on the operational stage of the building. The results of this assessment showed that simplified LCA methodologies can be accurate enough for decision making/support in building energy refurbishment.

According to a recent review of Vilches et al. [27], the more frequently studied life cycle stages in the building renovation sector are those related to Modules A1-3 (product stage) and B6 (energy use stage).

Different *databases* are currently used for assessing the environmental impacts of buildings and building components. Two types of databases exist for practitioners:

- *Background LCI databases*. They describe the supply chain of the energy carriers or material production processes (e.g. *ecoinvent* [28]). In such databases, it is possible to propagate uncertainties related to background processes.
- *LCIA databases for sector-specific uses*. In the building sector, more and more LCIA databases are being developed in Europe in the framework of EN 15804 (see e.g., a review in [29]). In Switzerland, a similar initiative is also being developed with the KBOB list of recommendations [30,31]. These data only present impact value per functional unit that can be used by practitioners to do building. It is not possible to modify the background data as the database does not allow for it. Similarly, it is not possible to directly address the uncertainty of the supply chain.

Lasvaux et al. [32] compared two LCA databases for buildings: the *ecoinvent* generic database and a French EPD database, through the calculation of 28 types of building materials in compliance with EN 15804. It has been found the generic and EPD databases can result in very different values at the database scale which depend on the type of environmental indicator. For building LCA results, the situation is different as a limited number of materials control the impacts. Finally, recommendations are presented for each environmental indicator to improve the consistency of the building LCA analysis in terms of the generic and EPD database.

Martìnez-Rocamora et al. [33] carried out an extensive review of existing LCA databases containing data on building materials, detecting that results, e.g. on Cumulative Energy Demand (CED) for the same material) noticeably fluctuate depending on the database used. The authors underline that it does not seem possible that the manufacturing characteristics for the different countries, where the LCA studies have been made, may vary that much, which makes it necessary for in-depth research into the sources to be carried out.

Many Life Cycle Impact Assessment (LCIA) *Indicators* have been developed in building LCA, describing environmental impacts (global warming, ozone depletion, acidification, etc.), resource use (energy and raw materials depletion, etc.) or additional environmental information (hazardous waste, etc.). Some documents, such as EN 15978, recommend using a wide range of indicators.

In building LCAs, the basis of choice of indicators often depends on what is easily comprehendible by the stakeholders involved, in comparison to what may be more relevant to the goal. According to a review by Anand et al. [34], similar to LCA's in other fields, energy and emissions are the most popular metrics used in the building LCA publications .

As mentioned in the beginning, the application of LCA in the building sector needs dedicated *tools* for architects and engineers. Building LCA tools developed in the EU are normally based on EN 15804 and EN 15978 standards. Various tools have been developed so far, most of them being based on existing LCA methodologies. A review of European tools conducted in the *EeBGuide* European project presents them in detail [35]. In Switzerland, based on the SIA 2032 and SIA 2040 technical books [22,23], design tools have also been developed for building LCAs or building component LCAs (e.g., *Lesosai Eco tool* or *Ecosai tool* [36,37]). In most of the tools, the use of a probabilistic approach is currently missing or not considered. The tools calculate the environmental impacts using a deterministic approach.

Recent and comprehensive reviews of studies in the field of building LCA are reported in [27,34,38,39]. Among existing LCA studies, there is not a lot of research addressing historic buildings specifically. This pattern can be explained by the limited historic building stock compared to the newer building stock. A recent review on this specific topic is reported in [40].

1.3 LCA and building components Service Life

The service life of a building component is a key parameter for planning the maintenance cycles and renovation plans for a building. It is a parameter that influences the replacement rates and maintenance cycles in the LCA of internal insulation renovation scenarios.

EN 15804 and EN 15978 define the operations for building materials occurring during the use phase in different modules. Modules B2, B3, B4, and B5 correspond respectively to maintenance, repair, replacement and refurbishment actions occurring in the LCA of a building element. According to the *EeBGuide* [41], in the case of sound statistical feedback on the replacement rate of a specific product for a given country or region, it is unlikely that a clear distinction between the causes of replacements can be easily made. In that EeB specific case, replacement causes would naturally encompass all cases: i.e. premature failure, failure due to foreseeable ageing and obsolescence.

Figure 1 presents an illustration of the different operations during the use phase (maintenance, reparation, replacement and refurbishment) taken into account in EN 15804 and EN 15978.

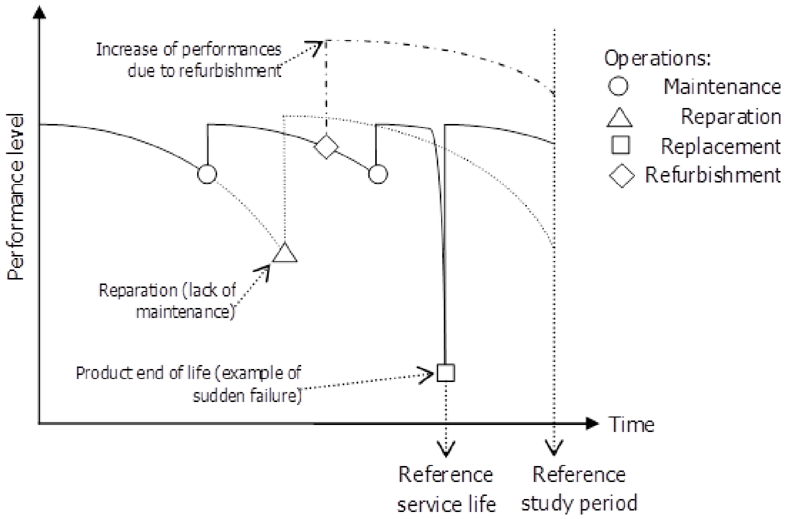


Figure 1 : Exemplary case of different performance levels of a building component across time depending on maintenance, reparation, replacement and refurbishment operations (taken from the EeBGuide InfoHub)

This figure is mainly of explanatory nature, but applied to other cases, such as:

- performance stability over the reference study period;
- overall decrease of performance despite maintenance operations;
- failure at implementation.

Furthermore, as stated by EeBGuide, "*service life planning can only address foreseeable changes. Since service life planning is concerned with foreseeable risks, it is not applicable to the estimation of obsolescence […] or to defective performance resulting from unforeseeable events or processes*".

Indeed, many factors influence the service life of a building element. The end of service life has been defined for various contexts, such as the physical deterioration, the economic obsolescence, the functional obsolescence, the political decisions and the aesthetics [42–45].

Many methods have been proposed for estimating the Reference Service Life (RSL) and Estimated Service Life (ESL) of building components and detailed in ISO 15686 and [45]. Overall, the transition from reference service life to estimated service life can be mainly generalized in three ways: 1) factor method; 2) engineering method; 3) stochastic method [46]. All methods attempted to consider the degradation process, a key parameter in the service life estimation.

Ideally, it is preferable to use the controlled experiments (or preferably the real-life data) simulating the degradation and the structural durability. Various regression techniques can be applied to fit on a set of sample data collected either from the empirical test or the real life. But in reality, the laboratory tests are not practical [47,48].

Therefore, many studies proposed to model the structural degradation as a stochastic process, where the variability of the degradation process of the structural components is analysed via advanced probabilistic algorithms. These methods are well illustrated in [45,46]. Among all the probability modelling, the Markov chain model is the most commonly used method but more often applied in bridge engineering in structural health monitoring other than on buildings. While some other approaches, for example, the fuzzy logic set, Bayesian theorem and decision tree were also reported in the building sector. Besides, some the advanced computational models, for instance, the artificial neural network models based on the explanatory variables were also used to analyse the severity of degradation process. Overall, these methods focus on modelling the structural durability and the degradation behaviour over time.

A number of authors used the random variables to describe the complexity of the degradation phenomenon, for instance, Lounis et al. [49] developed a discrete Markov chain model to analyse the performance of roofing components. Winden and Dekker [50] proposed a Markov decision model to rationalize the building maintenance plans. Duling [51] applied the neuro-fuzzy artificial intelligence method to supplement the historic data for the development of Markovian transitional probability matrices, to determine the service life based on the condition changes over time and the effects of maintenance levels of buildings. Silva et al. [45] used artificial neural network model to estimate the service life of claddings based on their degradation. Talon et al. [52] determined the service life from the degradation scenario based on failure modes and effects analysis (FMEA). Frangopol et al. [53] applied the Markov chains method on studying the structural deterioration under various maintenance plans. Liang et al. [54] suggested the prediction of bridge service life based on the fuzzy logic method. Faber et al. [55] proposed the probability method of fault and decision trees, to evaluate the structure deterioration level until the failure.

However, the pure probabilistic models are complex and data demanding. Therefore, the factorial method, originally established in Japan and ruled by the international standard ISO 15686-1 [56], is a main approach today for the service life estimation.

The estimated service life (ESL) is defined as the multiplication of a reference service life (RSL) by various durability factors, concerning the characteristics of the elements under analysis, according to the following Eq. 1. The RSL is the basic value for application of the factor method, together with specific values of the individual durability factors included. The meaning of each factor is defined in ISO 15686-7 [57] and also explained in [45],

$$ESL = RSL \cdot A \cdot B \cdot C \cdot D \cdot E \cdot F \cdot G$$

Eq. 1

Where,
ESL is the estimated service life;
RSL is the reference service life;
A is the factor related to the quality of the materials;
B is the factor related to the design level;
C is the factor related to the execution level;
D is the factor related to the internal environmental conditions;
E is the factor related to the external environmental conditions;
F is the factor related to the in-use conditions;
G is the factor related to the level of maintenance;

According to [45], these durability factors, can be expressed by two approaches:

- The deterministic approach (the classic approach), whereby scenarios via the absolute values are specified deterministically to quantify the durability factors. The deterministic approach is simple to use, but has its drawback on the lack of consideration for the complex degradation processes, examples of its application can be found in [58–61];
- The engineering approach, by adjusting a probability distribution for each durability factor, thus resulting in the estimated service life expressed by a probability distribution. Examples can be found in [46,62].

Silva et al. [63] proposed a comprehensive methodology regarding the building service life prediction including the engineering method. Marteinsson et al. [64] detailed the methods for the building service life prediction, based on the degradation model and the factor method.

Several authors investigated the impact of the uncertainties on service life parameters on the building LCA [61,65–68].

In the application of the factorial method, RSL is a key parameter to specify. It can be determined based on various sources including for instance, the experts opinion, previous experience, knowledge of buildings and components' behaviour subjected to similar conditions [59,69], scientific research, regulations and building standards (with conventional or recommended service lives data to use), technical information from producers, laboratory tests and statistical analysis [67,69,70]. In addition, investment banks, professional building owners or tenants also provide service lives data.

By way of example, in the tables reported in Appendix 1, reference values for service lives of building materials, especially insulations, are presented, coming from different sources and different bodies, including the environmental products declarations (EPDs).

1.4 Probabilistic approaches to LCA in the building context

LCA procedures applied to energy renovation measures for historic buildings may suffer from several intrinsic uncertainties, also considering the long-term perspective of the interventions and the presence of several constraints, that oblige the renovation measure to respect the integrity, authenticity and compatibility between the old and the new materials and techniques.

For this reason, taking into account uncertainty and variability in LCA has been identified as one of the key challenge to improve the reliability of decision making [71,72]. While in some fields of engineering and computing sciences uncertainty assessments are part of standard framework, in LCA, only little has been done and international standards are not extensive regarding this aspect. Studies on building LCA are usually performed considering "deterministic" data inputs for practical reasons e.g., the lack of simulation tools capable of performing a probabilistic LCA, the challenges on the involvement of vast amounts of data in the calculation, the absence of guidance in the existing standards, or insufficient data samples to perform the uncertainty modelling. As a result, the inherent uncertainties are rarely considered. Nevertheless, proper uncertainty management allows for more robust results and conclusions in support of science-based decision-making [72].

When dealing with uncertainty, any LCA practitioner is basically faced with three problems [73]:

- at the input step: uncertainties need to be identified, e.g., how large are they? This is the uncertainty characterisation phase;
- at the processing step: how do we translate input uncertainties into output uncertainties? This is the uncertainty propagation phase;
- on the output side: how can we visualize and communicate uncertain results, and how influential is each input? This is the uncertainty and sensitivity analysis phase.

1.4.1 Uncertainty and variability consideration

A practical problem when dealing with uncertainty in LCA is that the terminology (e.g. the definition of uncertainty, variability, sensitivity) is confusingly non-standardized [73]. Different authors developed frameworks to classify different types of uncertainty and variability in LCAs [73–77].

In a recent review, Rosenbaum et al. [72] proposes a pragmatic approach for the use in LCA in practice, even not always covering all aspects around statistical concepts. They use the definition of *uncertainty* as comprising everything they do not know, expressed as *the probability or confidence for a certain event to occur*, including both random and systematic errors, mistakes, and epistemic uncertainty. They mean *variability* as the variety or spread in the data that can be observed, measured and quantified, but never reduced. Table 1 presents examples of uncertainty classification in LCA according to several studies.

Table 1 Uncertainty classifications in LCA according to several studies

Huijbregts 1998 [74]
Parameter uncertainty
Model uncertainty
Uncertainty due to choices
Spatial variability
Temporal variability
Variability between objects and sources
Bjorklund 2002 [77]
Data inaccuracy
Data gaps
Unrepresentative data
Model uncertainty
Uncertainty due to choices
Spatial variability
Temporal variability
Variability between objects and sources
Epistemological uncertainty
Mistakes
Estimation of uncertainty
Huijbregts 2003 [78]
Parameter uncertainty
Model uncertainty
Scenario uncertainty
Lloyd 2007 [76]
Parameter uncertainty
Model uncertainty
Scenario uncertainty
Baker 2009 [75]
Database uncertainty
Model uncertainty
Uncertainty in preferences
Uncertainty in a future physical system, relative to the designed system
Statistical/measurement error

In the review of Lloyd et al. [76], the authors underlined that, in the majority of works dealing with uncertainty in LCA, the consideration of uncertainty simply ranged from descriptions of variability and uncertainty to frameworks for considering or reducing uncertainty. In the minority of studies that really used probabilistic LCA to evaluate a product system and quantified uncertainty in an inventory or impact outcome, Lloyd et al. could categorize uncertainty simply as *parameter*, *scenario*, or *model* uncertainty. This classification is widely used in many fields of applications and most of the uncertainty types listed in Table 1 are essentially sub-classes of these three types [72].

Parameter uncertainty includes the variability and uncertainty relating to model input parameters. *Model uncertainty* indicates the uncertainty of the model itself and equations used. *Scenario uncertainty* can be interpreted as uncertainty in the application of the model under predefined conditions and assumptions. Whereas parameter and model uncertainty contribute to the uncertainty of the numerical model results, scenario uncertainty may also contribute to uncertainty in the interpretation of the model results and, hence, that of a consequent decision [72].

Among the studies on the LCA uncertainties for buildings, most studies focused on *parameter uncertainty* (such as building materials quantities or impacts, the energy mix evolution, the service life data, etc.), whereby the *scenario* or the *model* uncertainty is rarely studied. According to Chouquet et al. [79] uncertainty sources in building LCA models can be defined as follows: (i) environmental data quality (incomplete, inaccurate, obsolete), (ii) building description (incomplete, inaccurate), (iii) building lifespan and components service life (assumptions on lifespan, degree of refurbishment) and (iv) building operation (performance of heating equipment, long term evolution of costs and resource depletion, etc.)

Parameter uncertainty is essentially the most accessible uncertainty type and therefore the most frequently assessed type of uncertainty in current LCA practice and also in recent LCA standards. For example, in some Environmental Product Declaration (EPD) studies conducted according to a standardised model and scenarios (according to EN 15804), most of the uncertainties remains linked to the input parameters. As an illustration, there is in France a new regulation on EPDs for building products requiring uncertainty and sensitivity analysis when groups of manufacturers' EPDs have to be calculated [80]. The calculation procedure is defined in a national addition (NF EN 15804/CN) to the core standard EN 15804. The analysis is conducted for at least three environmental indicators (greenhouse gas emissions, primary non-renewable process energy, non-hazardous waste). The aim is to characterize the variability (or the aleatory uncertainty) of the EPD. Then, if the impact value at 95% of the distribution is above 1.4 time of the mean value, the group of manufacturers is allowed to report the average value of the EPD. In the other case (i.e., where the variability is more important), the value at 95% must be reported in the EPD. By doing so, the regulation aims at avoiding that too many manufacturers with different environmental performances of their products be averaged in a single LCA and EPD data.

1.4.2 Methods for uncertainty characterisation and propagation

The uncertainty related to a model input parameter can be conceptualised by a probability distribution. The probability distribution of a continuous variable is the probability density function (PDF) measured over a range from a minimum to a maximum value. The shape of the PDF varies depending on the frequency of the values of the variable. Typical examples of shape patterns of continuous distributions are normal, uniform, log-normal, beta, triangular, etc.

Uncertainty assessment requires quantifying the PDF of the model's input parameters. One of the major limitations for the development of uncertainty assessments in research field such as LCA is the difficulty to access sufficient sample data in order to properly define the PDFs. For the characterisation of uncertainties in LCA, authors usually distinguish among *quantitative approaches* and *qualitative approaches*.

Quantitative approaches consist on define the parameters' PDF based on available reliable data provided by literature research, measurements or expert judgement. Estimation of the range is closely associated with fitting data into the number of known families of probability distribution functions.

Several authors [61,81–84] especially focused on the application of probabilistic methods to characterise the building components service life. Re Cecconi [46,62] considered the durability factors of the probabilistic factorial method as expressed by triangular distributions and applied the Monte Carlo simulation to calculate the PDF of building components service life.

Among the *qualitative approaches* in LCA, we find the *pedigree matrix data quality approach* developed by Weidema et Wesnaes [85], which proposes data quality indicators in combination to scores. These scores can be transformed into estimates of the additional uncertainty due to the insufficient data quality. An uncertainty factor (expressed as a contribution to the square of the geometric standard deviation) is attributed to each of the scores, based on expert judgements. In the qualitative approach, the flows are characterized by a grade from 1 to 5, according to five criteria relating to the overall reliability of the data.

Qualitative approaches can also be "converted" into quantitative numbers by applying one uncertainty value for each criterion and an overall PDF function can then be defined. This approach has been developed and proposed by Frischknecht [4] and used in the *ecoinvent* database for the life cycle inventory data of a process. A simplified standard procedure has been developed there to quantify the uncertainty of the amount of a specific input or output in the cases (quite numerous) that it cannot be derived from the available information, since there is only one source of information that provides only the mean value, without any information about the uncertainty of this value. Thus, for each flows of an inventory, in *ecoinvent*, a score for the five indicators is given. Then, based on these scores, the pedigree matrix gives numerical values to be considered together for the calculation of the flow uncertainty (Table 2).

Table 2 Default uncertainty factors (contributing to the square of the geometric standard deviation) applied together with the pedigree matrix. From [86]

Indicator score	1	2	3	4	5
Reliability	1.00	1.05	1.10	1.20	1.50
Completeness	1.00	1.02	1.05	1.10	1.20
Temporal correlation	1.00	1.03	1.10	1.20	1.50
Geographical correlation	1.00	1.01	1.02		1.10
Further technological correlation	1.00		1.20	1.50	2.00
Sample size	1.00	1.02	1.05	1.10	1.20

In addition, a basic uncertainty is added. This basic uncertainty is based on expert judgement and depends of the type of considered processes. Once the pedigree matrix is filled and the basic uncertainty selected, the uncertainty related to the flow is calculated as follow in Eq. 2:

$$SD_{g95} = \sigma_g^2 = \exp^{\sqrt{[\ln(U_1)^2]+[\ln(U_2)^2]+[\ln(U_3)^2]+[\ln(U_4)^2]+[\ln(U_5)^2]+[\ln(U_b)^2]}}$$

Eq. 2

With:
U_1: uncertainty for reliability
U_2: uncertainty for completeness
U_3: uncertainty for temporal correlation
U_4: uncertainty for geographic correlation
U_5: uncertainty for other technological correlation

U_b: basic uncertainty

This formula yields the geometric standard deviation based on the pedigree matrix approach and is applied in *ecoinvent* by considering that the flows are lognormally distributed. Further details can be found in Mutel [87].

The Uncertainty Analysis (UA) evaluates the distribution of the output as a result of the possible variance of the input parameters using uncertainty propagation methods. Generally speaking, Monte Carlo simulation is the most often applied approach in building LCAs. In MC methods, every input parameter is considered as a stochastic variable with a specified probability distribution. The distribution of the outcomes is calculated by running the model a number of times with randomly selected parameter representations (or according to precise sampling schemes). The potential of effectiveness of MC methods are widely documented in the activities of Annex 55 [88]. They can be briefly summarized as:

- the possibility to use various parameter distributions (different types of PDFs or discrete variables) in the models;
- the possibility to manage complex and non-linear models;
- the computational efforts needed to increase the quality of the output can be reduced by using efficient sampling techniques and/or developing more efficient models (or metamodels).

In conventional Monte-Carlo-based uncertainty analysis (with basic random sampling), repeated calculations of the output equation with different input draws produce a distribution of the output values, reflecting the combined parameter uncertainties. A minimisation of the number of required Monte Carlo runs can be obtained through sampling strategies, that allows attaining such desired accuracy levels with a minimal number of simulation runs. Among sampling methods, we cite Latin hypercube sampling, whose superiority over random sampling has been already corroborated [89] and quasi-random sampling (e.g. Sobol's sequences) [90].

Several authors applied the stochastic modelling of the Monte Carlo algorithm to study the uncertainties of the parameters, and the pedigree matrix approach on the quality of the data [67,91–94]. Chouquet et al. [79] discussed several available analytical methodologies for the uncertainty analysis in building LCA, especially focusing on Monte Carlo simulation. Favi et al. [95] proposed a probabilistic approach to building retrofit measures LCA including: (i) quantification of data input uncertainties in terms of their Probability Density Functions; (ii) input sampling and propagation through Monte Carlo methods; (iii) analysis of the output distributions.

Despite the above mentioned commonly used methods, other probabilistic approaches are also available for the uncertainty quantification, such as the fuzzy set theory, Taylor series expansions, Bayesian theorem, the first-order second-moment (FOSM) method, decision tree model and the Markov Chain modelling etc. However, their application in the building LCA is still rare. In some examples, Taylor series expansion are used to investigate the uncertainty parameters on building LCA [25,96], or Monte Carlo is coupled with Markov Chain Modelling [47].

1.4.3 Methods for Sensitivity analyses

Sensitivity analysis (SA) goes one step further compared to the uncertainty analysis by apportioning the output variations to the input variations. Sensitivity Analysis can be then performed to establish how sensitive an output result is to an input change and which input uncertainty contributes most to the result uncertainty [97,98].

Local Sensitivity Analysis includes methods for the estimation of the sensitivity as the effect of a certain change in input on the output by varying one parameter at a time or by parameter variation around their nominal value.

Many publications have presented these methods for handling sensitivity analyses. For instance, in building LCA, Junnila et al. and Cousins-Jenvey et al. [99,100] performed a sensitivity analysis by using the best, average and the worst values on selected parameter. Oregi et al. [26] performed a sensitivity analysis by combining the extreme values of the dominant parameters on 32 refurbishment scenarios. In whole building LCA studies, a recent work conducted by Pannier et al. [101] looked at the influential parameters in a decision tool linked dynamic energy simulation and LCA for buildings. The authors used the Morris method to solve the computational and time costs issue while not decreasing the accuracy of the sensitivity analysis. Other examples are reported in Chouquet et al. [102], Aktas et al. [67], Baker et al. [75].

While they are straightforward to implement, these types of SA are not representing completely the parameter influences. Furthermore, although the computational cost of these methods is low, they can be highly biased for non-linear systems. Therefore, the reliability of their application is not guaranteed [103].

That is the reason why researchers have also investigated more robust *Global Sensitivity Analysis* (GSA) methods, including e.g. Variance based decomposition (such as the calculation of Sobol Indices). These methods consider the range of variation of input parameters as a function of their uncertainty, varying them all at the same time. Detailed and clear information and review on the various SA methods can be found in [104] and their synthesis is reproduced in Figure 2.

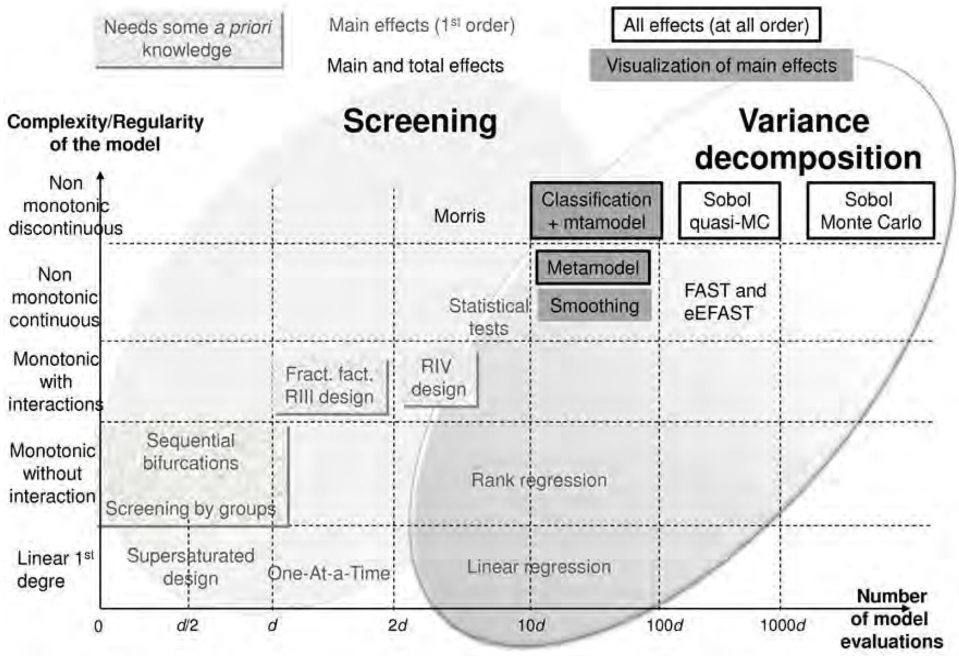


Figure 2 SA method. Graphical synthesis from [104]

According to the model complexity (and the SA objectives too), the type of SA will differ and the number of model evaluation will increase with the model complexity. In practice, for complex models, computational costs can be a barrier to the applicability of uncertainty and sensitivity assessment especially when dealing with GSA. Thereby, in addition to the proper choice of the method, sampling strategies need to be properly defined. In some cases, simplified models can be of strong interest to reduce the calculation costs, interesting insight and information can be found in [105].

Recently, Global Sensitivity Analysis approaches have been used in the field of LCA. Padey et al. [106] applied the GSA to define a simplified LCA for wind power electricity. The methodology relies on the application of global sensitivity analysis to identify key parameters explaining the impact variability of systems over their life cycle. Simplified models are then built upon the identification of such key parameters. Lacirignola et al. [107] developed an interesting methodology to analyse the sensitivity of the GSA results (i.e. the stability of the ranking of the inputs) with respect to the description of such inputs of the model (i.e. the definition of their inherent variability) and applied it to geothermal systems, enriching the debate on the application of GSA to LCAs affected by high uncertainties. To our knowledge, development of a comprehensive application of GSA methods in the field of buildings is still pending.

1.5 Conclusions

As demonstrated in the *section 1.1*, several specific LCA methodologies have been developed for buildings and building components and the European context now has a basis for the building LCA methodological rules based on EN 15804 and EN 15978.

From the brief analysis performed in *section 1.2* on the specific aspects, e.g. system boundaries, databases, indicators, that should be taken into account when performing an LCA in the building field, some general considerations were drawn and used in the following development of the specific WP5 probabilistic LCA approach.

From the literature review, it arose that the more frequently studied *life cycle stages* in the building renovation sector are those related to Modules A1-3 (product stage) and B6 (energy use stage). Several authors demonstrated that simplified LCA methodologies, limited to those stages, can be of sufficient accuracy for decision making in building energy refurbishment.

Even if many LCIA *Indicators* have been developed in a building LCA, the basis of choice of indicators should depend on what is easily comprehendible by the stakeholders involved, in comparison to what may be more relevant to the goal. According to the state-of-art, similar to LCA's in other fields, energy and emissions are the most popular metrics used in the building LCA publications.

It was also highlighted how data for building materials included into LCA *databases* noticeably fluctuate depending on the database used, thus affirming once again the importance of conducting LCA based on probabilistic approaches.

Section 1.3 especially treated the relationship between building LCA and components Service Life, a key parameter in building renovation projects, impacting the maintenance cycles and renovation plans for a building. In particular, the potential of the probabilistic factorial method in the field of building components service life characterisation has been presented, paving the way for its application into a comprehensive probabilistic building renovation LCA.

Finally, *section 1.4* presented a brief summary of the already conducted works on probabilistic approaches to LCA, particularly focusing on the researches performed in the building sector. As seen, the definition of uncertainty and variability in LCA is confusingly non-standardized [73]. Different authors developed frameworks to classify different types of uncertainty and variability in LCAs. *Parameter uncertainty* is essentially the most accessible uncertainty type and therefore the most frequently assessed type of uncertainty in current LCA practice and also in recent LCA standards. Generally speaking, *Monte Carlo simulation* is the most often applied approach in probabilistic LCA, even if its application for the uncertainty and sensitivity analysis in the building LCA are still very limited. As a consequence, existing building LCA studies or building LCA tools rarely consider systematic uncertainty and sensitivity methods for improving the credibility of results. So, there is a need to tackle this issue more comprehensively by developing a robust probabilistic LCA methodology where the users are made aware of and try to “quantify” the uncertainty related to the results.

Next Section 2 then presents the specific probabilistic LCA methodology developed in the field of internal insulation solution of historic buildings, following the main problems that are commonly encountered when dealing with “uncertainty” in a specific model, calculation or process: its characterisation, propagation and analysis. Even if specific assumptions are made for the LCA performed at the “component level” (the internal insulation solution), the methodology developed is a robust example of probabilistic approach to LCA, that could find other interesting applications in the building refurbishment sector.

2 Development of a probabilistic methodology for the LCA of internal insulation solutions in historic buildings

In this section, the probabilistic LCA methodology (PM) developed within RIBuild Task 5.2 for the assessment of internal insulation solutions of historic buildings is described. The PM is useful to:

- provide decision support during the design phase, giving insight into design robustness and possible ranges of performance indicators (environmental impacts) of a specific design option (the insulation solution);
- investigate and compare different design options (types and thicknesses of insulation solutions). The methodology can be applied e.g. to estimate the level of confidence that insulation option A performs better than option B (e.g. by comparing output distributions for each of the two alternatives), or in general to identify the best performing alternative minimizing the likelihood of exceeding environmental thresholds;
- provide an idea of the significance of input parameters' uncertainties and their impact on the result (through sensitivity analysis).

This section reports the main phases of the PM for LCA of internal insulation solutions in historic buildings developed, following the main problems that are commonly encountered when dealing with "uncertainty" in a specific model, calculation or process: the uncertainty characterisation, its propagation and analysis, the sensitivity analysis.

This section especially reports the specific assumptions made for the LCA performed at "component level" (internal insulation solution level) and the calculation inputs included in the assessment. Subsequently Monte-Carlo methods for the uncertainty propagation and sensitivity analysis are described.

Exemplary cases of the PM application are then reported in section 3 to illustrate its potential and possible uses also in view of future developments of RIBuild web tool in WP6. The methodology has been implemented in the WP5 software tool, described later in section 4.

2.1 Goal and scope for the LCA

The goal and scope for the LCA are defined based on the discussion among Task 5.2 partners originated from the literature review performed and from some preliminary exercises on "deterministic" LCA of insulation solutions in historic buildings carried out at the early stage of the Task and reported in Appendix 4.

The probabilistic LCA is performed at "component level" and is based on the procedures defined in ISO 14040-14044 and EN 15804 and EN 15978 standards.

The goal of the study is to assess the environmental impacts of internal insulation measures installed on historic building facades. The functional unit (FU) is defined as *"the insulation intervention using several possible internal insulation systems and technologies needed to cover 1 m^2 of facade for a building reference study period*[5] *expressed in years*".

[5] Conventional term introduced in EN 15804 and EN 15978. In other parts of the document that term is used in an equivalent manner to "calculation period".

The functional unit for the LCA of a building component can comprise several functions depending on the goal of the study. In the PM developed, there are no mandatory functions integrated in the FU, but in the next project progress within WP6, depending on the results of the hygrothermal assessments of internal insulation solutions, different requirements could be defined along with the FU, e.g. a maximum (or given) insulation thickness below which there is a low moisture risk; or an insulation thickness compliant to a given U-value (based on renovation standards) if there is no moisture risk.

The scope of the study comprises the assessment of the environmental impacts of construction materials and the transmission heat losses assuming a given energy scenario, e.g. a heat source to convert the energy needs in final energy. The impacts of the new internal insulation systems after renovation cover next to the manufacturing and dismantling at the end-of-life, the use phase impacts related to the possible needs for maintenance and replacement of material layers or of the whole insulation system.

As the distinction between modules B2 (maintenance), B3 (repair), B4 (replacement) is not straightforward in EN 15804 and EN 15978 standards, *EeBGuide* guidance[6] recommends, based solely on the distinction between the causes of end of life related to performance decrease over time (e.g. aging, decay, degradations, etc.):

- causes related to foreseeable events (i.e. related to reference service life) under a defined set of conditions leading to maintenance and replacement scenarios;
- causes related to unforeseeable events leading to repair scenarios.

As addressed by *EeBGuide*, the maintenance should be understood as the set of operations performed under normal conditions in each context (e.g. maintenance of a product could change depending on the climate).

So, in the PM developed, the maintenance measures can vary depending on the study context (country, location, type of wall and insulation system). At the aim of the probabilistic LCA of internal insulation on historic building, the *maintenance* is considered as the need of periodic replacement of the internal finishing material, i.e. the rendering or the painting, which depends on these specific materials' estimated service lives. Instead, *replacement* involves the whole insulation system, according to its estimated service life.

As a result, the following life cycle stages are included in the RIBuild LCA methodology: the production stage (modules A1-A3), the use stage (modules B2 maintenance, B4 replacement and B6 operational energy use) and the End of Life (EoL) stage (modules C1-C4), as summarized in Figure 3.

According to the state-of-the-art and the initial "deterministic" LCA of internal insulation measures performed by Task 5.2 partners (reported in Appendix 4), it seems that the relevance of the construction processes be of little relevance in the LCA of building components (as also demonstrated by [24–27]). The End of Life stage (modules C1-C4) was finally included in the methodology, considering the major difference found in literature regarding this stage [27], but in a logic of flexibility, the WP5 software users can decide to neglect this stage, according to the goals of the analysis.

[6] https://www.eebguide.eu/?p=3623

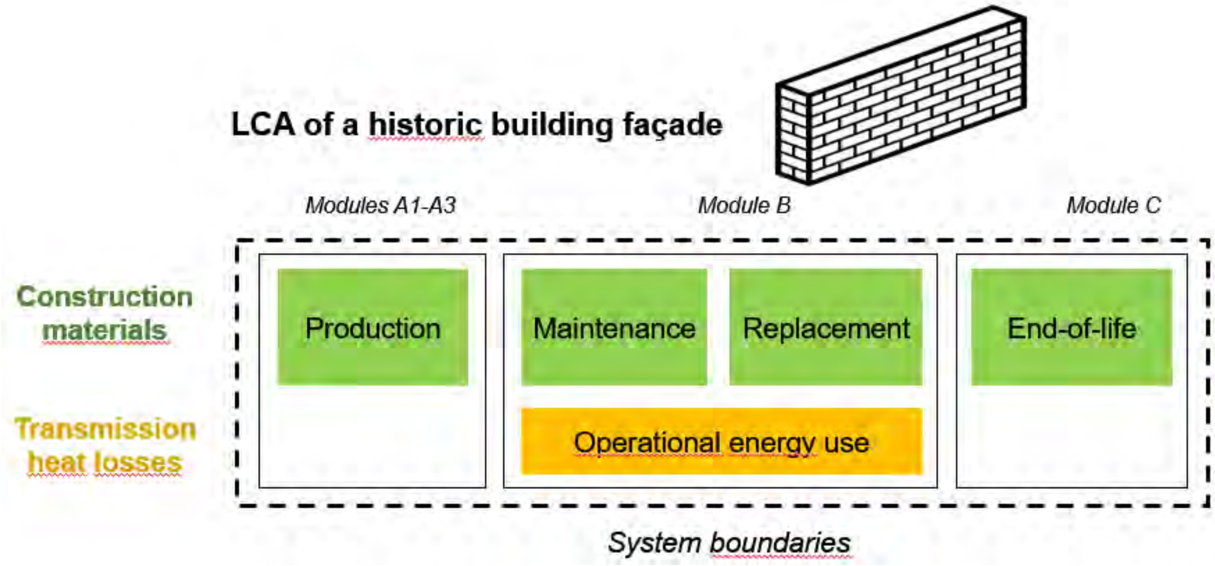


Figure 3 System boundaries for the LCA

The LCA data used to model the environmental impacts of an internal insulation renovation are normally defined in a national context using available product specific data provided by companies producing market available insulation systems. If the LCA data are not available for a country, European average data can be used instead, as available in LCI databases like e.g. *ecoinvent*, *Gabi*, *ELCD*.

The allocation rules and other methodology rules for the LCA of a building element are based on EN 15804 and EN 15978 requirements and are not described in more details here.

The LCA is calculated for at least two environmental indicators namely the Climate Change and the non-renewable Cumulative Energy Demand (CED_{NRE}) according to [4]. These indicators, clear and understandable also to building designers LCA non-experts, have been selected based on the literature review and considering the specific system under analysis. Since the study is addressing building renovation measures, energy and natural resources are of primary importance. To address these perspectives, this study uses Human Health and Resources mid-point impact categories from the internationally accepted impact assessment method ReCiPe [108]. The climate change impact category within the ReCiPe mid-point method includes all greenhouse gases specified in the Kyoto Protocol using global warming potentials from the IPCC Fourth Assessment Report with a 100-year time horizon [109]. The cumulative energy demand (CED) method [110] is used, additionally, as a single-issue indicator to evaluate energy demand associated with a product's life cycle. The default ReCiPe mid-point method perspective used is the Hierarchist (H) version referred to the normalisation values of Europe. Perspective H is based on the most common policy principles concerning 100 years' timeframe (as referenced in the ISO 14044 standard).

As reported in section 4, the software tool developed, implementing the LCA probabilistic methodology, allows the user to use an additional third indicator at his choice.

2.2 Initial requirements for the probabilistic methodology

2.2.1 Multi-layer sampling scheme as a framework

Within the LCA PM, it is proposed to sort out the LCA simulation parameters, related to several design options under several possible simulation scenarios, according to a *multi-layered sampling scheme* proposed by Van Gelder et al. [111]. This approach is based on the necessity to manage and combine multiple design options (the internal insulation systems), to subject all design options to the same uncertainties types and to check the validity of results in potential scenarios (subject to different uncertainties) (Figure 4).

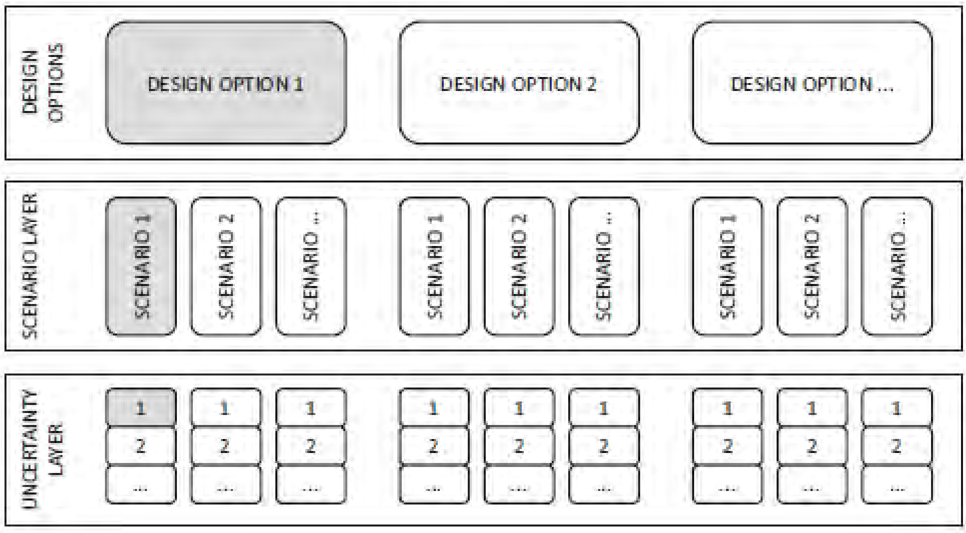


Figure 4 Multi-layered sampling scheme according to [111]

Applied specifically to the context of the LCA of internal insulation renovation of historic buildings, a schematic illustration is provided in Figure 5 to illustrate this approach for four possible design options (insulation solutions), installed in a specific wall configuration, and under four different energy scenarios for the heating system. With the approach presented in Figure 5, it is possible to compare the performance of several design options under the same scenario and/or assess the performance of a specific design option under different possible scenarios.

It should be noted that in this simplified illustration, only the energy sources are assumed to belong to the scenario layer, while, in reality, further possible scenarios can be included in the assessment, i.e. several reference study periods.

According to this approach, three simulation layers are distinguished:

1. The **design options layer** contains the design options, which are the internal insulation solutions, with specific design levels (insulation thicknesses). The internal insulation solutions and their design levels may be different from country to country. In the PM, the design options are "deterministically" identified, but once selected, their related input parameters are subjected to uncertainties (in the uncertainty layer).
2. The **scenario layer** contains the alternative simulation scenarios. Each design option can be evaluated considering different building reference study periods, application configurations (original walls) and energy scenarios (possible energy sources and consequently energy

impacts). These scenarios are, again, “deterministically” identified, but once selected, their related input parameters are subjected to uncertainties (in the uncertainty layer).
3. The **uncertainty layer** contains all the inherently uncertain parameters related to the design option and scenario choices.

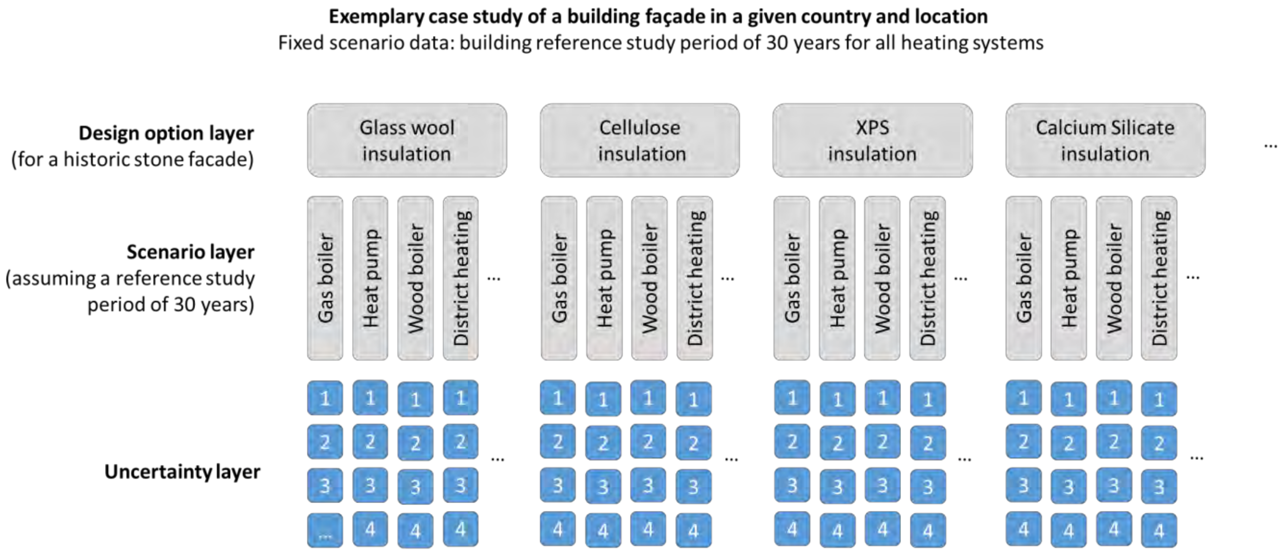


Figure 5 Multi-layered sampling scheme adapted from [111] in the specific case of LCA of design options; in this figure the scenario layer only considers the different heating systems for a fixed building reference study period

Within the uncertainty layer, a distinction is also made between
- *Aleatory* uncertainty types representing uncertainties which cannot be reduced (e.g., the thickness of the original stone wall, if a solution is sought for the general spectrum of wall thicknesses in a building, a region, a country);
- *Epistemic* uncertainty types representing uncertainties which can be reduced by a higher accuracy or a higher level of knowledge (e.g., the uncertainty related to LCA data of insulation material: if the user has a specific manufacturer data with a high confidence in the impact value).

As it will be demonstrated in more detail below, the possible uncertain parameters in the PM for LCA of internal insulation systems are:
- Mass of material, material Service Life, unitary Environmental Impacts of a material and EoL of a material, whole insulation system Service Life. These are the stochastic variables related to a specific *design option* choice;
- Heat transmission losses before/after renovation. It is the stochastic variable related to a specific *installation configuration scenario* choice (*historic wall+climatic context)*;
- Building overall efficiency for heating, conversion factor from delivered to primary energy, and the unitary environmental impact of the energy vector. These are related to a specific *energy scenario* choice.

2.2.2 Uncertainties vs. level of knowledge and information

The epistemic uncertainties are related to the system’s knowledge or to the level of details of the modelling. They can be reduced by more accurate information. The probabilistic methodology (and the software tool developed) relies on an active role for the final users (building designers, engineers) and allows the user to achieve greater outcome accuracy by entering more specific input data.

Figure 6 presents a graphical –qualitative- illustration of the relationship between the uncertainty range and the amount of information or knowledge of the system under study. Schematically, the level of uncertainty (range of possible environmental impact output) decreases with the amount of information the user can provide. The procedure is presented in Figure 7.

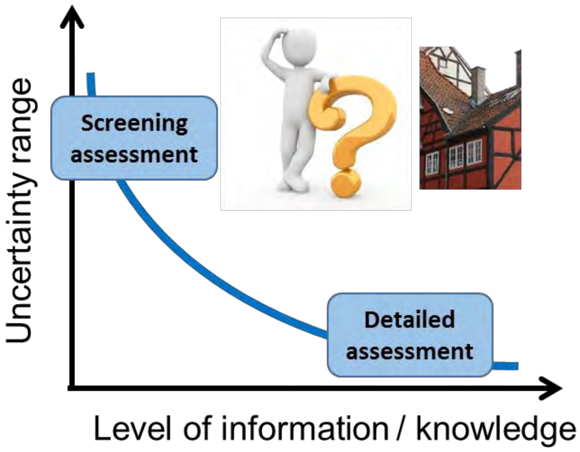


Figure 6 Relationship between the uncertainty range and the amount of information or knowledge of the system under study

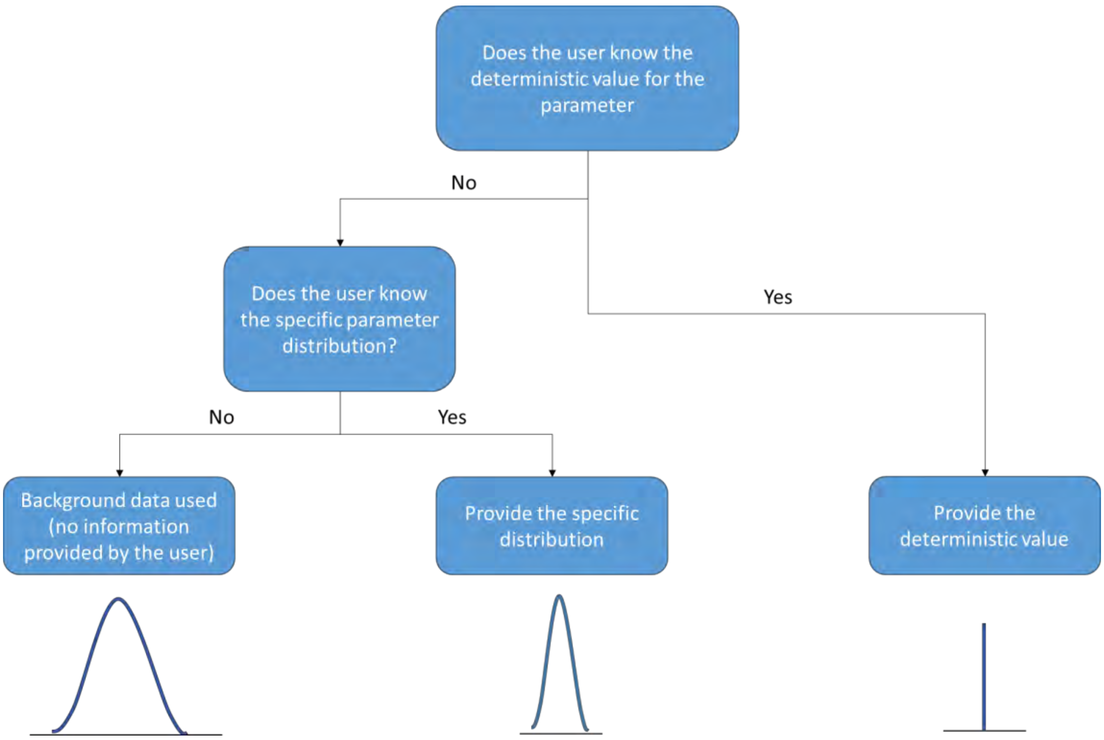


Figure 7 Decision tree for the characterization of the model's input parameters

The decision tree depends on the amount of information (and hence knowledge) available to the user on the system under study (e.g., environmental impacts and service life of materials). For a given parameter, if the user has no information, then the probabilistic LCA methodology will use generic background Probability Density Functions (PDF), implemented into a database of cases included into the software tool[7]. If the user has some information on the uncertainty characterization, it is possible to customize the distributions. Finally, if the user is in possession of values with (very) low uncertainty, the input parameter is considered “deterministic”. For example, the service life of the internal insulation systems included in the software database is modelled using a certain distribution as background PDF. But the user can also specify another distribution (e.g., a triangle distribution) or reduce the range of uncertainty of the initial background PDF. Lastly, it is possible to provide a “deterministic” value, according to a justification (manufacturer’s information, conventional data in the national LCA methodology, etc..).

The proposed approach is applicable to the probabilistic LCA but also to other probabilistic assessments in RIBuild i.e., the hygrothermal assessment, or the LCC.

2.2.3 Heat transmission losses calculation methods

The LCA assessment requires input data on transmission heat losses before and after the renovation measure, in order to account for the use phase (operational energy use, module B6 of EN 15978) and determine the environmental burden savings. As the LCA is performed at “component level”, the operational energy use is considered the only heat transmission losses through the wall.

The LCA PM developed can be coupled to different preliminary calculation methods to perform the annual calculations of heat losses through the facade (during the heating season). Three different approaches (options) are here proposed:

1. coupled heat and mass (HAM) transfer numerical model based on hourly climate data;
2. monthly calculation between the internal temperature and the average monthly temperature;
3. annual calculation based on annual Heating Degree Days (HDD).

Option 1 allows having an accurate and consistent assessment on hygrothermal aspects prior to the LCA. However, option 1 is highly demanding in terms of accurate climatic data and indoor conditions, material properties of the historic facade and of the chosen internal insulation systems. The details of the heat loss calculations using a coupled heat and moisture transfer simulation are not part of Task 5.2 nor presented in this report. Nevertheless, the software tool for probabilistic LCA of internal insulations developed within Task 5.2 (WP5 software Tool) allows using HAM tools results (even provided as PDFs) for the LCA assessment.

The two other calculation procedures can be used when a HAM simulation is either not feasible or not possible (i.e. calculation cost or time issue, missing material properties leading to irrelevant HAM simulations etc.). The procedures can be used, as stand-alone calculation methods, to estimate the heat losses through the facade using simplified but standardised approaches, as described in the next sub-sections. *Option 3* has been implemented into the WP5 software tool in order to easily obtain transmission losses through the wall in a probabilistic or deterministic way[8].

[7] As shown in chapter 4, the software tool now includes a database with several national cases from Italy, Switzerland and Denmark, implemented to illustrate the probabilistic methodology developed. The LCA inputs distributions have been defined for these cases, but the software user can easily modify them or enter deterministic values, according to his level of available information.

[8] Option 2 has been implemented in a proof-of-concept tool to perform HAM assessments in comparison with results of approach 1 (WP4 activities) and to obtain the heat losses for the Swiss case study documented in paragraph 3.1.

2.2.3.1 Monthly calculations of heat losses

Heat transmission losses are calculated as soon as there is a temperature difference between the internal temperature (e.g. set at 20°C) and the mean monthly temperature. This calculation method requires input parameters such as the monthly external temperatures for the corresponding country and location. Such data are usually available either in national climate stations databases or in national standards for thermal calculations. The calculation is based on the following Eq. 3:

$$Q_h=\frac{U}{1000}.\left(T_{int}-T_{ext\_i}\right).n_i.HH \quad [kWh/m^2]$$

Eq. 3

Where:
Q_h is the heat transmission loss through the wall [kWh/m^2]
U is the wall U-value [W/m^2K]
T_{int} is the internal monthly temperature [K]
T_{ext_i} is the external monthly temperature for month i [K]
n_i is the number of days in month i [-]
HH is the heating hours a day [h] (set at 24 hours)

The U-value of the wall is calculated with the following Eq. 4:

$$U=\frac{1}{R_{si}+R_{se}+R_w+R_{is}} [W/m^2K]$$

Eq. 4

Where:
R_{si} and R_{se} are the internal and external surface resistances [112]: R_{si} = 0.13 [m^2K/W] and R_{se} = 0.04 [m^2K/W]
R_w is the original wall thermal resistance [m^2K/W]
R_{is} is the applied insulation system thermal resistance [m^2K/W] (insulation system comprising different layers of materials).

2.2.3.2 Annual Heating Degree Days

The calculation is based on the following Eq. 5:

$$Q_h=\frac{U}{1000}.HDD.HH \ [kWh/m^2]$$

Eq. 5

Where:
Q_h is the heat loss through the wall [kWh/m^2]
U is the wall U-value [W/m^2K]
HH is the heating hours a day [h] (set at 24 hours)
HDD are the annual heating degree-days [K]

The U-value of the wall is calculated with the same equation as Eq. 4.

2.3 Overview of the probabilistic methodology

The probabilistic LCA methodology is based on an uncertainty and sensitivity analysis applying the Monte Carlo (MC) method. It couples the calculation of environmental impacts to MC methods, in order to build the entire output probability distribution and to assess global uncertainty and sensitivity [88]. The PM developed consists in four main steps described in detail in the next paragraphs and summarized below.

1. **Explicit Life Cycle Inventory (LCI) reference model**. This step establishes the specific procedure to be applied for the LCA of internal insulation solutions. The main input parameters are identified; the output parameters and a suitable model to simulate them are selected (section 2.4).
2. **Uncertainty characterization**. In this step the selection and characterization of the uncertainties that are considered in the assessment is conducted. The most uncertain LCA data inputs are identified and procedures for characterization of their PDFs are proposed (section 2.5).
3. **Uncertainty propagation**. This step applies the MC methods in combination with a specific sampling procedure (section 2.6).
4. **Uncertainty and Sensitivity Analysis**. In the last step it is the intention to represent the output distribution and to calculate the sensitivity indices which allow for establishing the parameters most influential on the output uncertainty (section 2.6).

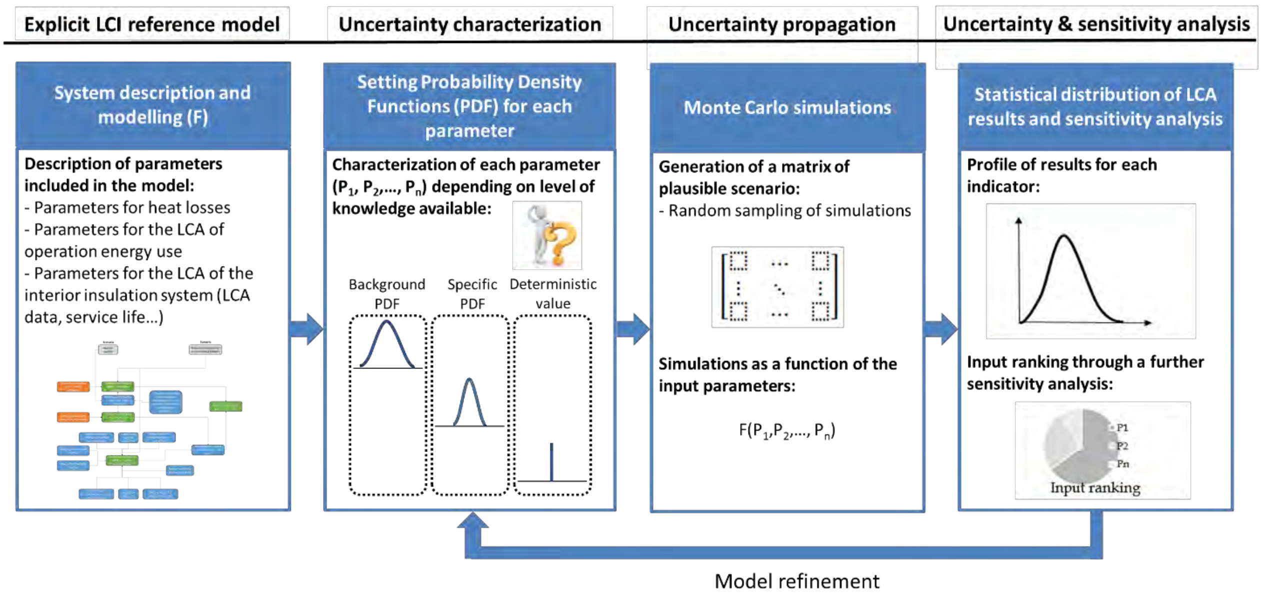


Figure 8 LCA probabilistic methodology overview with the different steps

2.4 Explicit Life Cycle Inventory (LCI) reference model

The life cycle inventory reference model is set for the heat losses calculations before and after renovation, if not calculated through external HAM tool (option 1), as well as for the subsequent LCA. This section describes the LCI reference models as well as the parameters used in the calculations of the heat losses (section 2.4.1) and the subsequent LCA (section 2.4.2).

First, design options and scenario layers should be defined to set the “case-studies” to be assessed, using the probabilistic methodology. In the following, we refer to a “case-study” when we consider an internal insulation solution (with a specific insulation thickness) applied in a certain original wall configuration under certain climatic conditions. The same case study can be assessed in several scenarios: energy scenarios or reference study periods.

Table 3 presents the possible design options and scenarios.

Table 3 Design options and scenarios identified in the probabilistic LCA methodology

Design options	**Comments**
Type of insulation systems (and thicknesses/U-value considered in the functional unit).	Country-specific information.
Scenarios for the Heat transmission loss calculation[9]	**Comments**
Historic wall installation configuration (type of historic wall and structural material).	Country-specific information. See, e.g. RIBuild deliverable D1.1.
Location (Climatic context).	Country-specific information.
Scenarios for the LCA	**Comments**
Energy sources and features of the heating system.	Country-specific information. Different heating systems and sources available depending on buildings.
Building reference study period.	Different deterministic values possible, e.g. 30, 45, 60 years.

2.4.1 Heat transmission losses reference model and parameters

As already introduced in section 0, within the PM, three options have been proposed to determine the wall heat losses.

As shown later in section 4, PDFs or deterministic values of the heat losses obtained through accurate HAM simulations (option 1) or other methods can be directly entered into WP5 software tool case studies database. Alternatively, option 3 is implemented into WP5 software tool in order to perform a real-time calculation of the transmission losses through the wall in a probabilistic or deterministic way.

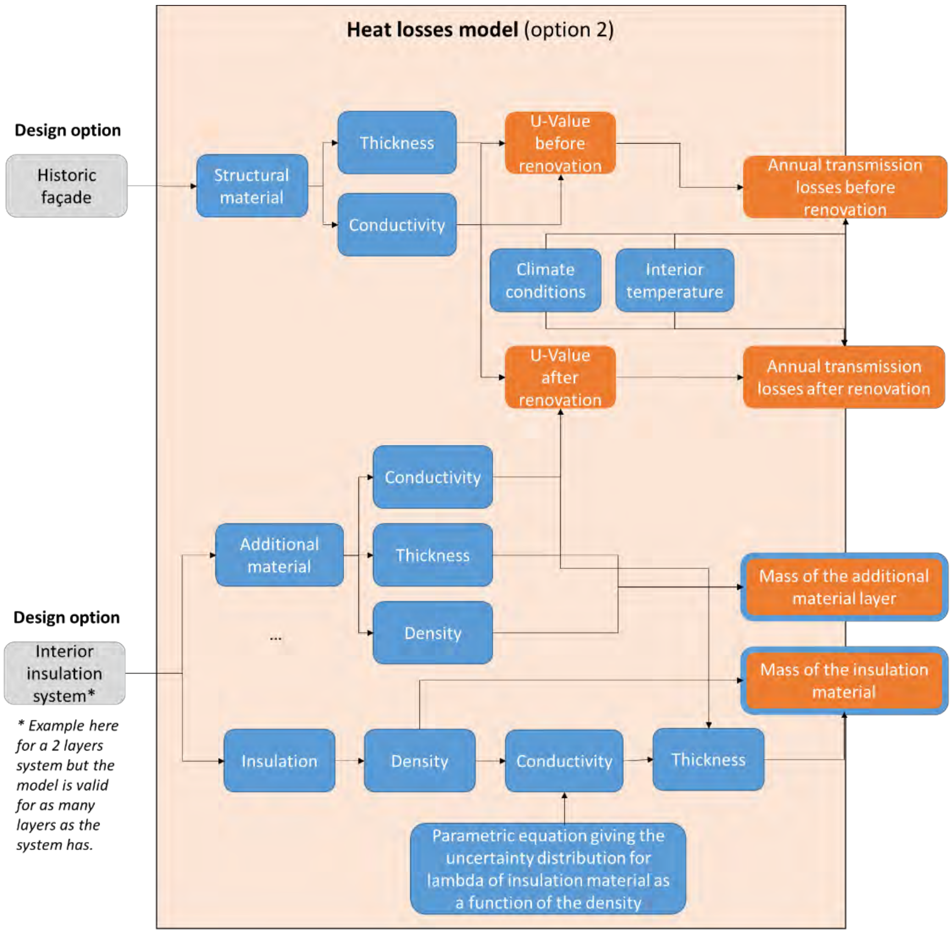
A HAM simulation accounts for much more parameters than monthly and annual calculations. The last two approaches are simplified and cannot address the hygrothermal properties of the walls in an hourly time step for instance. However, options 2 and 3 can be used under specific conditions (within their validity domain) to determine the U-value and the heat losses prior to any LCA. In this section, the heat losses reference model suitable for options 2 (monthly calculations) and 3 (annual calculations) are presented.

[9] If the heat transmission losses are provided by an external HAM tool (option 1), it is necessary that the scenarios of the HAM calculation and the LCA be consistent (HAM and LCA should adress the same “case study”). Nevertheless, specific informations on climatic conditions or original wall structures are not necessary for the LCA.

Monthly calculations of heat losses (option 2)

Figure 9 presents the heat losses reference model for option 2 that includes the parameters:

- Historic wall
  - Thickness of structural and original material
  - Density of structural and original material
  - Thermal conductivity of structural and original material
- Internal insulation system
  - Thickness of insulation material installed
  - Density of insulation material installed
  - Thermal conductivity of insulation material installed
  - Thickness of rendering material used as finishing element
  - Density of rendering material used as finishing element
  - Thermal conductivity of rendering material used as finishing element



Legend:

Grey boxes: design options and scenario parameters
Blue boxes: uncertain parameters considered with sampling (if the user has not specified a deterministic value)
Orange boxes: calculated values for the use phase (heat losses) from different approaches (options 1, 2 or 3)
Blue and orange boxes: recalculated values using uncertain parameters as input values

Figure 9 Input parameters for the heat losses monthly calculations (option 2)

Regarding the scenario layer, for the climate conditions, outside temperature and internal temperature are considered.

As intermediate results, the U-values of the wall before and after renovation are calculated (Eq. 4). Then, transmission losses are calculated using external climate conditions and chosen internal temperature (Eq. 3). Within the model, the opaque facade is considered as being homogenous. The calculation method is able to handle a wall with different layers of added materials after renovation.

All the parameters, identified in blue in

Figure 9 can be subject to an uncertainty while the parameters, identified in orange, are intermediate (e.g. U-values) or final output of the calculations (transmission losses before/after renovation). A specific aspect concerns the mass of the materials included in the internal insulation systems. They are recalculated parameters based on materials properties (density, thickness) which can be subject to uncertainties (see section 2.5.1).

Annual Heating Degree Days (option 3)

Regarding the design option layer, the following parameters are considered (and required by WP5 software tool, as documented in section 4):

- Historic wall
  - thermal resistance of the historic wall [m^2K/W]
- Internal insulation system
  - thermal resistance of the whole insulation systems [m^2K/W]

Concerning the scenario layer, as climate conditions, the procedure considers the statistical annual hating degree-days HDD [K] of a given EU country or region. HDD data for all the RIBuild Countries were extracted from Eurostat database, as calculated by the Joint Research Centre (Institute for Environment and Sustainability - IES/MARS Unit)[10], and included in WP5 software tool. They are reported in Appendix 2.

Data are detailed at national and regional level, and this allows performing the LCA considering "general" case studies (under the whole Country climatic variability) or specific cases (in a specific geographic region).

Data are provided for years from 2000 to 2009 (for the regions) and from 2000 to 2016 (for the whole Countries) thus including the variability during time.

2.4.2 LCA model and parameters

Regarding the LCA model, the following input parameters are considered:

- Design option layer
  - Masses of the material layers
  - Service life of the whole insulation system[11]
  - Service life of the material layers[12]

[10] http://ec.europa.eu/eurostat/web/energy/data
[11] influencing the number of replacements

    - Unitary environmental impact of each material layer
        - Manufacturing stage
        - End-of-life stage
- Scenario Layer
    - Building reference study period
    - Heat transmission losses before/after renovation[13]
    - Unitary environmental impact of the energy carrier
    - Energy conversion factor
    - Overall global efficiency for heating.

The following Figure 10 reports an illustration of the relationships among all the LCA parameters.

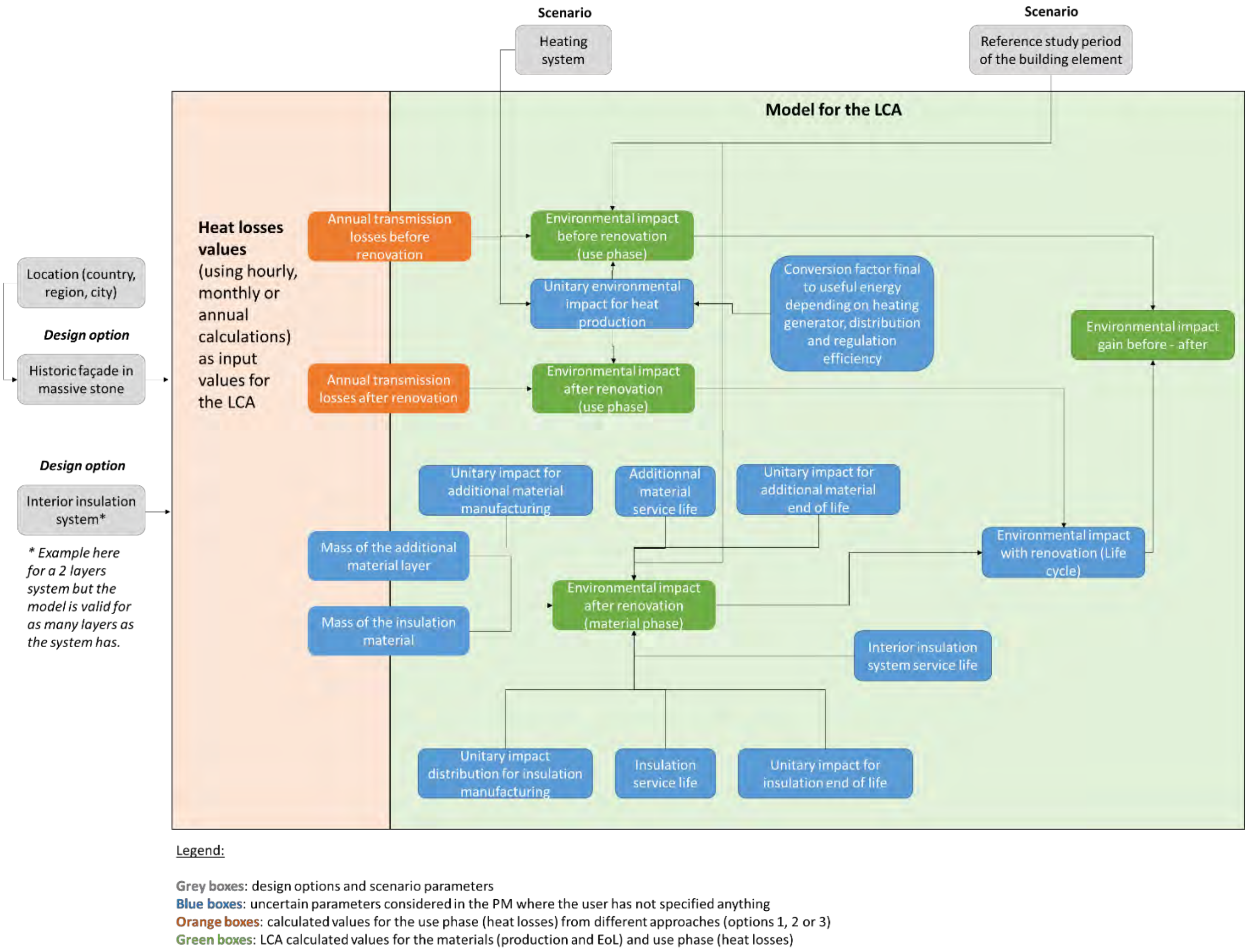


Figure 10 Illustration of the relationships among all the LCA parameters

In Table 4, the uncertain parameters identified in the LCA model are further defined, according to the specific LCA stage.

All these parameters are included in the WP5 software tool.

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[12] influencing the number of replacements of the internal finishing layer (maintenance phase).
[13] Directly provided by the user if the heat loss calculation is performed through an external tool.

Table 4 LCA model input parameters

LCA Stage (EN 15978 nomenclature)		**LCA Parameter description**
Production Stage	**Material**	Mass of the materials composing the insulation system [kg]
		Unitary environmental Impact of material [Unit of indicator]
Use stage	**Maintenance**	Material Service Life (which affects the need of periodic replacement of the finishing layer of the insulation system) [years]
	Replacement	Insulation System Service Life (which affects the whole insulation system replacement) [years]
	Energy Consumption	Heat transmission losses through the wall before/after renovation [kWh/year]
		Building overall efficiency for heating, depending on the heating generator, distribution and regulation efficiency [-]
		Energy conversion factor [-]
	Energy Impact	Unitary environmental Impact of heating system [Unit of indicator]
EoL stage	**EoL material impact**	Unitary environmental EoL Impact of material [Unit of indicator]

The LCA probabilistic methodology addresses the *parameters uncertainties* (according to the definition reported in section 1.4.1). Then all the LCA parameters reported in the table are considered stochastic variables of the assessment.

2.5 Uncertainty characterisation

The uncertainty analysis requires quantifying the PDF of the model's input parameters. This phase of uncertainty identification and characterisation consists on developing a systematic approach in order to:

- identify the uncertainty sources to be considered in the LCA of internal insulation measures;
- characterize through PDFs the uncertainty sources, based on available data sets, literature, databases, time series, etc.;

The general procedure for the uncertainty characterisation of input parameters in the PM is the following:

1. Data collection based on literature and databases for each uncertainty source identified and eventually depending on the national context;
2. Use a quantitative approach based on parameter estimation techniques and time series analysis and goodness-of-fit tests to fit distributions when sufficient data is available;
3. Experts' judgement when limited data are available or uncertainty is subjective.

Uncertainty arises due to a lack of information. Formally, uncertainty can be reduced by increasing the level of knowledge related to the studied system. In order to take into consideration this aspect, the approach proposes to set some of the parameters of the case studies developed (section 4) with a proposed "background PDF", that can be modified by the user.

The characterisation of some parameters can be strongly dependant on the typology of design options selected and on the local context. So, in the methodology, background PDFs of some parameters are either mandatory or only suggested.

2.5.1 Uncertainty characterisation for heat losses

Heat losses uncertainty characterization is presented below only for monthly and annual calculations (respectively options 2 and 3, see section 2.4.1).

Table 5 presents the list of parameters considered in the heat losses calculations in option 2 and the chosen distribution type in background PDF when a consensual distribution can be proposed. Otherwise, it has to be defined in the case study applying the methodology (taking into account the local context and availability of data).

The internal insulation system is breaking into two parts: the insulation material and the additional materials (rendering or others) to ease the presentation of parameters and PDFs.

Table 5 Uncertainty characterisation of heat losses parameters for option 2 (monthly heat losses calculation)

	Parameter description	**Distribution type in background PDF**
Historic wall	Thickness of structural existing material	Uniform distribution (if the thickness changes from bottom to top of wall)
	Thermal conductivity of structural existing material	No mandatory PDF, depending on the case study
	Density of structural existing material	No mandatory PDF, depending on the case study
	U-value of the structural existing material	*Calculated value (from the thickness, density and thermal conductivity)*
Internal insulation system	Thickness of the insulation material	No mandatory PDF, depending on the case study (e.g., uniform distribution)
	Thermal conductivity of the insulation material	Log-normal distribution for insulation material
	Density of insulation material	Triangle (according to [113])
	Thickness of the additional materials (rendering or other)	No mandatory PDF, depending on the case study (e.g., uniform distribution)
	Thermal conductivity of the additional materials (rendering or other)	No mandatory PDF, depending on the case study
	Density of the additional materials (rendering or other)	No mandatory PDF, depending on the case study
	U-value of the wall (structural material + new internal insulation system	*Calculated value (from the thickness, density and thermal conductivity)**
Climate conditions	Climate conditions (external)	Equiprobability (choice between national weather stations)
	Internal temperature	Triangle (to take into account the uncertainty due to user behaviour)
	Humidity level (internal)	-
Input parameter for the LCA (Use phase)	Annual transmission heat losses before renovation	*Calculated value*
	Annual transmission heat losses after renovation	*Calculated value*
* In the methodology, the user can also specify the U-value of the insulation material (if the user would like to comply with a limit U-value for renovation according to national standards) instead of specifying the thickness first. If the user does not specify anything, a distribution is applied on the thermal conductivity as a function of their type and density based on [113]. If the material is not available in the work reported by [113], a distribution can be defined based on another justification.		

Table 6 presents the parameters considered in the heat losses calculations in option 3, that is implemented in WP5 software tool, as presented in section 4.

Table 6 Uncertainty characterisation of heat losses parameters for option 3 (annual heat losses calculation)

	Parameter description	Distribution type in background PDF
Historic wall	Thermal Resistance of structural existing material	Normal distributions (automatically calculated by WP5 software, based on an uncertainty range defined by the user).
Climate conditions	Heating Degree Days	Normal distribution. Eurostat data were processed obtaining normal distributions with good approximations (data-fitting Shapiro test). HDD original data from Eurostat database and data-fitting results are provided in Appendix 2.
Internal insulation system	Thermal Resistance of the insulation system	Deterministic value
Input parameter for the LCA (Use phase)	Annual transmission heat losses before renovation	*Calculated value*
	Annual transmission heat losses after renovation	*Calculated value*

2.5.2 Uncertainty characterisation for LCA

Two levels of uncertainty can be identified for the LCA parameters:
- uncertainty of the life cycle inventory (LCI) background data for material manufacturing, end of life as well as for heating systems;
- uncertainty of the system under study (e.g., service life, mass of materials etc.).

The uncertainty of the unitary environmental impact for LCI background data can be considered by using the Pedigree matrix characterization proposed within the *ecoinvent* database (already introduced in section 1.3). Thus, regarding the unitary environmental impact, the distributions can be taken from a unit process LCI database or equivalent. Then, a sampling is made on the unitary environmental impact background data.

Depending on the local context and available information, background PDF for the unitary environmental impact can also be replaced with distribution information in some Environmental Product Declarations (EPD), e.g. as presented in the state-of-the-art for the specific case of France[14], or directly by deterministic values obtained from EPDs.

Once the PDFs for the unitary environmental impact of *composing materials* are defined, it is necessary to calculate the unitary environmental impact at *whole insulation system level*, considering the masses (and related uncertainties) of each material. As also described in the following section 4.2.3, this is done through a basic random Monte-Carlo process and distributions are estimated through a data-fitting test. This procedure is implemented into WP5 software.

The uncertainty characterization for the service lives is presented in more details in the next paragraph.

In Table 7 the proposed distributions are illustrated for the uncertain parameters identified in the LCA model.

[14] In some situations, product-specific LCA data in the form of Environmental Product Declarations (EPD) can be used and sampled together within a same material type.

Table 7 Uncertainty characterisation of LCA input parameters

LCA Stage (EN 15978 nomenclature)		LCA Parameter description	Proposed distribution types
Production Stage	**Material**	Mass of the materials composing the insulation system [kg]	No mandatory PDFs
		Unitary environmental Impact of material [Unit of indicator]	Lognormal/Normal distributions based on Pedigree matrix and background LCI databases EPDs
Use stage	**Maintenance**	Material Service Life (which affects the need of periodic replacement of the finishing layer of the insulation system) [years]	No mandatory PDFs PDFs can be established based on the probabilistic factorial method (see 2.5.3)
	Replacement	Insulation System Service Life (which affects the whole insulation system replacement) [years]	No mandatory PDFs PDFs can be established based on the probabilistic factorial method (see 2.5.3)
	Energy Consumption	Heat transmission losses through the wall before/after renovation [kWh/year]	No mandatory PDFs PDFs can be defined based on calculation options 1,2 or 3
		Building overall efficiency for heating, depending on the heating generator, distribution and regulation efficiency [-]	No mandatory PDFs
		Energy conversion factor [-]	No mandatory PDFs (usually deterministic values are established at national level)
	Energy Impact	Unitary environmental Impact of heating system [Unit of indicator]	Lognormal/Normal distributions based on Pedigree matrix and background LCI databases
EoL stage	**EoL material impact**	Unitary environmental EoL Impact of material [Unit of indicator]	Lognormal/ Normal distributions based on Pedigree matrix and background LCI databases

2.5.3 Uncertainty characterisation for materials service life

According to ISO 15686: 2011, the service life (SL) can be defined as the period of time after installation in which the buildings or their parts meet or exceed the minimum performance requirements.

As seen, in the PM developed, the estimated SL of the internal finishing material of the insulation system affects the need of periodic *maintenance* (module B2 of the LCA), while the estimated SL of the whole insulation system affects the need of periodic *replacement* (module B4 of the LCA). Obviously, the whole system service life is longer than the internal finishing material service life, but, at the same time, it should be established considering the SLs of all the other materials composing it.

As presented before, the characterisation of the service lives of the materials and insulation systems is let flexible in the methodology. So, proper PDFs or values can be chosen considering the available data and literature on this topic.

Nevertheless, among the characterisation methods, the PM proposes the use of the probabilistic factorial method to go from the reference to the estimated SL, described in section 1.3 and included in ISO 15686-8, which takes account of the specific operational conditions and the uncertainties of the degradation processes. Due to the specific environmental exposure, maintenance policies and other factors, the actual estimated service life (ESL) differs from reference service life (RSL).

Useful databases of building materials SL have been provided in Appendix 1. Material EPDs can also provide RSL data.

As presented in section 1.3, in the probabilistic factorial method, the ESL is defined as the multiplication of the RSL by seven durability factors, which represent the real operational condition. That is, A is the factor related to the quality of the materials; B is the factor related to the design level; C is the factor related to the execution level; D is the factor related to the internal environmental conditions; E is the factor related to the external environmental conditions; F is the factor related to the in-use conditions; G is the factor related to the level of maintenance. In practice, in the probabilistic factorial method, each factor is defined by a probability distribution function and the PDF of the ESL is obtained through a Monte-Carlo process that combines the factors PDFs.

2.6 Uncertainty propagation and sensitivity analysis

This section presents the choice made for the last two steps of the probabilistic LCA methodology as presented in Figure 8 (uncertainty propagation, uncertainty and sensitivity analysis).

For uncertainty propagation, Monte Carlo methods are chosen to propagate the heat losses and LCA parameter uncertainties into a distribution of the output variable. The output sample can then be visually represented by Probability Density Functions (PDF), Cumulative Density Functions (CDF) or box whiskers plots, which can be used to empirically compare the performance of several design options under the same scenarios (or under several scenarios), as shown in the exemplary cases presented in section 3.

In the methodology and WP5 tool developed, Sobol's sequences are used as quasi-random sampling technique, in order to generate samples as uniformly as possible and effectively perform the sensitivity analysis through variance based decomposition (Sobol' method) techniques, part of the Global Sensitivity Analysis (GSA) [90,97]. Indeed, the SA based on Sobol's variance decomposition approach imperatively needs the input sample generated by the Sobol sequences [114]. The number of model evaluations (sample size) depends on the number of variables [115]. The smallest sample size for the Sobol indices calculation is $n(2k+2)$, where n is the minimum model evaluations for estimating one individual effect; n takes the value of 16, or 32, 64…; k is the number of input variables [115]. The sampling efficiency can be assessed by comparing the PDFs of the output sample with a reference Basic Random sample (BRS) simulation at high number of runs [89].

The variance based decomposition (Sobol' method) technique for sensitivity analysis is embedded in the methodology and WP5 tool developed. The SA allows identifying the most influential parameters on the output uncertainty and, if needed in subsequent analysis, to neglect the uncertainty of some less influential variables, which can therefore be considered "deterministic".

Through these methods, it is possible to obtain two sets of indices for each stochastic input: the "first order" and the "total order" indices. The first-order sensitivity index represents the main contribution of each input factor to the variance of the output. The total order index measures the contribution to the output variance due to each input, including the variance caused by its interactions with any other input variables [97]. The higher the value of the sensitivity indices, the most influential are the related parameters of the model. In particular, the total order indices (STi) allow to "cut-off" those parameters presenting a very low value, which can be considered less influential for the output uncertainty. "Importance" in SA is a relative notion and there is no established threshold for indices. In general, one can look at the absolute values of indices and at the distance between them and consider e.g. as threshold the value of 0.05.

Since SA allow establishing which parameters need accurate distributions and which parameter variations can be neglected without compromising the output reliability, if needed for future assessments, the LCA model can be simplified by considering for the not-influential inputs their "deterministic" values.

2.7 Conclusions

This section presented the probabilistic LCA methodology developed within RIBuild Task 5.2 in the field of internal insulation solution of historic buildings.

It is based on an LCA assessment performed at "component level", according to international ISO 14040-14044, EN 15804 and EN 15978 standards, including production stage (modules A1-A3), use stage (with modules B2 maintenance, B4 replacement and B6 operational energy use) and End of Life stage (modules C1-C4). The LCA calculation is coupled with a Monte-Carlo based method for the propagation of the inputs' probability distributions into the output distributions, in terms of at least two environmental indicators namely the Climate Change and the non-renewable Cumulative Energy Demand.

The LCA PM can be applied to assess the environmental performance of several design options (internal insulation solutions) in several possible scenarios (original wall applications, climatic contexts, energy sources, reference study periods). At this aim, the LCA simulation parameters are sorted out according to a *multi-layered sampling scheme* [111]. This allows managing multiple design options, to subject all design options to the same uncertainties types and to check the validity of results in potential scenarios (subject to different uncertainties). This is the approach that can be used to assess the environmental impact of several insulation solutions, in several existing walls configurations and in different climates, in order to realize the WP6 web tool on internal insulation.

The PM is based on a flexible approach, tailored to the user needs. In particular, it proposes three alternative methods, at increasing difficulty and accuracy level, to assess the heat transmission losses through the building wall before and after the renovation measure, necessary to assess the operational energy use and determine the environmental burden savings. The PM can be coupled to accurate (probabilistic) HAM tools, to monthly steady-state calculations, or to a simplified annual HDD method. The coupling to accurate (probabilistic) HAM tools, as those developed within RIBuild WP4, is foreseen during WP6 to realize the RIBuild web tool.

The next section presents exemplary case studies applying the methodology in different contexts. The different aspects of the methodology (influence of users' knowledge, comparison of design options, sensitivity analyses for identifying influential parameters) are illustrated.

Finally, the software tool, which implemented the methodology described, is presented in section 4.

3 Exemplary case studies of the application of the LCA probabilistic methodology

The aim of the exemplary case studies reported in this section is to show the potential application of the probabilistic LCA methodology developed for historic building renovations with internal insulation measures, also in view of future progress of RIBuild web tool or, in general, in building renovation projects. In the following sections four different applications are presented:

- Influence of the users' knowledge level of LCA inputs on the results (from screening to detailed assessment);
- Comparison of the environmental performance of several design options;
- Assessment of results robustness under different scenarios for energy sources and building reference study periods;
- Identification of influential parameters on the outcome uncertainty.

3.1 Influence of users' knowledge level on LCA results

The goal of this case study is to compare the results obtained from the application of a deterministic LCA and the probabilistic LCA methodology developed, also linking heat losses results to the LCA. A decreasing level of uncertainties is considered for three assessment types ranging from a "screening LCA" to a more "detailed LCA" (Figure 11). In this exemplary case study, heat losses are determined from the monthly calculation method (option 2, see section 2.2.3.1)[15].

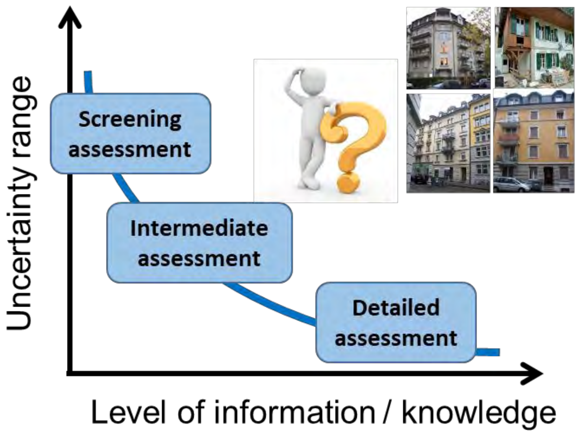


Figure 11 Qualitative illustration of the types of assessments considered in this case study

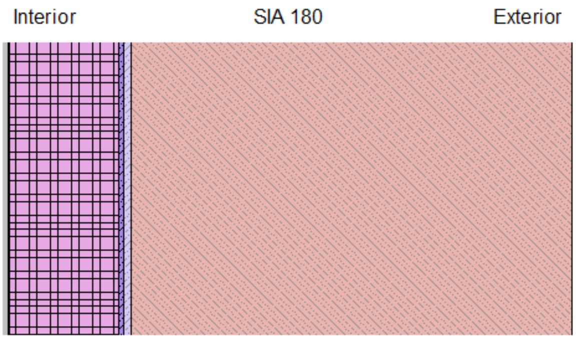
The starting point is the deterministic Swiss case-study reported in Appendix 4. The main limitation of the deterministic case study was to exclude considerations relating to the inherent uncertainties of the historic facade properties as well as the uncertainties related to the design options. Similarly, the study was unable to assess a stone facade representative of the Swiss plateau. To tackle these different limitations, a three step assessment is presented applying the methodology developed in section 2. For each step of the analysis, the level of uncertainty is adjusted to the level of available information from the case study.

[15] Option 2 has been implemented in a proof-of-concept R script developed by HES-SO.

3.1.1 Definition of design options and simulation scenarios

The assessment is performed for one design option and one scenario for the building reference study period (30 years) and the heating system (gas boiler).

The chosen design option is an aerated concrete: fifteen centimetres of *Multipor* were considered to reach the required thermal performance (U-value 0.25 W/m^{2}K) in a 60 cm stone wall thickness with a thermal conductivity of 1.3 W/mK. *Multipor* is provided as rigid panels that can be glued to the existing wall using a light mortar provided by the same manufacturer. No additional fixings are required. The internal side is then also coated with mineral roughcast. Figure 12 presents the sketch of the renovated facade and the thermal parameters.



Material	Thickness [cm]	Conductivity [W/(mK)]	Density [kg/m³]
Natural Stone	60	1.3	2000
Mineral coating	1	0.7	1400
Light mortar	0.5	0.18	450
Multipor WI	15	0.045	115
Mineral cover coat	0.5	0.7	1200

Figure 12 Renovated facade using a Multipor in the deterministic LCA assuming fixed thicknesses, conductivities and densities (cf. Appendix 4, Swiss case study).

Three different levels for the assessment were addressed, with a different use of "distributions" for the input values:

- *Screening assessment*: the user does not know where the building is situated in Switzerland, except that it is located in the Swiss plateau (i.e. not in mountains). The user does not know anything in detail about the internal insulation systems and case study (e.g., no measured data on stone properties, no information from occupancy behaviour or manufacturer of insulation…);
- *Intermediate assessment*: the user knows the internal insulation system well (e.g., reliable lambda value) and which manufacturer produced the aerated concrete and thus no further uncertainty is considered for the background LCA data on the insulation system. No losses are considered for the on-site implementation of the system. Similarly, the historic building location is known;
- *Detailed assessment*: same as intermediate assessment but with a higher accuracy for the thermal properties of the historic facade (as some measurements were done on the lambda value of the facade). In the detailed assessment, no more epistemic uncertainties will be found. The only remaining uncertainties are the aleatory ones (e.g., the thickness of the historic facade is higher at the bottom than at the top).

The next Table 8 presents the assumptions made for the case study.

Table 8 Design options and scenarios identified in this exemplary case study

Design options for the LCA	**Screening LCA**	**Intermediate LCA**	**Detailed LCA**
Type of insulation systems (and thicknesses/U-value considered in the functional unit).	Aerated concrete allowing to reach a U-value of 0.25 W/m^{2}K for the facade after renovation		
Scenarios for the Heat transmission loss calculation	**Screening LCA**	**Intermediate LCA**	**Detailed LCA**
Historic wall installation configuration (type of historic reference wall and structural material).	stone wall representative of Swiss historic buildings (as presented in RIBuild deliverable D1.1)	stone wall description of one historic building (without measured stone hygrothermal properties)	stone wall description of one historic building (with measured stone hygrothermal properties)
Location (Climatic context).	Swiss plateau sampling	Payerne (VD)	Payerne (VD)
Scenarios for the LCA	**Screening LCA**	**Intermediate LCA**	**Detailed LCA**
Energy sources and features of the heating system.	Gas boiler		
Building reference study period.	30 years		

In the screening assessment, the type of historic facade is considered without any more details. Hence, in the exemplary case study, a stone facade is considered. This type of facade represents 28% of Swiss historic building facade (see RIBuild document deliverable D1.1). The location of the case study is on the Swiss plateau but is not known precisely, so the climate data are taken assuming a sampling on the Swiss plateau climate stations. In the two-other assessments (intermediate and detailed LCA), the location of the case study will be Lausanne (VD) using the nearby climate station of Payerne (VD).

In the screening LCA, the insulation option is a generic aerated concrete without information on the type of manufacturer. In the two-other assessments, the aerated concrete is a Multipor manufactured by Ytong.

3.1.2 Uncertainty characterization and propagation

Table 9 and Table 10 present the uncertainty characterization for both heat losses and LCA parameters.

Table 9 Uncertainty characterisation of heat losses parameters for option 2 (monthly calculation)

	Parameter description	**Screening LCA**	**Intermediate LCA**	**Detailed LCA**
Historic wall	Thickness of structural existing material [m]	Uniform (0.4;0.6)	Uniform (0.4;0.6)	Uniform (0.4;0.6)
	Thermal conductivity of structural existing material [W/m^{2}K]	Triangle (1.38;3.2;2.3)	Triangle (1.38;3.2;2.3)	Deterministic value (1.8 W/m^{2}K)
	Density of structural existing material [kg/m^3]	Deterministic value (1400 kg/m^3)		
	U-value of the structural existing material	*Calculated as a function of the material properties*		
Internal insulation	Thickness of the insulation	*Calculated with*	Deterministic	Deterministic value

	Parameter description	Screening LCA	Intermediate LCA	Detailed LCA
system	material	*density and Thickness for 1m² of opaque facade*	value	
	Thermal conductivity of the insulation material	Log-normal distribution for insulation material	Deterministic value	Deterministic value
	Density of insulation material	Triangle (according to [113])	Deterministic value	Deterministic value
	Thickness of the additional materials (rendering or other)	*Calculated value (as a function of the density, thickness and material choice)*	Deterministic value	Deterministic value
	Thermal conductivity of the additional materials (glue, wood, gypsum fiber board, mineral rendering)	Uniform for each additional layer	Deterministic values	Deterministic values
	Density of the additional materials (rendering or other)	Deterministic values		
	U-value of the wall (structural material + new internal insulation system	0.25 W/m²K	Calculated function of thickness and lambda	Calculated function of thickness and lambda
Climate conditions	Climate conditions (exterior)	Equiprobability (choice between national weather stations in the Swiss plateau)	Payerne (VD)	Payerne (VD)
	Interior temperature	Triangle (18;23;21)	Triangle (20;22;21)	Deterministic (21)
Input parameter for the LCA (Use phase)	Annual transmission heat losses before renovation	*Calculated value*,***		
	Annual transmission heat losses after renovation	*Calculated value*,***		

* In the proof-of-concept tool, the user can also specify U-value of the insulation material (if the user would like to comply with a limit U-value for renovation according to national standards) instead of specifying the thickness first. If the user does not specify anything, a distribution is applied on the thermal conductivity as a function of their type and density based on [113]. If the material is not available in the work reported by [113], a distribution can be defined based on another justification.
**Function of the U-value and the monthly temperature difference between climate station and interior temperature. It considers neither the solar gains nor the thermal bridges

Table 10 Uncertainty characterisation of parameters for the LCA

LCA Stage (EN 15978 nomenclature)		LCA Parameter description	Screening LCA	Intermediate LCA	Intermediate LCA
Production Stage	Material	Mass of the materials composing the insulation system [kg]	Based on assumptions used for the heat losses calculations		
		Unitary environmental Impact of material [Unit of indicator]	Lognormal distribution (probabilistic KBOB[16] data of each material as implemented in ecoinvent v2.2.2016.12	Product-specific KBOB data of each material	Product-specific KBOB data of each material

[16] https://www.kbob.admin.ch/kbob/de/home/publikationen/nachhaltiges-bauen.html

LCA Stage (EN 15978 nomenclature)		**LCA Parameter description**	**Screening LCA**	**Intermediate LCA**	**Intermediate LCA**
			database and the Pedigree matrix uncertainty calculation)		
Use stage	**Maintenance**	Material Service Life (which affects the need of periodic replacement of the finishing layer of the insulation system) [years]	-	-	-
	Replacement	Insulation System Service Life (which affects the whole insulation system replacement) [years]	Triangle distribution based on SIA 2032 SL data is considered (see Appendix 1). Triangle (15;45;30)	Same approach as in screening LCA with a reduced distribution Triangle (20;40;30)	Same approach as in the intermediate LCA with a reduced distribution Triangle (25;35;30)
	Energy Consumption	Heat transmission losses through the wall [kWh/year]	Calculated value (see Table 9)	Calculated value (see Table 9)	Calculated value (see Table 9)
		Building overall efficiency for heating, depending on the heating generator, distribution and regulation efficiency [-]	Lognormal distribution (meanlog=0.0204444, sdlog=0.047327)*	Lognormal distribution (meanlog=0.0204444, sdlog=0.047327)*	Deterministic value Efficiency (LHV): 1
	Energy Impact	Unitary environmental Impact of heating system [Unit of indicator]	Lognormal distribution using the probabilistic KBOB data of each material	Product-specific KBOB data of each material**	Product-specific KBOB data of each material**
EoL stage	**EoL material impact**	Unitary environmental EoL Impact of material [Unit of indicator]	Lognormal distribution using the probabilistic KBOB EoL scenario of each material	EoL scenario of KBOB for each material**	EoL scenario of KBOB for each material**

* based on Swiss KBOB data for energy input (on LHV) to get 1 kWh of useful energy. The max value is defined by the UHV/LHV ratio in order to have a 100% max efficiency on UHV, i.e. max efficiency=1.11, where Ratio UHV/LHV is the gas ratio from KBOB assumption i.e., 1.11; and Efficiency on UHV is the Efficiency on Low Heating Value

The Monte Carlo simulations were conducted for 5000 runs using the statistical software R.

3.1.3 Results

Figure 13 presents the environmental impacts savings in terms of greenhouse gas emissions and non-renewable cumulative energy demand (CED_{NRE}). Results are presented as boxplots with the whiskers representing the minimum and maximum values while the upper and lower parts of the boxplot represent the first and third quartiles. The median is represented by the middle line.

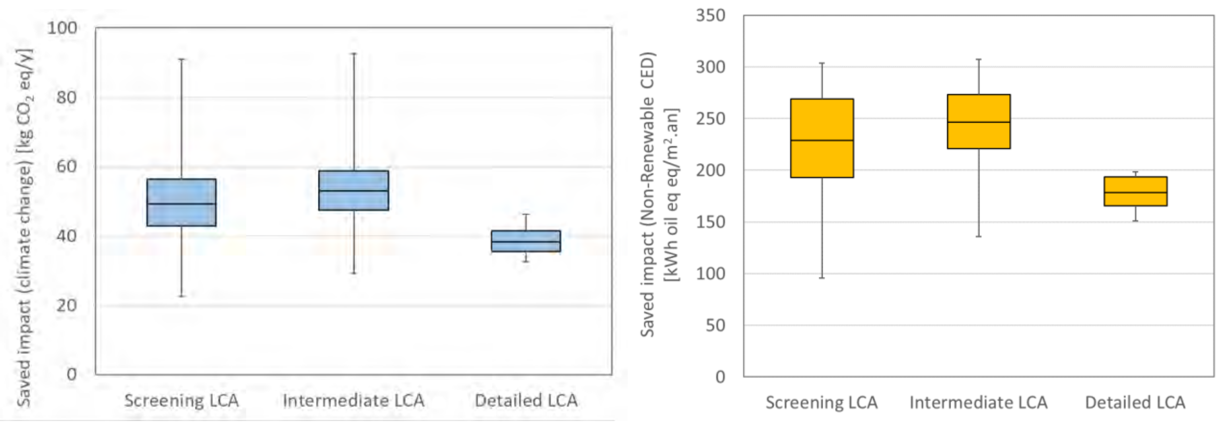


Figure 13 Saved environmental impacts (expressed in greenhouse gas emissions and non-renewable CED) according to the different LCA study types

The uncertainty range is a function of the chosen distribution and uncertainty of the input parameters. As expected, the range is higher for the screening LCA compared to the detailed LCA. The environmental impact saving potentials is about 20-100 $kgCO_2$.eq/m^2y and 100-300 kWh/m^2y in the screening assessment. In this case, few input parameters are known with confidence which results in a higher uncertainty in terms of potential savings. In opposite, the results of the detailed LCA present a smaller range of results (30-50 $kgCO_2$-eq/m^2y and 150-200 kWh/m^2y).

Interestingly, the results of the intermediate LCA are found much more uncertain than the results of the detailed LCA. The uncertainty of the results can be partly explained by the uncertainty of the interior temperature assumed to vary from 20 to 22°C. The range is slightly reduced compared to the screening assessment where a higher interior temperature range was considered (from 19 to 23°C). However, this parameter still has an important influence on the results.

As an illustration, Table 11 presents the share of impacts between operational energy use (through heat losses) and the construction materials added during the renovation of the facade.

Table 11 Share of environmental impacts between the operational energy use (through heat losses) and the insulation system added during the historic facade renovation

Share in %	Screening LCA	Intermediate LCA	Detailed LCA
Operational energy use	78% to 92 %	91% to 97%	91% to 97%
Construction materials (production + replacement + end of life)	8% to 22%	3% to 9%	3% to 9%

Results of the impact contributions show that the share of the new insulation system is about 3 to 22% in the three assessments. This finding confirms the results of the deterministic LCA and hence that the heat losses have more influence on the results than the construction materials. The contribution of added materials is found smaller in the detailed assessment once the stone thermal properties are more accurate.

This case study is only an exemplary one to illustrate the potential of using different levels of details in the heat losses assessment and for the LCA. It uses a Swiss example of a stone facade but could be applicable to other contexts and wall types, as eventually requested by further developments in RIBuild WP6 to prepare the RIBuild web tool.

If there are no more aleatory uncertainties, by increasing the level of knowledge and information of the studied object, a probabilistic assessment will become a deterministic one as far as all parameters are known with high accuracy. The only situation where uncertainties are still present is when we have aleatory uncertainties in the studied object. For example, in the historic building facade case study, the wall thickness is assumed to vary from 40 cm to 60 cm and this uncertainty cannot be reduced unless we assume a constant thickness for a specific part of the facade. That is the reason why even in a detailed LCA, the methodology still takes into account an uncertainty on the input parameters and thus on the output results.

However, by assuming no uncertainties on the stone wall thickness as well as on the internal insulation service life, the detailed LCA becomes deterministic yielding a deterministic result of 33 kg CO_2-eq/m^2.an for greenhouse gas emission savings and 153 MJ/m^2.an savings for non-renewable CED. The magnitude of these values is consistent with the results of the deterministic LCA conducted for Switzerland (upon comparison of data from harmonized scenarios).

The use of these three levels of probabilistic assessment can help a practitioner addressing the inherent LCA uncertainties. The use of a screening LCA is recommended for users who do not know exactly the location of the historic facade within the country but know the type of facade (e.g. stone facade). Similarly, it is appropriate when the manufacturer of the internal insulation system is not known.

The intermediate LCA is a flexible assessment in between the screening and the detailed LCA. In this exemplary case study, we have assumed that the user knows the internal insulation characteristics (e.g., thermal conductivity, on-site implementation loss of materials…) but has not detailed characteristic of the historic facade.

The detailed LCA is dedicated to the assessment of a well characterized facade (e.g. hygrothermal properties) leading to a more representative and realistic estimation of environmental impacts savings.

3.2 Comparison of the environmental performance of several design options

This exemplary application of the LCA probabilistic methodology shows how the method can be effectively used to compare the environmental performance of several design options, within a specific assessment scenario.

3.2.1 Definition of design options and simulation scenarios

The case study investigates three design options, i.e. internal thermal insulations, typically used in Italy in building renovation context (from Table 12 to Table 14):

- Insulation system A: 10 cm Expanded Polystyrene insulating material (EPS) coupled with plasterboard, without vapour barrier, directly fixed to the wall through a specific mortar;
- Insulation system B: 12 cm Cork, finished with a specific mortar as surface rendering (similar to ETICS - External Thermal Insulation Composite Systems- applications used in building facades) and directly fixed to the wall through a mortar;
- Insulation system C: 10 cm Rockwool coupled with plasterboard, with vapour barrier, fixed to the wall through a metallic frame.

Table 12 Insulation system A

Layer	Standard thickness [m]	Density [kg/m^3]	Thermal conductivity (W/mK)
Adhesive Mortar	0.006	1 400.00	0.540
EPS	0.100	18.00	0.035
Adhesive Mortar	0.006	1 400.00	0.540
Plasterboard	0.013	680.00	0.200
skimcoat	0.004	1 200.00	-
primer + paint	0.0002	1 670.00	-

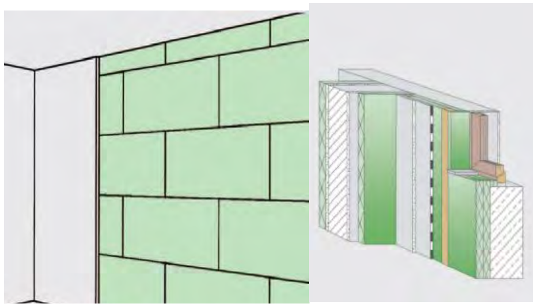
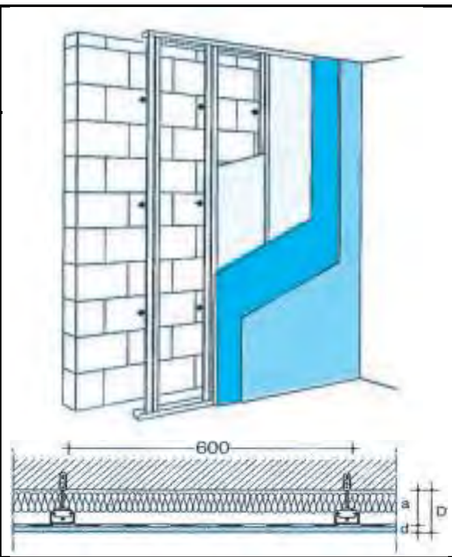


Table 13 Insulation system B

Layer	Standard thickness [m]	Density [kg/m^3]	Thermal conductivity (W/mK)
Adhesive Mortar	0.007	950.00	0.310
Cork	0.120	120.00	0.040
Surface rendering	0.007	950.00	0.310
primer + paint	0.0002	1 670.00	-

Table 14 Insulation system C

Layer	Standard thickness [m]	Density [kg/m^3]	Thermal conductivity (W/mK)
Rock Wool	0.1	70.00	0.035
Vapor barrier	0.0002	2 700.00	-
metal C profile		7 800.00	-
metal U-profile		7 800.00	-
fixing screw		7 800.00	-
Plasterboard	0.013	680.00	0.200
skimcoat	0.004	1 200.00	-
primer + paint	0.0002	1 670.00	-



The assessment is performed under the following scenario choices:

- Application to a plastered brick masonry configuration with a variable thickness (from 16 to 29 cm) that is supposed to be in the Italian region Emilia-Romagna, climatic zone "E";
- Reference study period of 30 years;
- Natural gas as heating source (with related equipment efficiency and conversion factor).

The functional unit is defined as the insulation intervention (realized with insulation systems A, B or C) needed to cover a wall area of 1 m^2, providing an average thermal resistance U ≤ 0.364 W/m²K (based on Italian Ministerial Decree 26/06/2015) for a building reference study period of 30 years.

The internal insulations allow reaching almost the same U-value for the wall based on the actual Italian law requirements. Italian Ministerial Decree 26/06/2015 imposes U ≤ 0.28 W/m²K for “second level renovation” interventions in the Italian climatic zone “E”. In accordance with D.M. 26/06/2015 this value has been increased by 30% since we are using internal insulation solutions: U ≤ 0.364 W/m²K). The U-values of the insulation systems are then: 0.33 W/m²K for the insulation system B and 0.34 W/m²K for the insulation systems A and C. The slight differences depend on the commercial insulation thicknesses available in the market.

3.2.2 Uncertainty characterisation and propagation

In the following Table 15, the PDFs of the parameters included in the LCA are summarized and their characterization procedure is described in the following paragraphs. The table has the same structure of the general table on PDFs characterisation proposed in section 2.5.2.

Table 15 PDFs of the parameters included in the LCA

LCA Stage (EN 15978 nomenclature)		**LCA Parameter description**	**PDF**
Production Stage	**Material**	Mass of the materials composing the insulation system [kg]	Triangular distribution
		Unitary environmental Impact of material [Unit of indicator]	Normal distribution
Use stage	**Maintenance**	Material Service Life (which affects the need of periodic replacement of the finishing layer of the insulation system) [years]	Deterministic value
	Replacement	Insulation System Service Life (which affects the whole insulation system replacement) [years]	Normal distribution
	Energy Consumption	Heat transmission losses through the wall [kWh/year]	Normal distribution
		Building overall efficiency for heating, depending on the heating generator, distribution and regulation efficiency [-]	Uniform distribution
	Energy Impact	Unitary environmental Impact of heating system [Unit of indicator]	Normal distribution
EoL stage	**EoL material impact**	Unitary environmental EoL Impact of material [Unit of indicator]	Normal distribution

All the inputs PDFs are presented in the data frames reported in Appendix 3, where the insulation solutions here presented as A, B, C are respectively numbers 1, 6, 7 of the data frame *insulation_system*.

The uncertainty analysis is performed through the *WP5 software tool* (presented in next section 4). Sobol’s sequences technique is used to generate samples from the input PDFs and propagate the uncertainties according to the methodology developed (section 2.6). 8192 simulation runs were performed, based on preliminary investigations on the accuracy of this sample size, and finally the probability distributions of the resulting environmental impacts were obtained.

Materials mass

The mass of the materials is subject to uncertainties due to the possible differences among provisional and real quantities installed during renovation. According to [25,96], a triangular distribution was assigned to the material mass, where the mode value is the quantity of material mass defined in the project; minimum and maximum value are defined considering a variation from -5% to +10% from the mode.

Materials and Insulation Systems Service Life

For the materials composing the insulation systems, the reference SL is considered as a deterministic value. When manufacturer's EPD (Environmental Product Declarations) for a specific product is available, the reference SL is taken from the EPDs, otherwise it is taken from literature or databases.

Since internal insulation solutions are composed of several materials with different service lives, the SL of the whole insulation system is established to be equal to the shortest SL among all the materials SLs, excluding the finishing material subjected to periodic maintenance. For the insulation systems, a value of RSL of 30 years is considered, and the ESL is calculated based on the probabilistic factorial method (ISO 15686-8), described in section 2.5.3. The following distributions have been assumed for the factors:

- Factor A (inherent performance level): uniform distribution (0.9; 1.1);
- Factor B (design level): uniform distribution (0.9; 1.1);
- Factor C (work execution level): uniform distribution (0.9; 1.1);
- Factor D (indoor environment): uniform distribution (0.9; 1.1);
- Factor E (outdoor environment): deterministic value (1);
- Factor F (usage conditions): uniform distribution (0.9; 1.1);
- Factor G (maintenance level): uniform distribution (0.9; 1.1).

It is assumed that all factors are influencing the SL of the insulation systems except for Factor E (outdoor environment). The PDF of the ESL obtained is a normal distribution.

Unitary Environmental production and EoL impacts of materials; energy vectors impacts

The characterisation is performed according to what described in section 2.5.2. Eco-Invent DB 3.1 has been used to characterize uncertainties of secondary data through the qualitative assessment of data quality indicators based on the pedigree matrix approach. Normal distribution has been assumed for all unit processes of ecoinvent data. Unitary environmental impacts for materials, energy vectors and EoL phases have been calculated by using SimaPro software v8.1, ReCiPe and CED methods, and then applying the uncertainty propagation through MonteCarlo method (500 runs). The following datasets have been selected from EcoInvent v3 to model materials:

- EPS: Polystyrene foam slab {RER}| production | Alloc Rec, U
- Cork. Cork slab {RER} | production | Alloc Rec, U
- Rockwool: Rock wool, packed {RER}| production | Alloc Rec, U
- Mortar and Surface rendering: Adhesive mortar {RoW}| production | Alloc Rec, U
- Plasterboard: Gypsum plasterboard {RoW}| production | Alloc Rec, U
- Metallic frame: Steel, low-alloyed, hot rolled {RER}| production | Alloc Rec, U
- Vapour barrier: Aluminium alloy, AlMg3 {RER} | production | Alloc Rec, U

The following datasets have been selected from EcoInvent v3 to model the energy vector:

- Gas: Heat, central or small-scale, natural gas {Europe without Switzerland}| heat production, natural gas, at boiler atm. low-NOx condensing non-modulating <100kW | Alloc Rec, U;

Due to the differences in the EcoInvent datasets for natural gas, which takes into account the specific boiler efficiency based on different technologies, the datasets values have been adapted according to data in Table 16.

Table 16 Adaptation of EcoInvent datasets for natural gas

	Dataset MC analysis from SimaPro			**Efficiency factor (inside the dataset)**	**Modified dataset**		
	PDF	**Mean**	**SD**		**PDF**	**Mean**	**SD**
Heat, central or small-scale, natural gas {Europe without Switzerland}| heat production, natural gas, at boiler atm. low-NOx condensing non-modulating <100kW | Alloc Rec, U - NO BOILER	rnorm	0.246	0.0418	100%	rnorm	0.246	0.0418
Heat, central or small-scale, natural gas {Europe without Switzerland}| heat production, natural gas, at boiler atm. low-NOx condensing non-modulating <100kW | Alloc Rec, U	rnorm	0.2605	0.0429	100%	rnorm	0.2605	0.0429
Heat, central or small-scale, natural gas {Europe without Switzerland}| heat production, natural gas, at boiler atmospheric low-NOx non-modulating <100kW | Alloc Rec, U	rnorm	0.282	0.0452	109%	rnorm	0.30738	0.0452
Heat, central or small-scale, natural gas {Europe without Switzerland}| heat production, natural gas, at boiler condensing modulating <100kW | Alloc Rec, U	rnorm	0.252	0.0443	98%	rnorm	0.24696	0.0443
Heat, central or small-scale, natural gas {Europe without Switzerland}| heat production, natural gas, at boiler fan burner low-NOx non-modulating <100kW | Alloc Rec, U	rnorm	0.294	0.0486	111%	rnorm	0.32634	0.0486
Heat, central or small-scale, natural gas {Europe without Switzerland}| heat production, natural gas, at boiler fan burner non-modulating <100kW | Alloc Rec, U	rnorm	0.275	0.0481	106%	rnorm	0.2915	0.0481
Heat, central or small-scale, natural gas {Europe without Switzerland}| heat production, natural gas, at boiler modulating <100kW | Alloc Rec, U	rnorm	0.267	0.045	104%	rnorm	0.27768	0.045

The following dataset has been selected from EcoInvent v3 to model the EoL phase for all the materials used:

- Municipal solid waste (waste scenario) {RoW}| Treatment of municipal solid waste, landfill | Alloc Rec, U.

The calculation of the impact at insulation system level, starting from materials impacts, is performed with the WP5 software tool through basic random Monte-Carlo simulations with 1000 iterations and distributions are estimated through a data-fitting test (see sections 2.5.2 and 4.2.3).

Heat transmission losses

The calculation of the heat transmission losses has been performed based on approach 3 (annual HDD), described in section 2.5.1 and implemented in WP5 software tool, with the following assumptions:

- Thermal Resistance of the original wall: from 0.22 to 0.40 m^2K/W (based on the wall thickness variation);
- HDD of Emilia Romagna Region, climatic zone E (Italy).

Energy source conversion factor

An energy conversion factor was applied to calculate primary energy from delivered energy, depending on the energy source typology. The conversion factor for natural gas is fixed at the deterministic value established by Italian Ministerial Decree 26/06/2015: 1.05.

Building global efficiency for heating

Considering the energy source scenarios, a uniform distribution was assigned to the heating equipment efficiency based on authors' judgment: 0.6-1 for natural gas.

3.2.3 Results

For the insulation systems, the output samples of the environmental impacts for the indicators selected (Climate Change and CED_{NRE}) are obtained. Results are presented through the box-whiskers plots in Figure 14, where red points represent the result of a ”deterministic” LCA assessment performed on the same solutions, and the cumulative distribution functions (CDF) in Figure 15.

As is observed from Figure 15, are the results associated with considerable uncertainty: the blue box plots represent only a 50% probability that impact values are contained within those ranges, which vary for the Climate Change indicator from about 162 to 221 kg CO_2-eq for solution A, from about 182 to 248 kgCO_2-eq for solution B and from about 159 to 217 kg of CO_2-eq for solution C. For CED_{NRE} indicators they vary from about 2339 to 3430 MJ for Solution A, from 2538 to 3663 MJ for Solution B and from about 2166 to 3236 MJ for Solution C.

The representation of CDFs (Figure 15) is useful to compare the probability that a certain solution reaches an environmental impact target. E.g., by fixing an environmental impact of 250 KgCO_2-eq, there is a probability of 85% that impacts of solutions A and C are below this level and of 70% for solution B. Cumulative curves present a similar trend for both Climate Change and CED_{NRE} indicators.

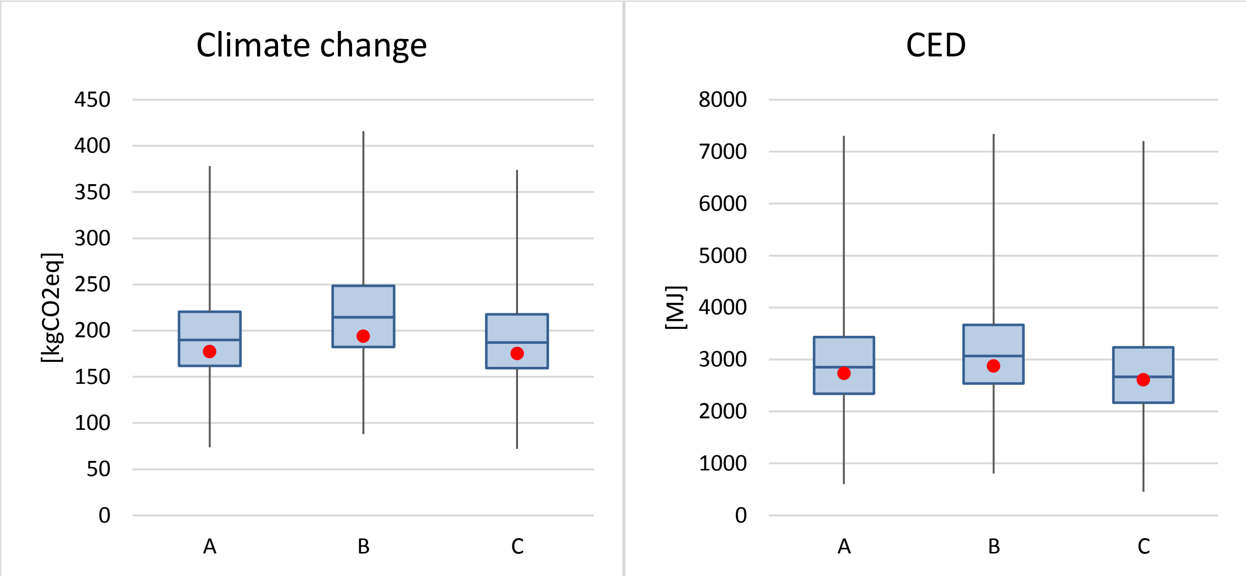


Figure 14 Box-whiskers plots of the environmental impacts (Climate change and CED_{NRE} indicators) for design options A, B, C, with natural gas as energy scenario and a reference study period of 30 years. Red points represent the result of a "deterministic" LCA assessment performed on the same solutions.

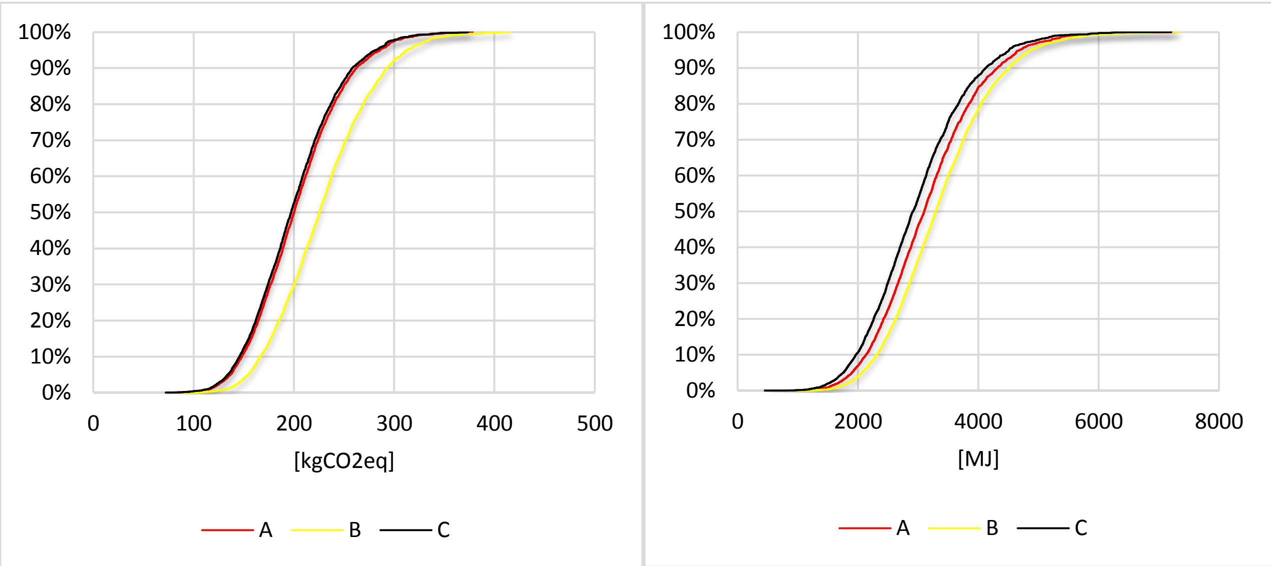


Figure 15 Cumulative distribution of the environmental impacts (Climate change and CED_{NRE} indicators) for design options A, B, C, with natural gas as energy scenario and a reference study period of 30 years

Inspecting the result details, concerning Climate Change indicator, insulation solution A (EPS) reaches a median value of about 193 kg of CO_2-eq with a standard deviation of about 44; while solution B (cork) reaches a median value of 218 kg of CO_2-eq with a standard deviation of about 48, and solution C (rockwool) reaches a median value of 190 kg of CO_2-eq with a standard deviation of about 43. Concerning CED_{NRE} indicator, insulation solution A (EPS) reaches a median value of 2932 MJ with a standard deviation of about 831; while solution B (cork) reaches a median value of 3139 MJ with a standard deviation of about 841; and solution C (rockwool) reaches a median value of 2750 MJ with a standard deviation of about 819.

Given the similarity among some of the median values of the distributions obtained, a statistical analysis was then performed (*two-tailed t-test*)[17], to establish whether the obtained distributions are statistically significantly different. According to the test results[18], the mean values of the distributions can be considered statistically different. What in general emerges from the results is that Solution C (rockwool) is the one able to guarantee minor median values of the impacts according to both indicators, followed by Solution A (EPS) and B (cork).

To further deepen the probabilistic results obtained, the impacts related to each phase of the total life cycle, are also analysed (Table 18).

In general terms solution A (EPS) and C (rockwool), the production phases (including the maintenance) have an impact which contribute with about 10-15% of the total life cycle impact, while the use phase ranges between about 82% and 90% and EoL between about 0% and 5%. For solution B (cork), the production phase contributes with an impact of about 20% of the total life cycle impact, while use the phase ranges between about 73% and 80% and Eol between about 0% and 7%.

Table 17 Life cycle phase impact weight for Solution A, B and C (Climate change and CED_{NRE} indicator), for gas scenario and a reference period of 30 years

Energy source	Phase	Climate change Indicator			CED_{NRE} Indicator		
		A	B	C	A	B	C
Gas	Production+Maintenance	13.65%	20.63%	12.16%	14.48%	20.36%	9.83%
	Use	81.71%	72.97%	83.14%	85.29%	79.33%	89.94%
	End of Life	4.64%	6.40%	4.70%	0.22%	0.30%	0.23%

Impacts related to the use phase are almost the same for all the insulation measures, due to the fact that their thicknesses have been defined to provide the same average thermal resistance. Likewise, impacts related to the EoL and the maintenance phase are almost the same for all the insulation measures.

Impacts related to production phase are on the other hand quite different for each solution (they depend on the typology of material used and their mass). Unitary environmental impacts of rockwool and cork are very similar to each other (both for Climate Change and CED_{NRE} indicators) and minor than those ones related to EPS. However, insulation material masses are quite different in the three systems: the mass of cork for a square meter is about 14 kg, therefore much higher than the ones for rockwool and EPS, which are respectively 7 kg and 1.8 kg. This fact therefore determines a higher total impact related to the production phase for Solution B (cork), followed by Solution A (EPS) and C (rockwool).

[17] The test allows to assess if the null hypothesis of equal means (equivalence of the mean values) is to reject or not. If the test results are lower than 0.05, we reject the null hypothesis of equal means, then the means are considered different.
[18] In all cases, the two-tailed t-test results are 0, then we reject the null hypothesis of equal means.

3.3 Assessment of results robustness under different scenarios for energy sources and building reference study periods – Case study 1

In this section, the methodology is applied to evaluate the robustness of the results obtained in the previous case-study, considering several assessment scenarios. This application of the methodology is useful to support designers in the selection of the best solution, under several possible conditions. In this case-study, three insulation measures are compared under three energy scenarios (Gas, Electricity and Oil as building energy sources) and two reference study periods (30 and 45 years).

3.3.1 Definition of design options and simulation scenarios

The design options are the same as those of the previous case in section 3.2, namely insulation systems A (EPS), B (cork), C (rockwool).

The assessment is performed under the following scenario choices:

- Application to a plastered brick masonry configuration with a variable thickness (from 16 to 29 cm) that is supposed to be in the Italian region Emilia-Romagna, climatic zone "E";
- 2 reference study periods: 30 and 45 years;
- 3 energy scenarios: Natural gas, Electricity and Oil as heating sources (with related equipment efficiency and conversion factor).

In Italy, even if the most widespread energy source for heating is natural gas, oil is still in use today mostly in centralized heating systems and old buildings, and, on the other hand, in recent years the electricity is more and more used to feed heat pumps for building heating, also depending on the diffusion of renewable energy sources (as photovoltaic).

The two functional units of the LCA, depending on the reference study periods, are then:

- the insulation intervention (realized with insulation systems A, B or C) needed to cover a wall area of 1 m^2, providing an average thermal resistance $U \leq 0.364$ W/m²K (based on Italian Ministerial Decree 26/06/2015) for a building reference study period of 30 years.
- the insulation intervention (realized with insulation systems A, B or C) needed to cover a wall area of 1 m^2, providing an average thermal resistance $U \leq 0.364$ W/m²K (based on Italian Ministerial Decree 26/06/2015) for a building reference study period of 45 years.

3.3.2 Uncertainty characterisation and propagation

The PDFs of the parameters included in the LCA are the same of the previous case in section 3.2. Furthermore, the following datasets have been selected from EcoInvent v3 to model the other two energy vectors:

- Electricity: Heat, central or small-scale, other than natural gas {Europe without Switzerland}| heat production, at heat pump 30kW, allocation exergy | Alloc Rec, U
- Oil: Heat, central or small-scale, other than natural gas {Europe without Switzerland}| heat production, light fuel oil, at boiler 100kW condensing, non-modulating | Alloc Rec, U;

The conversion factors for the other two energy sources considered are 2.42 and 1.07, respectively for electricity and oil. A uniform distribution was assigned to the heating equipment efficiency based on authors' judgment: 2.5-4 for electricity and 0.4-0.8 for oil.

As for the previous case in section 3.2, the uncertainty analysis is performed through the *WP5 software tool* under the same calculation assumptions.

3.3.3 Results

The results obtained are shown in the following figures, where the box-whiskers plots and cumulative distributions of the environmental impacts of the three insulation solutions under the three different energy scenarios are reported for a fixed reference study period and for each impact indicator (Climate change and CED_{NRE}).

Figure 16 16 and Figure 17 report the boxplots for a study period of 30 years. Red points represent results of a "deterministic" LCA assessment performed. Figure 18 and Figure 19 show the cumulative distributions of the three design options under each energy scenario in the same reference study period. It is evident how the energy scenario influences both the mean values and the variance of the environmental impacts of the solutions. "Electricity" scenario is able to guarantee the lower environmental impacts (both for Climate change and CED indicators), followed by Gas and Oil, and also a lower uncertainty on the results. "Oil" scenario entail higher impacts and higher uncertainty ranges.

This result is justified by the considerable impact weight induced by the operational energy related to the use phase impacts, if compared with the impacts of the other life cycle phases. Further reason is related to the fact the "Oil" represents the most impacting energy vector among those ones analysed (highest unitary environmental impact).

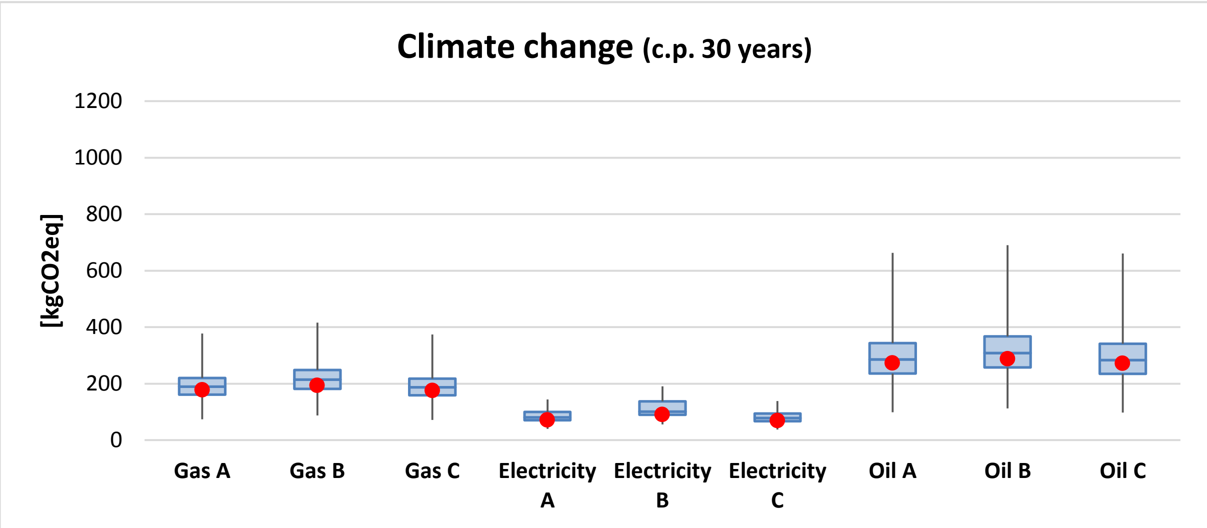


Figure 16 Environmental impact of Systems A, B and C (Climate change indicator) for electricity, gas and oil scenarios (reference study period 30 years). Red points represent the result of a "deterministic" LCA assessment performed on the same solutions.

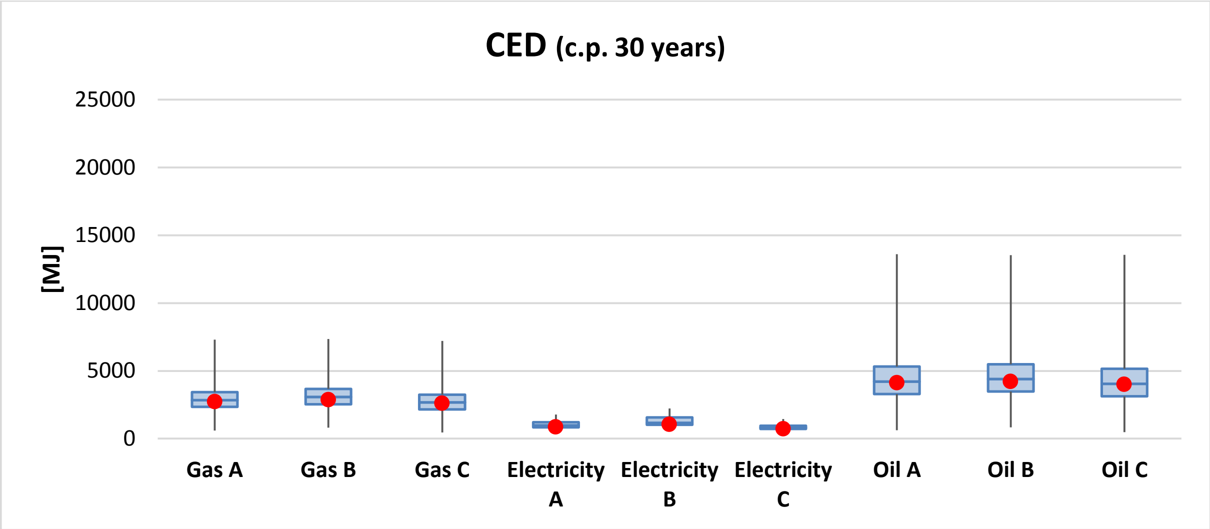


Figure 17 Environmental impact of Systems A, B and C (CED_{NRE} indicator) for electricity, gas and oil scenarios (reference study period 30 years). Red points represent the result of a "deterministic" LCA assessment performed on the same solutions.

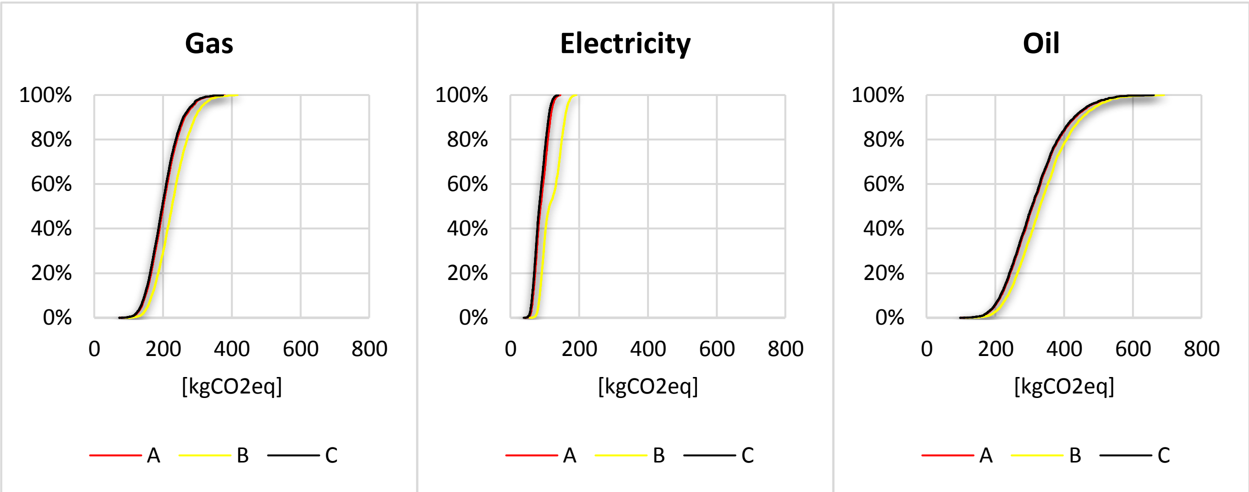


Figure 18 Cumulative distribution of the environmental impacts of Systems A, B and C (Climate change indicator) for gas, electricity and oil scenarios (reference study period of 30 years).

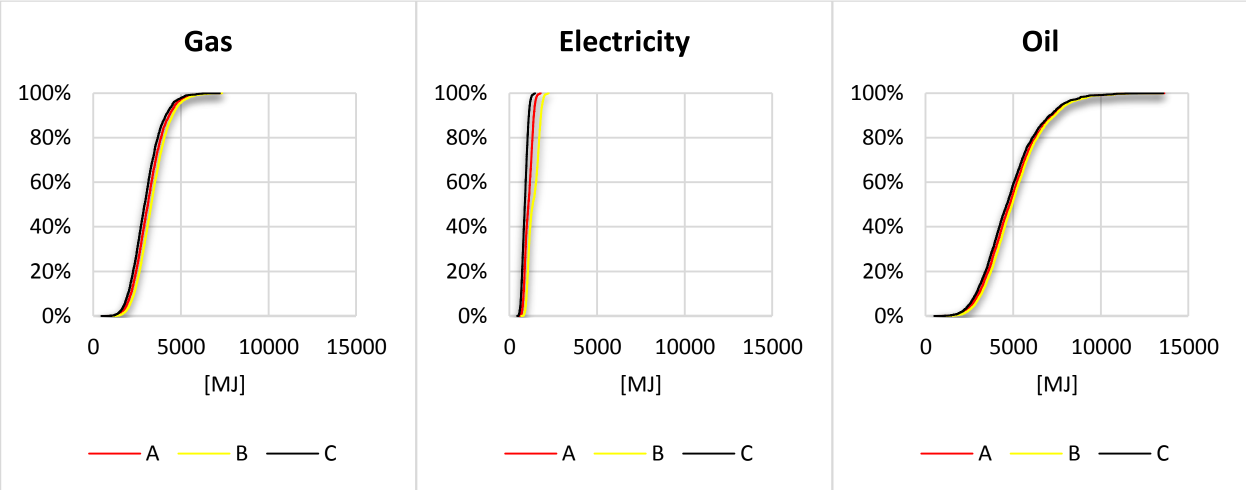


Figure 19 Cumulative distribution of the environmental impacts of Systems A, B and C (CED_{NRE} indicator) for gas, electricity and oil scenarios (reference study period of 30 years).

Looking at median values, the percentages for impacts at phase level can be derived, as shown in Table 18.

Table 18 Life cycle phases impact weight for Solution A, B and C (Climate change and CEDNRE indicator), for electricity, gas and oil scenarios and a reference period of 30 years

Energy source	Phase	Climate change Indicator			CED_{NRE} Indicator		
		A	B	C	A	B	C
Gas	Production+Maintenance	13.65%	20.63%	12.16%	14.48%	20.36%	9.83%
	Use	81.71%	72.97%	83.14%	85.29%	79.33%	89.94%
	End of Life	4.64%	6.40%	4.70%	0.22%	0.30%	0.23%
Electricity	Production+Maintenance	34.01%	44.33%	31.10%	45.34%	55.48%	34.80%
	Use	54.43%	41.93%	56.88%	53.97%	43.69%	64.38%
	End of Life	11.56%	13.74%	12.02%	0.70%	0.83%	0.81%
Oil	Production+Maintenance	8.87%	13.92%	7.85%	9.61%	13.84%	6.41%
	Use	88.12%	81.76%	89.12%	90.24%	85.95%	93.45%
	End of Life	3.01%	4.32%	3.03%	0.15%	0.21%	0.15%

The best performance is delivered by insulation solution C, based on median values of the environmental impacts, both for Climate change and CED_{NRE} indicator, is confirmed under all the three energy scenarios considered. Nevertheless, given the similarity among some of the median values of the distributions obtained, a statistical analysis was performed (two-tailed t-test)[19], to establish whether the obtained distributions are statistically significantly different. According to the test results[20], the mean values of the distributions can be considered statistically different in all cases, except under the energy "oil" scenario and for Climate Change indicator, where the mean values of insulation solutions A and C are very closed.

[19] The test allows to assess if the null hypothesis of equal means (equivalence of the mean values) is to reject or not. If the test results are lower than 0.05, we reject the null hypothesis of equal means, then the means are considered different.
[20] In all cases, the t-test results are 0, then we reject the null hypothesis of equal means.

The robustness of the results obtained on the best environmental performance of insulation solution C, followed by A and finally B, both for Climate change and CED_{NRE} indicator, can be then considered as confirmed under the energy scenarios “gas” and “electricity” and the two reference study periods, while the performance of solution C in the “oil” scenario and for Climate Change indicator is comparable to that of A.

Impacts related to the use phase are almost the same for all the insulation measures under a same energy scenario, due to the fact that their thicknesses have been defined to provide the same average thermal resistance. Solution C then presents lower impacts considering the other phases, in respect to the other solutions.

In Figure 20 to Figure 23 the same results are shown for a reference study period of 45 years. Trends are similar to those obtained for 30 years The environmental impacts are larger than those obtained for 30 years due to the extension of the calculation period and the subsequent increase of the operational use phase related impacts.

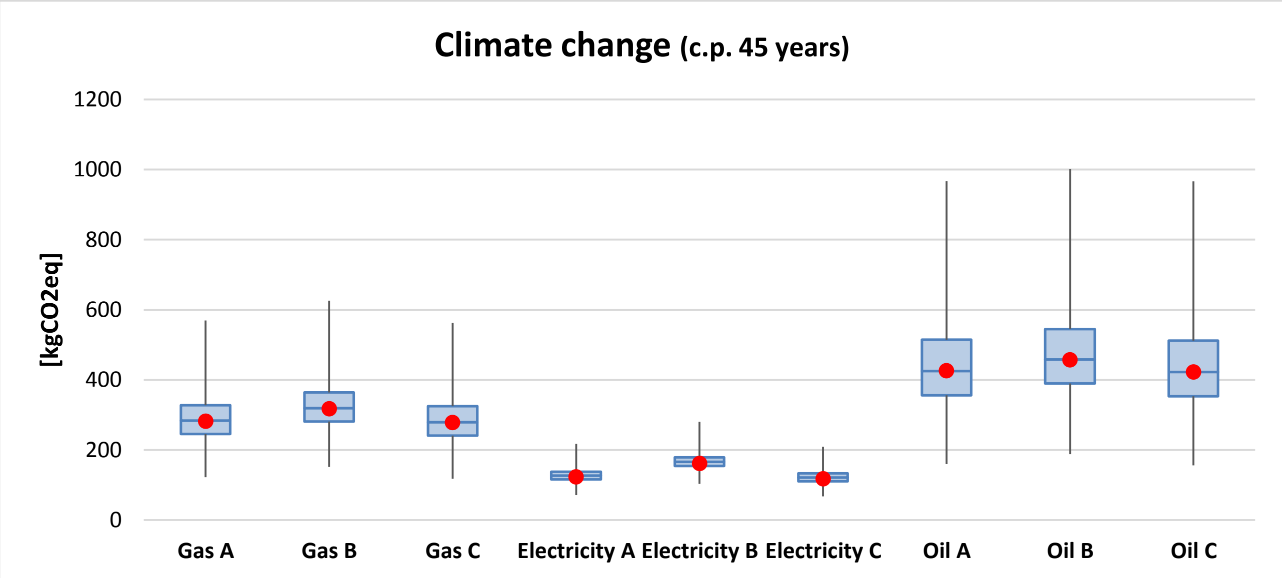


Figure 20 Environmental impact of System A, B and C (Climate change indicator) for Electricity, gas and oil scenarios (reference study period of 45 years). Red points represent the result of a “deterministic” LCA assessment performed on the same solutions.

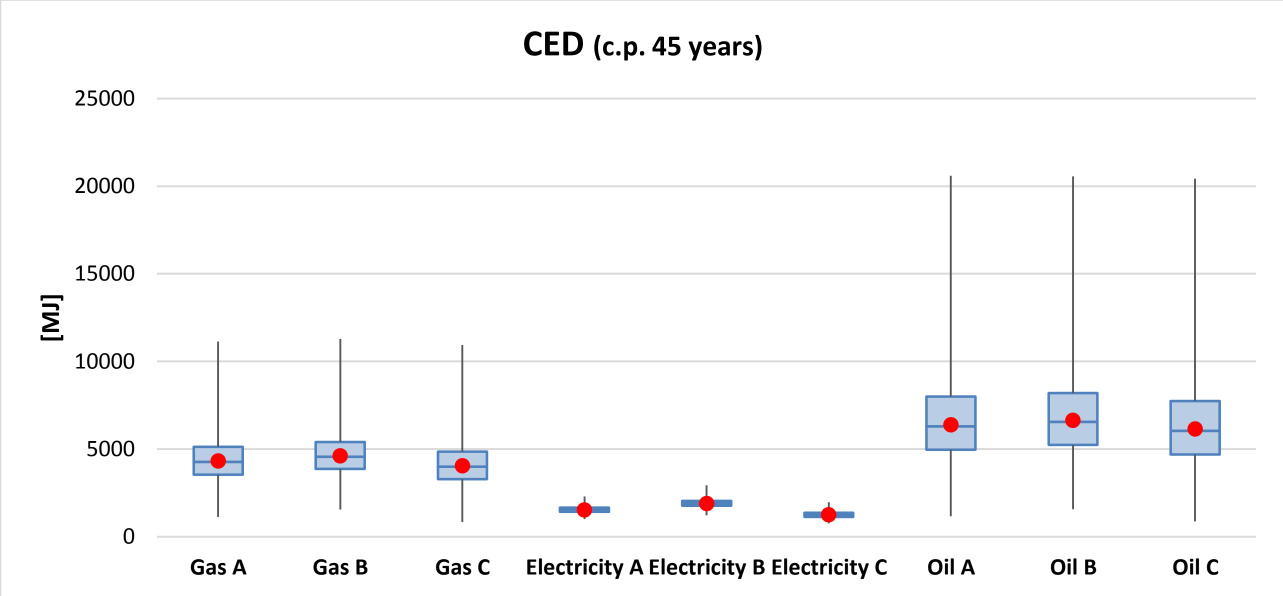


Figure 21 Environmental impact of System A, B and C (CED_{NRE} indicator) for Electricity, gas and oil scenarios (reference study period of 45 years). Red points represent the result of a "deterministic" LCA assessment performed on the same solutions.

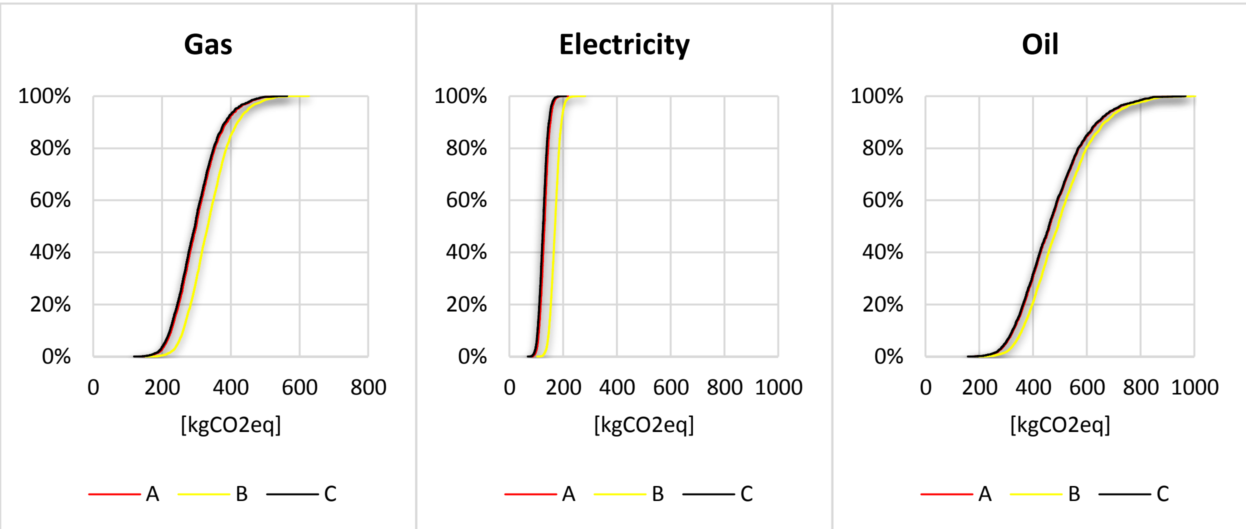


Figure 22 Cumulative distribution of the environmental impacts of Systems A, B and C (Climate change indicator) for gas, electricity and oil scenarios (reference study period of 45 years).

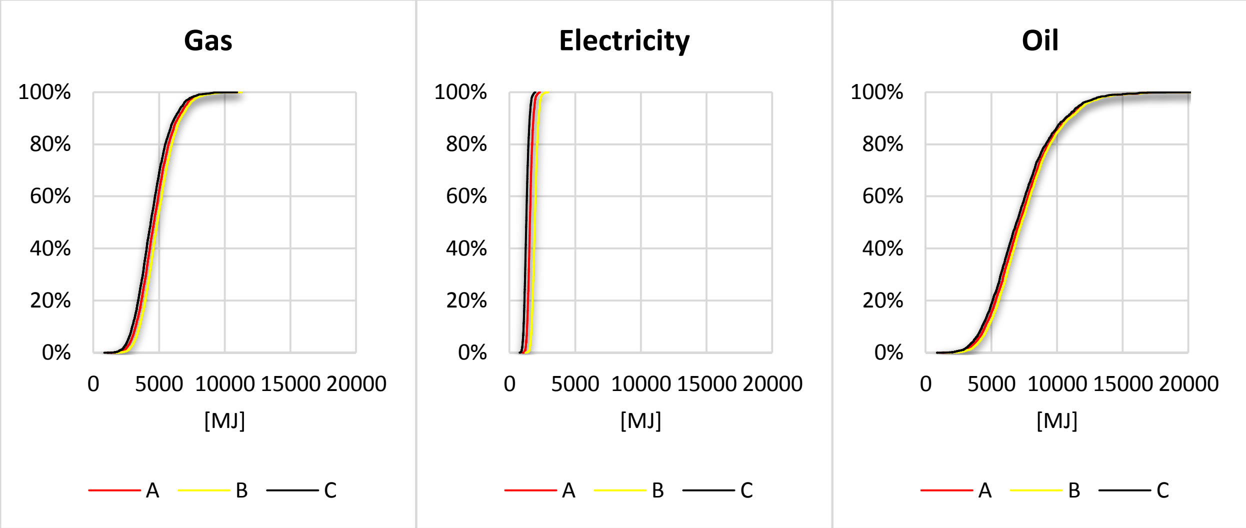


Figure 23 Cumulative distribution of the environmental impacts of Systems A, B and C (CED_{NRE} indicator) for gas, electricity and oil scenarios (reference study period of 45 years).

3.4 Assessment of results robustness under different scenarios for energy sources and building reference study periods – Case study 2

In this section, the methodology is applied to assess the robustness of the results on the environmental impacts of different design options under several energy scenarios, with the final aim to support designers in the selection of the best solution. In particular two insulation measures are compared under three energy scenarios (Gas, Electricity and District Heating as energy sources) under a reference study periods (30 years).

3.4.1 Definition of design options and simulation scenarios

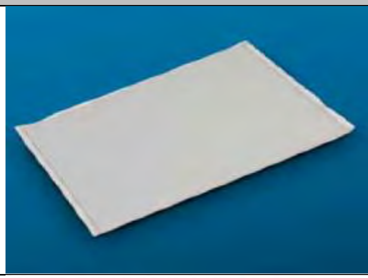
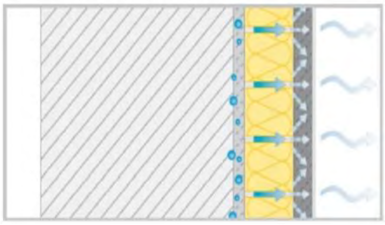
The case study investigates two design options, i.e. internal thermal insulations, typically used in Denmark in building renovation context, as detailed below (Table 19):

- Insulation System B: This system consists of 150 mm of Microtherm climate panel fully bonded with inorganic adhesive plaster and putty. The Microtherm insulation boards are fully adhered to the wall surface with 8 to 10 mm layer of “plus puds” (plus plaster). Plus puds is also used for the surface rendering of 2 to 3 mm.
- Insulation System C: The system consists of 80 mm IQ-Therm board (foam board), iQ-Fix (inorganic adhesives), IQ-Top (gypsum plasterboard), IQ-Fill (putty) and paintings.

The assessment is performed under the following scenario choices:

- Application to a plastered brick masonry configuration with a thickness of 35 cm, that is supposed to be in Copenhagen (Danish national climate zone);
- Reference study period of 30 years;
- 3 energy sources: Natural gas, Electricity and District Heating (with related equipment efficiency and conversion factor).

Table 19 Insulation systems B and C

Insulation system	Material Layers	Thickness [m]	Density [kg/m^3]	
B -MicroTherm insulation system	Microtherm climate panel	0.15	500	
	Inorganic adhesive plaster	0.005	1350	
	Putty	0.005	1400	
C -iQ-Therm insulation system	iQ-Therm board	0.08	45	
	iQ-Fix adhesive	0.005	1500	
	iQ-Top	0.005	630	
	iQ-Fill	0.003	1200	
	Pimer + Paint	0.003	1200	

In Denmark, even if the most widespread energy source for heating is district heating, natural gas is still in use today in centralized heating systems and old buildings, and, on the other hand, in recent years the electricity is more and more used to feed heat pumps for building heating.

The functional unit is defined as the insulation intervention (realized with insulation systems B or C) needed to cover a wall area of 1 m^2, providing an average thermal resistance for a building reference study period of 30 years. The thicknesses are chosen from the commercial insulation thicknesses available in the market.

3.4.2 Uncertainty characterisation and propagation

In this illustrative example, it is assumed that no failure or replacement occurred on the insulation system during the calculation period.

Three parameters are considered as stochastic in order to account for the inherent uncertainties: the mass of the insulation system; the unitary environmental impact during the production phase and the end of life (EOL) phase; the unitary environmental impact during the use phase for various energy sources. Their PDFs are mainly defined based on the data collected from the literature survey and existing LCI databases.

The uncertainty analysis is performed through the WP5 software tool (presented in next section 4). Details on all the inputs PDFs, described in the previous paragraphs, are presented in the data frames reported in Appendix 3, where the insulation solutions here presented as B and C are respectively numbers 15 and 19 of the data frame *insulation system*.

Table 20 presents the LCA stages included in the assessment, the identification and characterisation of the input parameters. The characterization procedure for stochastic inputs is detailed in the following paragraphs.

Table 20 PDFs of the parameters included in the LCA

LCA Stage (EN 15978 nomenclature)		LCA Parameter description	PDF
Production Stage	Material	Mass of the materials composing the insulation system [kg]	Triangular distribution
		Unitary environmental Impact of material [Unit of indicator]	Normal distribution/Deterministic value
Use stage	Energy Consumption	Heat transmission losses through the wall [kWh/year]	Deterministic value
		Building overall efficiency for heating, depending on the heating generator, distribution and regulation efficiency [-]	Deterministic value
	Energy Impact	Unitary environmental Impact of heating system [Unit of indicator]	Normal distribution/Deterministic value
EoL stage	EoL material impact	Unitary environmental EoL Impact of material [Unit of indicator]	Normal distribution/Deterministic value

Materials mass

The mass of materials is subject to uncertainties due to the possible differences among provisional and real quantities installed during renovation. According to [25,96], a triangular distribution was assigned to the material mass, where the mode value is the quantity of material mass defined in the project; minimum and maximum value are defined considering a variation from -5% to +10% from the mode.

Unitary Environmental production and EoL impacts of materials; Energy vectors impacts

The characterisation is performed according to what described in section 2.5.2. For the uncertainty characterization of the production and the EOL, the unitary environmental impacts for the adhesive mortars and painting are assumed to follow normal distributions. Unitary environmental impacts for materials, energy vectors and EoL phases have been calculated by using SimaPro software v8.1, using the ReCiPe (H) and CED methods based on the MC simulation (500 runs).

For all other materials, the unitary environmental impacts are considered as deterministic, provided by the Danish national EPDs. Table 21 presents the datasets that have been selected from EcoInvent v3 and EPDs to model materials impacts.

Table 21 LCI dataset for each material

Insulation option	**Material layer**	**LCI database** (Ecoinvent, Danish EPD)
MicroTherm insulation system	Microtherm climate panel	EPD-CSP-2013111-IAC3-EN Calcium Silicate Insulating Materials
	Inorganic adhesive plaster	Adhesive mortar {RoW}| production | Alloc Rec, U
	Putty	Adhesive mortar {RoW}| production | Alloc Rec, U
iQ-Therm insulation system	iQ-Therm PUR board	EPD for iQ-Therm PU (PUR / PIR) thermal insulation boards
	iQ-Fix adhesive	Adhesive mortar {RoW}| production | Alloc Rec, U
	iQ-Top	EPD Gyproc WallBoard S-P-00506
	iQ-Fill	Adhesive mortar {RoW}| production | Alloc Rec, U
	Primer + Paint	Metal coating facility {RER}| construction | Alloc Def, U

The EoL phase of materials without Danish EPD data is modelled by the following dataset from Ecoinvent:

- Municipal solid waste (waste scenario) {RoW}| Treatment of municipal solid waste, landfill | Alloc Rec, U.

The calculation of the impact at insulation system level, starting from materials impacts, is performed within WP5 software tool through basic random Monte-Carlo with 1000 iterations and distributions are estimated through a data-fitting test (see sections 2.5.2 and 4.2.3).

The following datasets have been selected from EcoInvent v3 to model the energy sources:

- Gas: Heat, central or small-scale, natural gas {Europe without Switzerland}| heat production, natural gas, at boiler atm. low-NO_x condensing non-modulating <100kW | Alloc Rec, U;
- Electricity: Heat, central or small-scale, other than natural gas {Europe without Switzerland}| heat production, at heat pump 30kW, allocation exergy | Alloc Rec, U
- District heating: Heat, district or industrial, other than natural gas {GLO}| market group for | Conseq, U

Other deterministic inputs

The calculation of the heat transmission losses has been performed based on annual HDD method, considering a thermal Resistance of the existing material of 0.261 m^2K/W and HDD of climate in Copenhagen, Denmark.

The conversion factors for the energy sources considered are 1, 2.5 and 1, respectively for natural gas, electricity and district heating.

Deterministic values were also assigned to the heating equipment efficiency based on authors' judgment: 0.9 for natural gas, 0.9 for electricity and 0.95 for district heating.

3.4.3 Results

The box-whisker plots in Figure 24, and the cumulative density functions (CDFs) in Figure 25 present the life stage contribution for two environmental indicators (climate change and the non-renewable primary energy) for the two insulation options, in the natural gas energy scenario.

In Figure 24, noticeable result uncertainties emerge, the blue box plots represent only a 50% probability that impact values are contained within those ranges, which vary for the Climate Change indicator from about 406 to 462 kg of CO_2 eq. for option B and from about 316 to 380 kg of CO_2 eq. for option C. For CED indicator, they vary from about 5639 to 7024 MJ for option B and from about 3842 to 5095 MJ for option C. The uncertainty ranges for the unitary environmental impacts of iQ-Therm and MicroTherm are similar both for Climate Change and CED indicators.

In particular, concerning Climate Change indicator, solution B (MicroTherm) reaches a median value of 434.36 kg of CO_2 eq. with a standard deviation of about 42.15, and solution C (iQ-Therm) reaches a median value of 348.47 kg of CO_2 eq. with a standard deviation of about 47.56. Concerning CED indicator, insulation solution B (MicroTherm) reaches a median value of 6336.27 MJ with a standard deviation of about 1024.37; and solution C (iQ-Therm) reaches a median value of 4470.25 MJ with a standard deviation of about 933.95.

The representation of CDFs (Figure 25) is useful to compare the probability that a certain solution reaches an environmental impact target. E.g., by fixing an environmental impact of 400 Kg CO_2-eq, there is a probability of 18% that impacts of solutions B are below this level and of 80% for solution C.

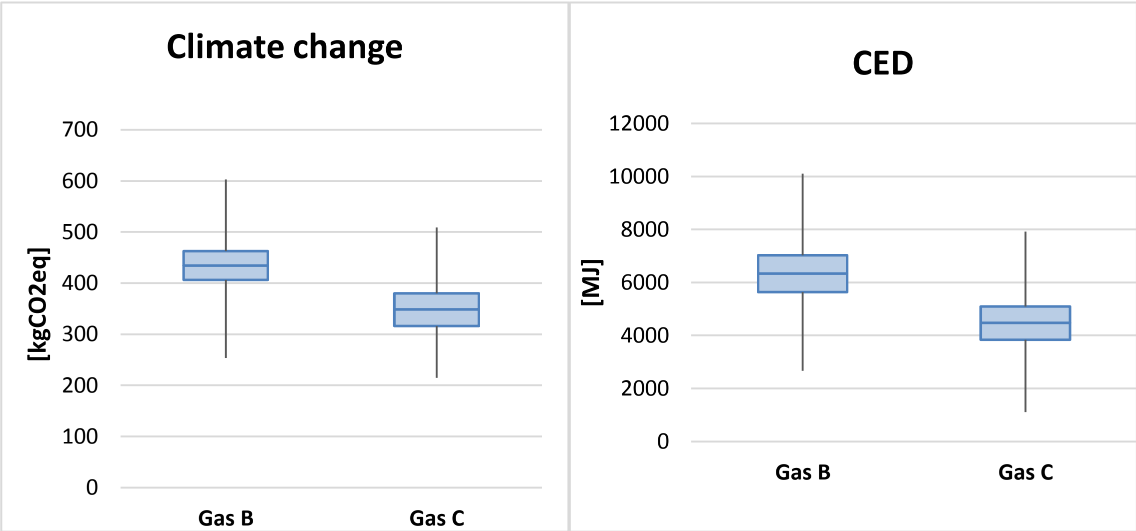


Figure 24 Box-whiskers plots of the environmental impacts (Climate change and CED indicators) for design options B and C, with natural gas as energy scenario and a reference study period of 30 years

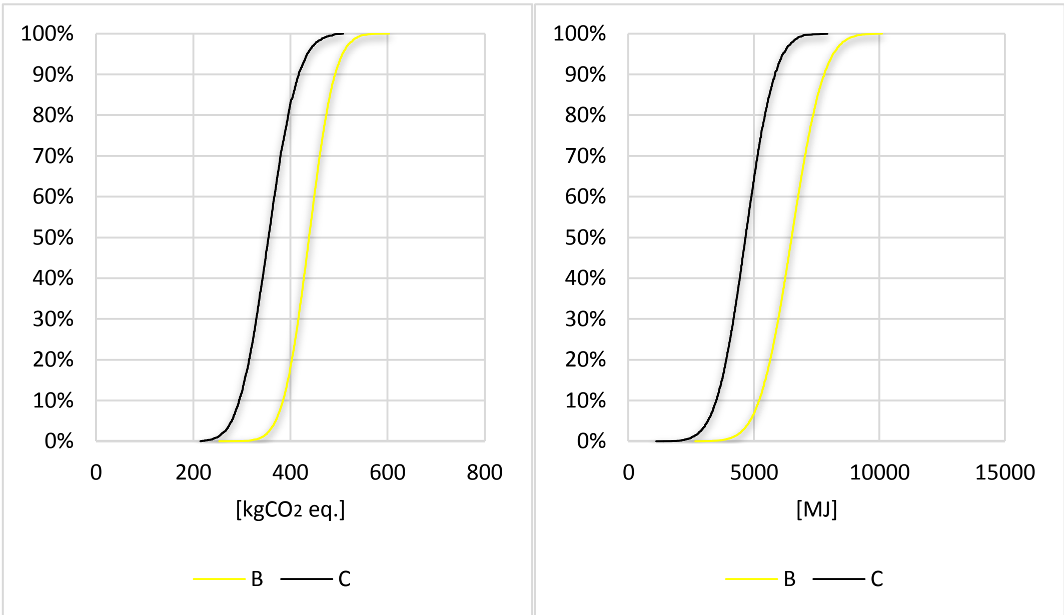


Figure 25 Cumulative distributions of the environmental impacts (Climate change and CED indicators) for design options B and C, with natural gas as energy scenario and a reference study period of 30 years

Figure 26 and Figure 27 represent the box-whisker plots for the environmental impacts of the two insulation solutions under the three different energy scenarios for a fixed reference study period of 30 years and for two impact indicators (Climate change and CED).

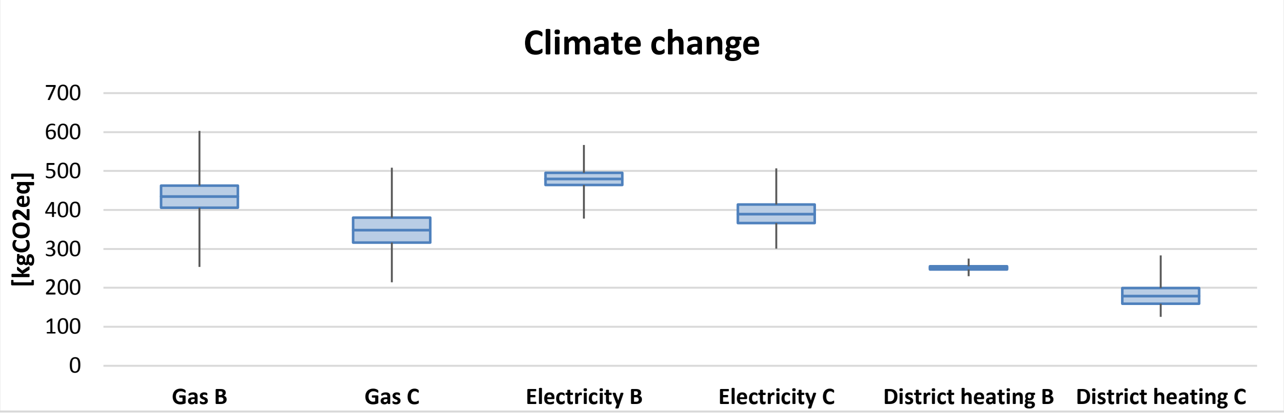


Figure 26 Environmental impact of Systems A, B and C (Climate change indicator) for Electricity, gas and oil scenarios (reference study period of 30 years)

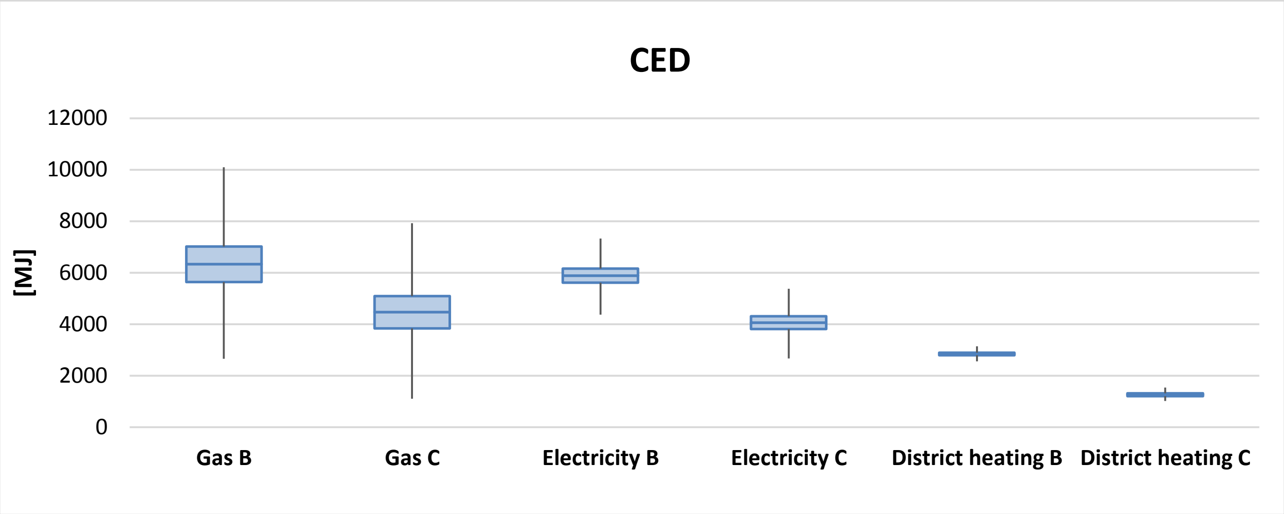


Figure 27 Environmental impact of Systems A, B and C (CED indicator) for Electricity, gas and oil scenarios (reference study period of 30 years)

It is evident how the energy scenario influences both the mean values and the variance of the environmental impacts of the solutions. "District heating" scenario entails the lower environmental impacts both for Climate change and CED indicators, followed by electricity and natural gas, and also a lower uncertainty on the results. The "natural gas" scenario entails higher impacts and higher uncertainty ranges.

Insulation solution C shows the most favourable performance, in terms of environmental impact both for Climate change and CED indicator, under all the three energy scenarios considered.

3.5 Identification of influential parameters on the outcome uncertainty

In this section, the methodology is applied to calculate sensitivity indices, with the aim to assess which input parameter uncertainty has more impact on results variance.
The analysis is performed under the simulation assumptions established for the cases of sections 3.2 and 0 and previously described: the three insulation measures A,B,C are compared under three

energy scenarios (Gas, Electricity and Oil as building energy sources) and two reference study periods (30 and 45 years).

3.5.1 Results

The following Figure 28, Figure 29 and Figure 30 represent the total order sensitivity indices of the LCA input data for the three insulation solutions, under the three different energy scenario and during a reference study period of 30 years[21]. The nomenclature used in the graph is the following:

- sI = insulation system environmental impact related to production phase;
- smI = insulation system environmental impact related to maintenance phase;
- EoLI = insulation system environmental impact related to end of life phase;
- Qhpost = heat transmission losses through the wall after renovation;
- ETAh = overall system efficiency for heating
- SL= insulation system service life
- EI = Unitary impact of the energy vector

From the graphs, it is evident how the input uncertainty impacts vary across the different energy scenarios, while a certain consistency is noticeable within the individual energy scenario and impact indicator specific result sets.

Furthermore, except for some exceptions, the sensitivity indices trends are similar for the three insulation solutions considered. This is more evident for the “gas” and “oil” scenarios (Figure 28 and Figure 30), while there are small differences in the indices ranking for the “electricity” case (Figure 29). This result can be related to the fact that electricity is the energy vector with the lowest unitary environmental impact, if compared with gas and oil. Consequently, the total life cycle impact of insulation systems is mainly influenced by the impact of the production phase which is different for the three systems.

In the “gas” and “oil” scenarios (Figure 28 and Figure 30), four inputs account for almost the whole output uncertainty: Qhpost, ETAh, EI and SL. The first three are related to the system energy performance and the energy vector impact and their great influence on output variance is due (1) to the importance of the operational energy use phase use in the whole LCA and (2) to their inherent uncertainties.

In the “electricity” scenario (Figure 29), the most influential input uncertainty is related to the system service life (responsible for the output variance of about 60% to 80%). This influence is due to the fact that within the electricity energy scenario, the operational energy use is of lower importance if compared to the other LCA phases. For this reason, Qhpost, ETAh, EI uncertainties are less influential on total uncertainty, both for CED_{NRE} and Climate change indicators.

Furthermore, another important phenomenon happens: as the mean value of the insulation solutions SL is set to 30 years, as well as the reference study period, during the Monte-Carlo sampling procedure some draws occur before 30 years, thus inducing the replacement of the whole insulation system and then affecting the outcome uncertainty.

[21] In the results obtained, the sum of the total order sensitivity indices of the LCA data inputs is always greater than 1, as requested by Sobol’s method [97].

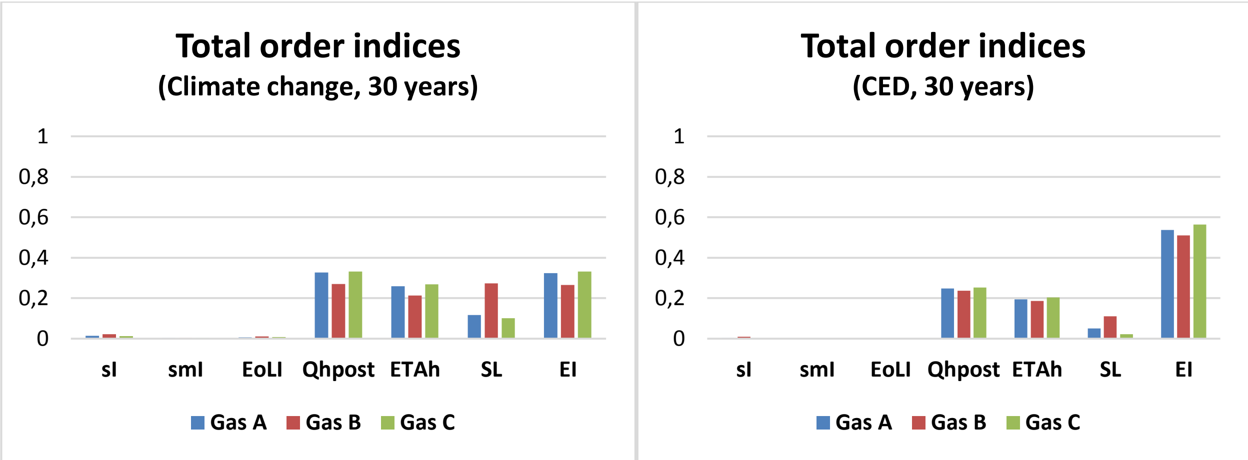


Figure 28 Total order indices of Systems A, B, and C (Climate change and CED_{NRE} indicators) for gas scenario and a reference study period of 30 years

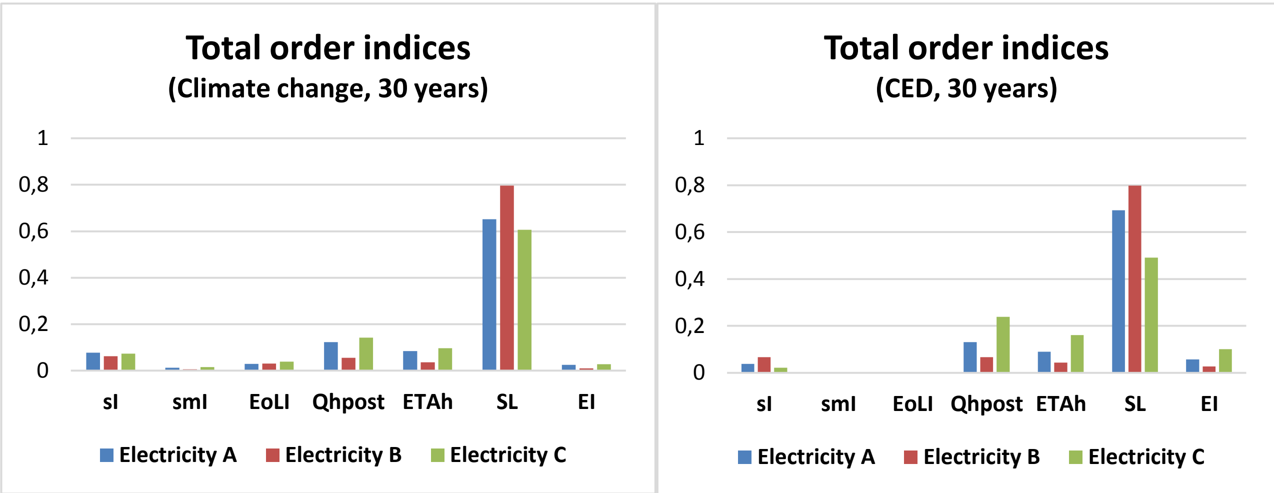


Figure 29 Total order indices of Systems A, B, and C (Climate change and CED_{NRE} indicators) for electricity scenario and a reference study period of 30 years

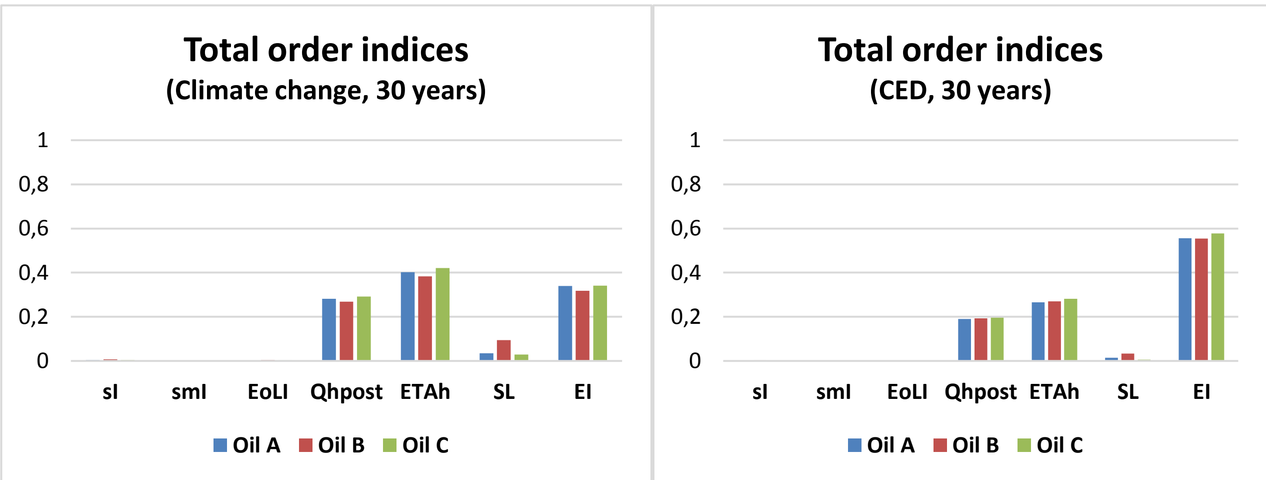


Figure 30 Total order indices of Systems A, B, and C (Climate change and CED_{NRE} indicators) for oil scenario and a reference study period of 30 years

This is further demonstrated if a reference study period of 45 years is taken into account, in order to include at least one insulation replacement during the assessment (Figure 31, Figure 32 and Figure 33). In this case, the SL uncertainty has a very low impact.

Furthermore, the results obtained in this reference study period, show once more the importance of the operational use phase in all scenarios, in particular with gas and oil as energy sources (Figure 31 and Figure 33). In the electricity scenario, the uncertainties of inputs related to the other phases have a slightly higher importance (Figure 32).

System maintenance and end of life uncertainties have a limited impact on results variance in all cases. It should be finally noticed that if the user is interested in conducting an LCA of an insulation solution in a specific building scenario or if he performs a more accurate heat loss calculation through a HAM tool, some of the uncertainties of the input parameters, as ETAh or $Q_h$post, could be reduced, thus increasing the impacts of the other uncertainties on input data.

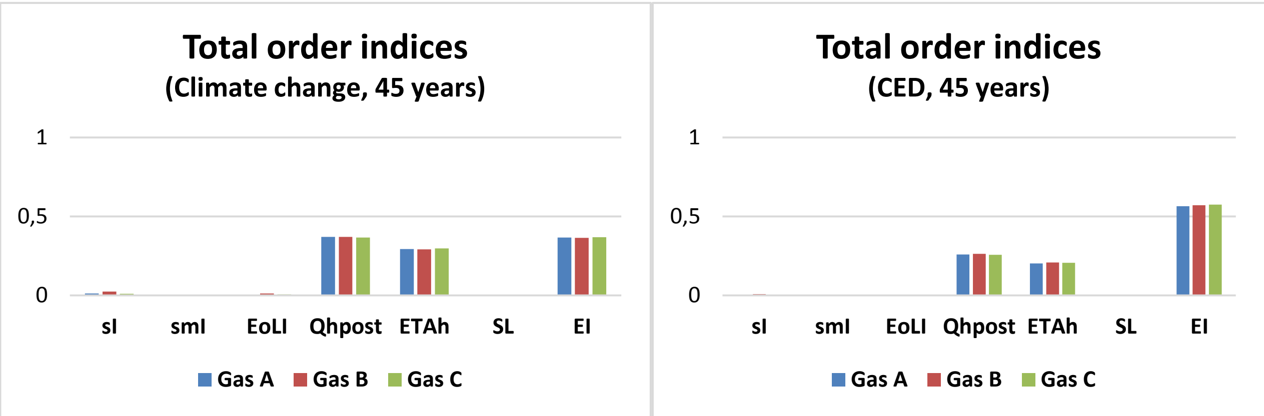


Figure 31 Total order indices of Systems A, B, and C (Climate change and CED_{NRE} indicators) for gas scenario and a reference study period of 45 years

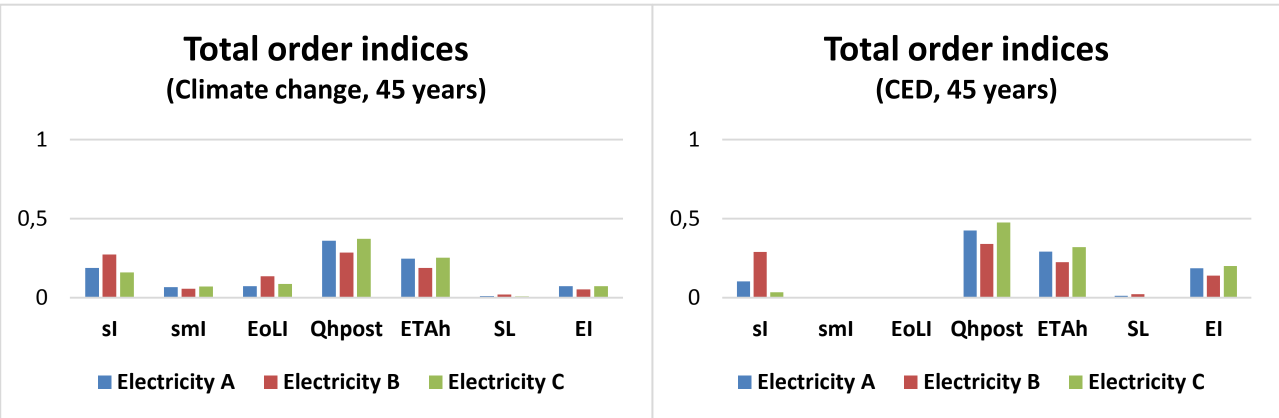


Figure 32 Total order indices of Systems A, B, and C (Climate change and CED_{NRE} indicators) for electricity scenario and a reference study period of 45 years

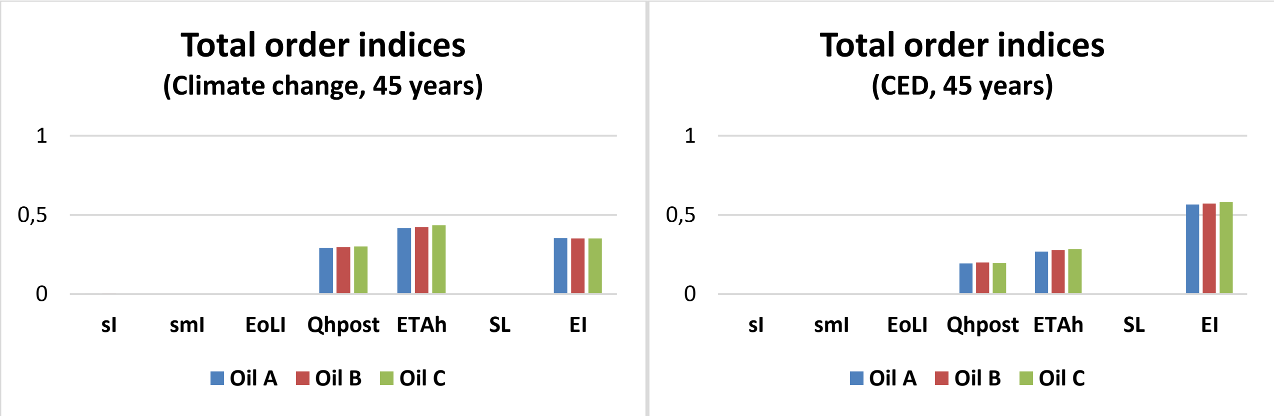


Figure 33 Total order indices of Systems A, B, and C (Climate change and CEDNRE indicators) for oil scenario and a reference study period of 45 years

3.6 Conclusions

This section reports exemplary cases of the methodology application in order to illustrate the methodology potential and its possible uses also in view of future progresses of the RIBuild web tool or, in general, in building renovation projects. Four different applications are presented:

1. Influence of the users' knowledge level of LCA inputs on the results (from screening to detailed assessment);
2. Comparison of the environmental performance of several design options;
3. Assessment of results robustness under different scenarios for energy sources and building reference study periods;
4. Identification of influential parameters on the outcome uncertainty.

(1) The goal of the *first case-study (section 3.1)* is to compare the results obtained from the application of a deterministic LCA and the probabilistic LCA methodology developed. A decreasing level of uncertainties, and consequently different PDFs for input values, are considered in three assessment types ranging from a "screening LCA" to a more "detailed LCA".

As expected, the uncertainty range of the outcomes are higher for the screening LCA compared to the detailed LCA. Results of the impact contributions show that the share of the new insulation system is about 3 to 22% in the three assessments. This finding confirms the results of the deterministic LCA that the heat losses have more influence on the results than the construction materials. This case study is only an exemplary one serving to illustrate the potential of using different levels of details in the heat losses assessment and for the LCA. If there are no more aleatory uncertainties, by increasing the level of knowledge and information of the studied object, a probabilistic assessment will become a deterministic one as far as all parameters are known with a higher accuracy.

(2) The goal of the *second case-study (section 3.2)* is to demonstrate how the probabilistic LCA methodology can be effectively used to compare the environmental performance of several design options, given a certain assessment scenario. The case study investigates three design options, applied to a specific wall configuration in a specific location, for a reference study period of 30

years and with natural gas as heating source. Almost all the LCA input parameters are considered stochastic in the assessment and characterised by PDFs.

Results are presented through box-whisker plots and cumulative distribution functions (CDF). The first representation allows the reader to easily perceive the result uncertainties, while the representation of the CDFs is useful to compare the probability that a certain solution reaches an environmental impact target. Results of the impact contributions confirm again the major impact of the use phase (73%-90%) compared to the material production (10%-20%). Nevertheless, the differences on the impacts among the three insulation solutions are mainly due to the differences in the production phase, as the impacts related to the use phase are almost the same for all the insulation measures (due to the same average thermal resistance).

(3) The *case studies related to the third point, reported in sections 0 and 3.4*, demonstrate how the methodology can be applied to assess the robustness of the results on the environmental impacts of different design options (as those of the previous case-study) under several assessment scenarios. Furthermore, the case studies show how the methodology can be used to evaluate the impact result variations, for the same design option, according to different possible energy sources or reference study periods scenarios, with the final aim to support designers in the selection of the best solution. In the case-studies, several insulation measures for different country contexts are compared under several energy scenarios and reference study periods. From the results obtained, it is evident how the energy scenario strongly influences both the mean values and the variance of the environmental impacts of the solutions.

(4) Finally, in the *last case-study reported in section 3.5*, the methodology is applied to calculate the sensitivity indices of the LCA stochastic inputs, with the aim to assess which input parameter uncertainty has more impact on the results variance. The analysis is performed under the simulation assumptions established for the case in section 0.

The results obtained demonstrate that the LCA inputs uncertainty impacts vary across the different energy scenarios, while a certain consistency is noticeable within the same energy scenario and for the various impact indicators. Furthermore, except for some exceptions, the sensitivity indices trends are similar for the three insulation solutions considered.

The LCA inputs related to the operational use phase (heat transmission losses, heating equipment efficiency, impacts of the energy vector) account for almost the whole output uncertainty in all scenarios, in particular in gas and oil scenarios. System maintenance and end of life uncertainties have a limited impact on results variance in all cases. Furthermore, another important phenomenon is highlighted: when the mean value of the insulation solutions SL is set at the same value of the reference study period, during the Monte-Carlo sampling procedure, the replacement of the whole insulation system may occur or not, depending on the input draws, then affecting the outcome uncertainty. This is further demonstrated if a longer reference study period is taken into account, in order to include at least one insulation replacement during the assessment. In this case, the SL uncertainty has a very low impact.

In conclusion, the case studies presented are only exemplary ones to illustrate the potential of the application of the probabilistic LCA methodology developed within RIBuild WP5 Task 5.2. Based on these, further extensive case-studies applications can be imagined, during RIBuild WP6 work, in order to assess the environmental performance of the insulation solutions included into the future RIBuild web tool.

4 Implementation of the probabilistic LCA methodology in the WP5 software tool

The LCA probabilistic methodology developed and documented in section 2 has been implemented into a software tool using *R*, an open source programming language and software environment for statistical computing and graphics [116], and *Shiny*, an *R* package addressed to build interactive and user-friendly web apps straight from *R*.

The *WP5 software tool* includes both the LCA and LCC Monte-Carlo based methodologies developed within, respectively, WP5 tasks 5.2 and 5.3[22] and allows the real-time calculation of the economic and environmental impacts of insulation systems applied to wall case studies under several possible scenarios (energy scenarios and calculation periods) with a small calculation time. Furthermore, the software tool can be used to assess other possible renovation measures than internal insulation, in order to maximise his impact in the field of building renovation[23].

The main idea behind the software is to allow a flexible use of it: it already includes a database of data inputs on national case studies on internal insulation, developed within RIBuild Task 5.2, that can be edited or enriched according to user preferences.

This section mainly addresses the LCA section of the tool, describing the calculation assumptions and providing a guide for the implementation of the inputs database and the software use.

4.1 Calculation assumptions

The calculation of the environmental impacts of the insulation systems embedded into the software, based on the methodology developed in Task 5.2 and described in section 2, is obtained through the following equations (Eq. 6 and Eq. 7):

$$\mathrm{IG1}=\left\{\left(\sum_{j=1}^{n}\mathrm{sI1_j}\right)+\left(\sum_{j=1}^{n}(\mathrm{sI1_j}^*\mathrm{s_j})\right)+\left(\sum_{j=1}^{n}\mathrm{EoLI1_j}\right)+\left(\sum_{j=1}^{n}(\mathrm{EoLI1_j}^*\mathrm{s_j})\right)+\sum_{i=1}^{cp}\left(\frac{\mathrm{Q_h}}{\mathrm{ETA_h}}{}^*\mathrm{EI1_i}^*\mathrm{EnFc}\right)+\left(\sum_{j=1}^{n}\mathrm{smI1_j}\right)\right\}\ [\mathrm{kgCO2\text{-}eq}]$$

Eq. 6

$$\mathrm{IG2}=\left\{\left(\sum_{j=1}^{n}\mathrm{sI2_j}\right)+\left(\sum_{j=1}^{n}\mathrm{sI2_j}^*\mathrm{s_j}\right)+\left(\sum_{j=1}^{n}\mathrm{EoLI2_j}\right)+\left(\sum_{j=1}^{n}(\mathrm{EoLI2_j}^*\mathrm{s_j})\right)+\sum_{i=1}^{cp}\left(\frac{\mathrm{Q_h}}{\mathrm{ETA_h}}{}^*\mathrm{EI2_i}^*\mathrm{EnFc}\right)+\left(\sum_{j=1}^{n}\mathrm{smI2_j}\right)\right\}\ [\mathrm{NRE\text{ - }MJ}]$$

Eq. 7

with the subscripts: $\mathrm{i} = \mathrm{year\ i-th}$; $j = \mathrm{system\ j-th}$; $k = \mathrm{material\ k-th}$; and 1 or 2 referred to the specific environmental indicators;

Where:

[22] The LCC section of the software is almost ready at this stage, but will be further developed within WP5 task 5.3 activities, as part of D5.2, by June 2018.
[23] The term “insulation system” in the following sections can be generically replaced by “system”, thus meaning “renovation measure”.

IG1 is the Global Impact expressed in terms of Climate Change-GWP [$kgCO_2$-eq];

IG2 is the Global Impact expressed in terms of non-renewable Cumulative Energy Demand [CED_{NRE} - MJ];

$$sI_j = \begin{Bmatrix} \sum_{k=1}^{n} UI1_k * m_k \text{ [kgCO2-eq]} \\ \sum_{k=1}^{n} UI2_k * m_k \text{ [NRE-MJ]} \end{Bmatrix}$$

Eq. 8

is the j-System environmental impact related to production phase; and:

UI_k is the unitary production impact of the k-material composing the j-System [$kgCO_2$-eq/kg] or [NRE - MJ/kg];

m_k is the mass of the k-material [kg];

$$s_j = \text{int}\left(\frac{cp - 1}{SL_j} \text{ [−]}\right)$$

Eq. 9

is the number of replacements of the j-System within the calculation period *cp* [years], considering the j-System Service Life SL_j [years];

$$EoLI_j = \begin{Bmatrix} \sum_{k=1}^{n} EOL1_k * m_k \text{ [kgCO2-eq]} \\ \sum_{k=1}^{n} EOL2_k * m_k \text{ [NRE - MJ]} \end{Bmatrix}$$

Eq. 10

is the j-System environmental impact related to the End of Life phase; and:

EOL_k is the unitary End of Life impact of the k-material composing the j-System [$kgCO_2$-eq/kg] or [NRE - MJ/kg];

EI_i is the unitary impact of the energy vector at year i-th; and:

Q_h is the heat transmission losses through the wall during the heating period [kWh/year]; Q_h can refer to the heat losses before ($Q_h$pre) or after ($Q_h$post) the insulation intervention.

ETA_h is the overall system efficiency for heating [-];

EnFc is the conversion factor from delivered to primary energy, according to national regulations [-];

$$smI_j = \begin{cases} \sum_{k=1}^{n} UI1_k * m_k * s_k \text{ [kgCO2-eq]} \\ \sum_{k=1}^{n} UI2_k * m_k * s_k \text{ [NRE - MJ]} \end{cases}$$

Eq. 11

is the k-Material environmental impact related to the Material replacement (System periodic maintenance); and:

$$s_k = \text{int}\left(\frac{cp - 1}{sl_k} [-]\right)$$

Eq. 12

Where s_k is the number of replacements of the k-material within the calculation period *cp* [years], considering the k-material Service Life sl_k [years];

The parameters included from Eq. 6 to Eq. 12 are summarized in the following Table 22.

Table 22 Input parameters of the LCA included in the software tool

Input Parameter	**Symbol**	**Unit**
Replacement coefficient for System j-th	s_j	[-]
Replacement coefficient for Material k-th	s_k	[-]
Calculation period	cp	[year]
Service Life for System j-th	SL_j	[year]
Service Life for Material k-th	sl_k	[year]
Unitary production impact of the material k-th	UI_k	[$kgCO_2$-eq/kg] or [CED_{NRE} - MJ/kg]
Unitary End of Life impact of the material k-th	EOL_k	[$kgCO_2$-eq /kg] or [CED_{NRE} - MJ/kg]
Mass of the material k-th	m_k	[kg]
Heat transmission losses through the wall during the heating period	Q_h	[kWh/year]
Overall system efficiency for heating	ETA_h	[-]
Unitary impact of the energy vector at year i-th	EI_i	[$kgCO_2$-eq /kWh] [CED_{NRE} MJ/kWh]
Conversion factor from delivered to primary energy	EnFc	[-]

As specified in sections 2.4.1 and 2.5.1, PDFs or deterministic values of $Q_h$pre or $Q_h$post obtained through accurate HAM simulations (option 1) or monthly calculation (option 2) can be directly entered into WP5 tool case studies database (see section 4.2.2). Alternatively, option 3 is implemented into WP5 software tool in order to perform a real-time calculation of the transmission losses through the wall in a probabilistic or deterministic way (see section 4.2.3).

4.2 Software User guide

The following sections provides instructions on:

- the installation of the WP5 software tool,
- the entry of data inputs of case studies into the software database of cases;
- the use of the WP5 tool, particularly focusing on the editing of the original data inputs, the managing of case studies and scenarios, the Monte-Carlo calculation, the uncertainty and sensitivity analysis.

4.2.1 Installation and run of the software tool

The WP5 tool is a Web App and therefore it is accessible through a web server on a local or remote machine. To install the WP5 tool Web App in a locale machine it is necessary to install preliminarily the following software:

- *R*, downloadable in https://cran.r-project.org/;
- *Rstudio*, downloadable in https://www.rstudio.com/;
- Java 64 bit.

Then it is necessary to personalize *R* installing the following needed *R*-packages using the command *install.packages*(Name of the package):

```
install.packages("triangle")
install.packages("shinythemes")
devtools::install_github('rstudio/DT@feature/editor')
install.packages("shinyFiles")
install.packages("rlist")
install.packages("shinyBS")
install.packages("leaflet")
install.packages("rmarkdown")
install.packages("devtools")
devtools::install_github("ThomasSiegmund/D3TableFilter")
install.packages("fitdistrplus")
install.packages("dplyr")
install.packages("mvtnorm")
install.packages("zoo")
install.packages("urca")
install.packages("lmtest")
install.packages("xts")
install.packages("TTR")
install.packages("forecast")
install.packages("dse")
install.packages("purr")
install.packages("plotly")
install.packages("mc2d")
install.packages("rhandsontable")
install.packages("shinyjs")
install.packages("DT")
install.packages("vars")
```

install.packages("NMF")
install.packages("chron")
install.packages("gdata")
install.packages("gender")
install.packages("igraph")
install.packages("irlba")
install.packages("openNLP")
install.packages("openNLPdata")
install.packages("plotrix")
install.packages("qdap")
install.packages("qdapDicti")
install.packages("randtoolbox")
install.packages("rngWELL")
install.packages("sensitivity")
install.packages("xlsx")

Packages installation instructions are also provided in the commented (#) code lines in the header of the file named *Global.R*. At the first start uncomment all these lines and launch *Global.R* inside *Rstudio* environment.

Once the packages installations have been concluded, the user web interface of the tool can be launched through: "Run App→external" (upward in *Rstudio*) and the internet browser will open. The app launch could require a few dozen seconds.

4.2.2 Creation of the software database

The data inputs for the LCA assessment of a certain number of insulation systems, case studies and scenarios to be included into the tool database must be entered in the following 4 data frames (files *.csv*) provided into the folder "WP5 software tool": *Materials.csv; Insulation_systems.csv; Case_studies.csv; Energy_sources.csv.* Once data are filled, it is strictly necessary that the files remain included into the tool folder.

At the moment, the data frames contain the data input provided by RIBuild Task 5.2 partners (reported in Appendix 3).

The data frames must be filed according to the following general instructions:

1. Cells must contain texts or numbers, according to the specific instructions here below.
2. Point is used as decimal separator.
3. LCA input parameters can be entered as "deterministic" values or "probability distributions", among the available PDFs typologies included in the software, reported in
4. Table 23. Information's on input PDFs are reported in 4 columns of the data frame for each input:
   The first column must be filled with a <u>text</u> (the distribution name in Table 23) and indicates if the parameter is entered as a single deterministic value ("det") or a distribution (from line 2 to line 7 in the table).

Table 23 Name of PDFs typologies included in the software tool

	Distribution name for the data frame	**Distribution typology**
1	det	= deterministic value
2	rnorm	= normal distribution

3	runif	= uniform distribution
4	rgamma	= gamma distribution
5	rweibull	= weibull distribution
6	rlnorm	= lognormal distribution
7	rtriangle	= triangle distribution

- The other three columns must be filled with numbers, which represent the single deterministic value or the specific parameters characterizing the PDFs (their description in *italic* in Table 24). When for the deterministic value only the first column is filled, or when the distributions are characterized by only two values, insert a 0 (zero) in the other columns.

Table 24 Input parameters characterizing the PDFs

Distribution name for the data frame	**Parameter characterizing the PDF: 1**	**Parameter characterizing the PDF: 2**	**Parameter characterizing the PDF: 3**
det	*value*	*0*	*0*
rnorm	*mean*	*sd*	*0*
runif	*min*	*max*	*0*
rgamma	*shape*	*scale*	*0*
rweibull	*shape*	*scale*	*0*
rlnorm	*meanlog*	*sdlog*	*0*
rtriangle	*min*	*max*	*mode*

The following sections provide the specific instructions for filling each data frame.

materials.csv

This file contains the list of all possible materials composing the insulation systems included in the case studies to be assessed. Each line identifies a material, and the following information must be provided:

- **ID** = identifier. It must be a three-digit number. It can be conventionally set to be a number starting from 101 for a Country (101, 102, 103…….), from 201 for another one (201, 202, 203, …), etc…
- **Name** = univocal name of the material.
- **Country** = Country name, e.g. Italy, Belgium, Denmark, Germany, Latvia, Sweden, Switzerland, etc…
- **de** = material's density [kg/m^3]. This is a single deterministic value**.**
- **sl** = material's service life [years]. It can be entered as a deterministic value or a PDF, so it is represented by four columns, as explained: sl_DISTR (distribution name), **sl_1**, **sl_2**, **sl_3** (deterministic value or distribution parameters expressed by numbers according to the description in Table 24).
- **UI** = Unitary production impact of the material. Three different types of impact can be entered, identified by a number which ranges from 1 to 3 (**UI_1**, **UI_2**, **UI_3**):
  - **UI_1** is the CO2-eq emission $\left[\frac{kgCO_2eq}{kg}\right]$
  - **UI_2** is the non-renewable primary energy $\left[\frac{NRE-MJ}{kg}\right]$

  UI_1 and UI_2 are the indicators established for WP5 LCA methodology, as described in section 2. If whished, it is possible to fill data for a third indicator **UI_3**.

  UI data can be entered as deterministic values or PDFs, so they are represented by four columns, as explained.

- **EOL** = Unitary end of life impact of the specific material. As for the UI, three different types of impact can be entered, consistently with those of UI (and in the same order). Also EOL data are represented by four columns, as explained. If EOL data are not available (or the user does not want to assess this LCA phase), write 0 (zero) in the parameters' values, but always a text in the distribution type **EOL_DISTR** (e.g. rnorm).

insulation_systems.csv

This file contains the information on the insulation systems included in the case studies. For each line, identifying an insulation system, the user must enter the following data:

- **ID** = insulation systems identifier. It must be a number starting from 1 (1,2,3,4…).
- **Name** = univocal name of the insulation system. It must be provided in the form: Comp_1, Comp_2, Comp_3 etc., according on the number of insulation systems to assess in the case studies.
- **Country** = Country name, e.g. Italy, Belgium, Denmark, Germany, Latvia, Sweden, Switzerland, etc…
- **SL** = the service life of the whole insulation system. It is represented by four columns, as explained.
- **n_mater** = number of materials (layers) composing the insulation system.
- **materials** = list of the materials identifiers included in the data frame *materials.csv*, composing the insulation system. Identifiers must be entered separated by a single space, e.g.:101 102 103 etc. This part is mandatory for the LCA assessment, in case of only LCC assessment, the user can also write 0 (zero).
- **m_mater** = mass [kg] of the materials composing the insulation system. The mass can be entered as a deterministic value or a PDF. In the column **m_mater_DISTR** enter the PDF typology for each material listed in the column **materials**, separated by a single space, e.g.: rtriangle rnorm rtriangle det etc… Even if the distribution type is the same for all the listed materials, enter the text several times according to the material numbers, e.g.: rtriangle rtriangle rtriangle rtriangle rtriangle rtriangle, for six materials composing the insulation system. In the columns **m_mater_1**, **m_mater_2**, **m_mater_3**, enter the deterministic values or PDFs parameters values, according to the instructions included in Table 24, as numbers separated by a single space. This part is mandatory for the LCA assessment, in case of only LCC assessment, the user can also write 0 (zero).
- **M_selection** = identify the material of the insulation system which needs periodic maintenance (for instance the periodic replacement of the internal painting). If data are not available, or the user does not want to include this LCA phase in the assessment, write 0 (zero). This part is mandatory for the LCA assessment, in case of only LCC assessment, the user can also write 0 (zero).
- **DU** = Thermal resistance of the insulation system (m^2K/W), surfaces resistances excluded. It is considered as a single deterministic value. This information is necessary only if the pre-processing module for the calculation of the heat loss of the insulation systems, based on option 3 (according to section 2.2.3.2) is used (also see section 4.2.3).

Columns related to **CI** (investment cost) and **CM** (maintenance cost) are to be filled for the LCC assessment and are documented in RIBuild Deliverable 5.2[24]. For the only LCA assessment, the

[24] The LCC section of the software is almost ready at this stage, but will be further developed and documented in D5.2, by June 2018.

user can write 0 (zero) in the parameters' values, but always a text in the distribution type (e.g. rnorm).

case_studies.csv
This file allows defining the case studies to assess, that represent the insulation systems installed in a wall configuration. The same insulation system can be assessed in different original wall configurations, producing different case studies. For each line, identifying a case study, the user must enter the following data:

- **ID** = case study identifier. It must be a number starting from 1 (1,2,3,4…).
- **Name** = the name of the case study. It must be provided in the form: C_S_Test1, C_S_Test2, C_S_Test3, etc…, depending on the number of case studies considered.
- **Country** = Country name, e.g. Italy, Belgium, Denmark, Germany, Latvia, Sweden, Switzerland, etc…
- **Qhpost** = Heat transmission loss through the wall after renovation (kWh/year). It can be entered as a deterministic value or a PDF, so it is represented by four columns, as explained.
- **Qhpre** = Heat transmission loss through the wall before renovation (kWh/year). It can be entered as a deterministic value or a PDF, so it is represented by four columns, as explained.
- **CN** = number of insulation systems included in the case study. It must be set = 1[25].
- **C1** = the insulation systems identifiers (1,2,3 etc..) in the data frame "insulation_systems", that represents the insulation system that is assessed in the specific case study.
- **sur** = the surface (m²) of the insulated facade area. It must be set = 1[26].

Note that data on Qh_{post} and Qh_{pre} must be filled if the user wants to use an external software for their assessment (based on calculation options 1 and 2, see sections 2.4.1 and 2.5.1). If the user wants to use the calculation method included into WP5 tool (as described below and based on calculation option 3), he can write 0 (zero) in the columns related to PDFs parameters' values, but always a text in the column related to distribution type (e.g. rnorm).

energy_sources.csv
This file contains the information on the energy scenarios for the LCA assessment. For each line, identifying an energy scenario, the user must enter the following data:

- **ID** = energy source identifier. It must be a number starting from 1 (1,2,3,4…).
- **Name** = univocal name of the energy scenario. It must be provided in the form: Tar_1, Tar_2, Tar_3 etc, according on the number of scenarios considered.
- **Country** = Country name, e.g.: Italy, Belgium, Denmark, Germany, Latvia, Sweden, Switzerland, etc…
- **En_S** = Energy source name, e.g.: natural gas, oil, electricity, etc…
- **EnFc** = the conversion factor from delivered to primary energy, which depends on the energy source typology, established at national level for some European Country. As for other input parameters, it is represented by four columns, as explained.
- **ETAh** = the overall system efficiency for heating. As for other input parameters, it is represented by four columns, as explained.

[25] If the software is used to assess several renovation measures applied to a case-study (e.g. internal insulation, heating equipment, etc…), this number will correspond to the number of renovation measures included in the case-study assessment.
[26] As the functional unit selected for Task 5.2 methodology refers to 1 m^2. If the functional unit is different, e.g. at building level, when several renovation measures are addressed for the same case study, this number must be understood as a multiplicative factor of the unitary impacts of the systems.

- **EI** = Unitary impact of the energy vector. As for the UI, three different types of impact can be entered, consistently with those of UI (and in the same order), and each UI is represented by four columns.
  - **EI_1** is measured in $\left[\frac{kgCO_2eq}{kWh}\right]$
  - **EI_2** is measured in $\left[\frac{NRE-MJ}{kWh}\right]$

Columns related to **EnT** (Energy Tariff) are to be filled for the LCC assessment and are documented in RIBuild Deliverable 5.2[27]. For the only LCA assessment, the user can write 0 (zero) in the parameters' values, but always a text in the distribution type (e.g. rnorm).

4.2.3 Use of the software tool

Once the App is launched, the internet browser opens and the home page in Figure 34 appears[28]. The tool web interface contains the main menu on the top with the following items: *Home*, *Pre-processing*, *Editing*, *LCC Run*, *LCA Run*, *Save results*.

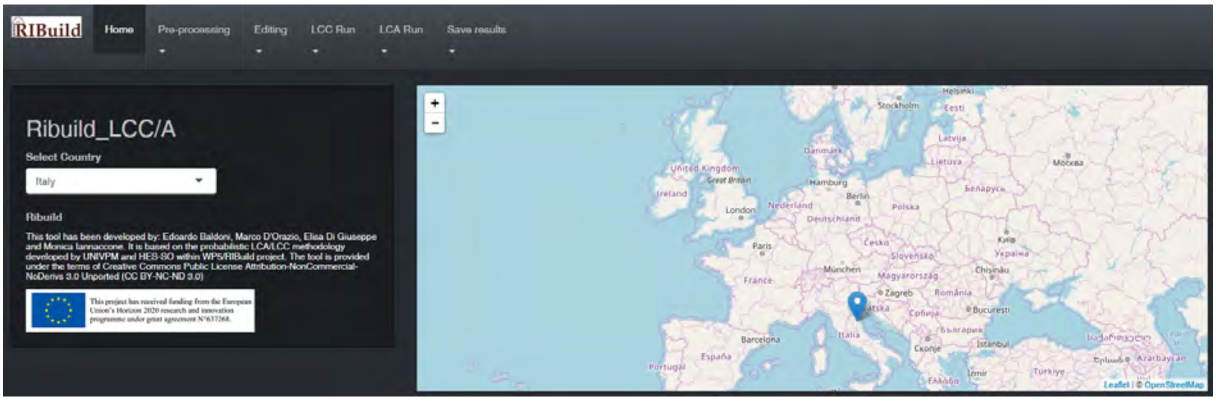


Figure 34 WP5 software tool homepage

[27] The LCC section of the software is almost ready at this stage, but will be further developed and documented in D5.2, by June 2018.
[28] The map in the home page will appear only if the computer is connected to internet.

Home

In the *Home* page, on the left it is possible to select the Country, whose insulation case studies are included into the tool database, in order to filter the case studies and energy scenarios to address with the actual LCA assessment (Figure 35).

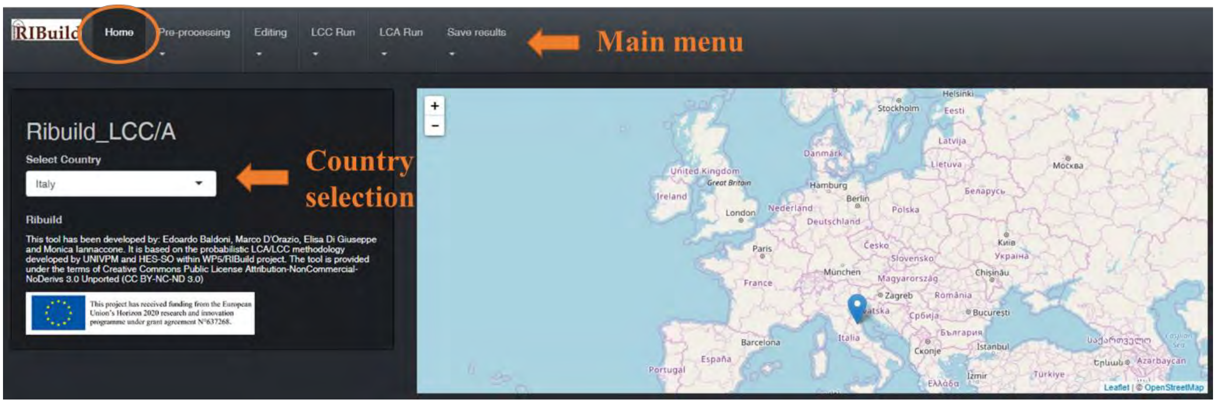


Figure 35 WP5 software tool homepage. Country selection

Pre-processing

The *Pre-processing* menu contains the following items: *Visualize data*, *New system impact generation*, *Economic Scenario visualization* (for the LCC assessment, as documented in D5.2), *Qh calculation*.

In *Visualize data* (Figure 36), the user selects the insulation systems included into the database and, by pushing on *visualize* button, he visualizes the PDFs of the related LCA (and LCC) data inputs, as the system SL (service life), sI (environmental impact related to the production phase), smI (environmental impact related to the maintenance phase), EoLI (environmental impact related to the end of life phase).

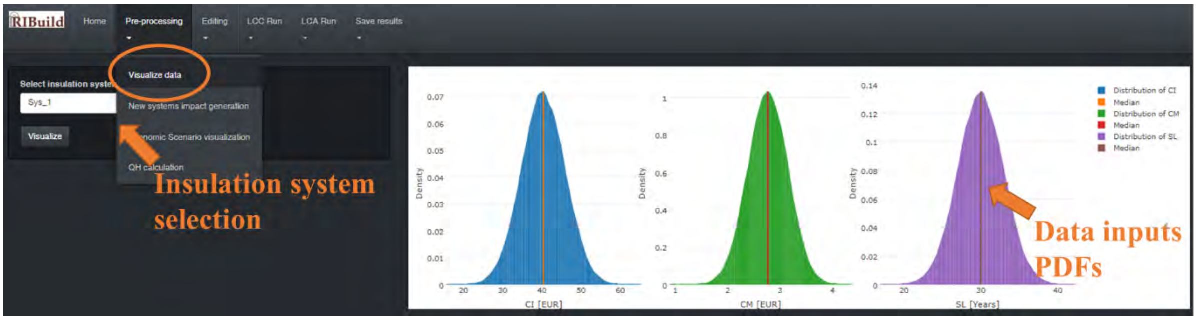


Figure 36 Pre-processing menu → Visualize data, visualization of the PDFs of LCA (and LCC) data inputs

In *New system impact generation* (Figure 37), the user can create a new insulation system based on the materials available in the database (materials' data are reported in the *materials.csv* data frame and in table on the right in the figure), and calculate the environmental impacts induced by production, maintenance and end of life phases.

At this aim, the user must (1) select the materials composing the new insulation system by highlighting their name on the table on the top left (multiple selection through CTRL or SHIFT is allowed) and pushing on the right arrow. Left arrow can be used to remove materials from the selection. The user can also directly edit materials data reported on the material database (table on the right) in order to personalize some materials' information.

Then the user can (2) decide which materials of those selected will be subjected to periodic maintenance (if any) e.g. the internal painting, considering the material service life reported in the database (table on the right), and then (3) push the *generate new system* button. The new system generated is now included at the end of the table on the right (with a progressive numbering).

In order to calculate the environmental impact at system level starting from the materials' impacts, it is necessary to (4) establish the evaluation statistics typology (Log-likelihood or Akaike criterion) and then (5) push the *Calculate impact at system level* button. The calculation is performed through basic random Monte-Carlo with 1000 iterations and distributions are estimated through a data-fitting test. Negative values for the impacts are not considered, so normal distributions are automatically converted into truncated normal distributions. The calculation may take a few dozen seconds (a time bar will appear on the right).

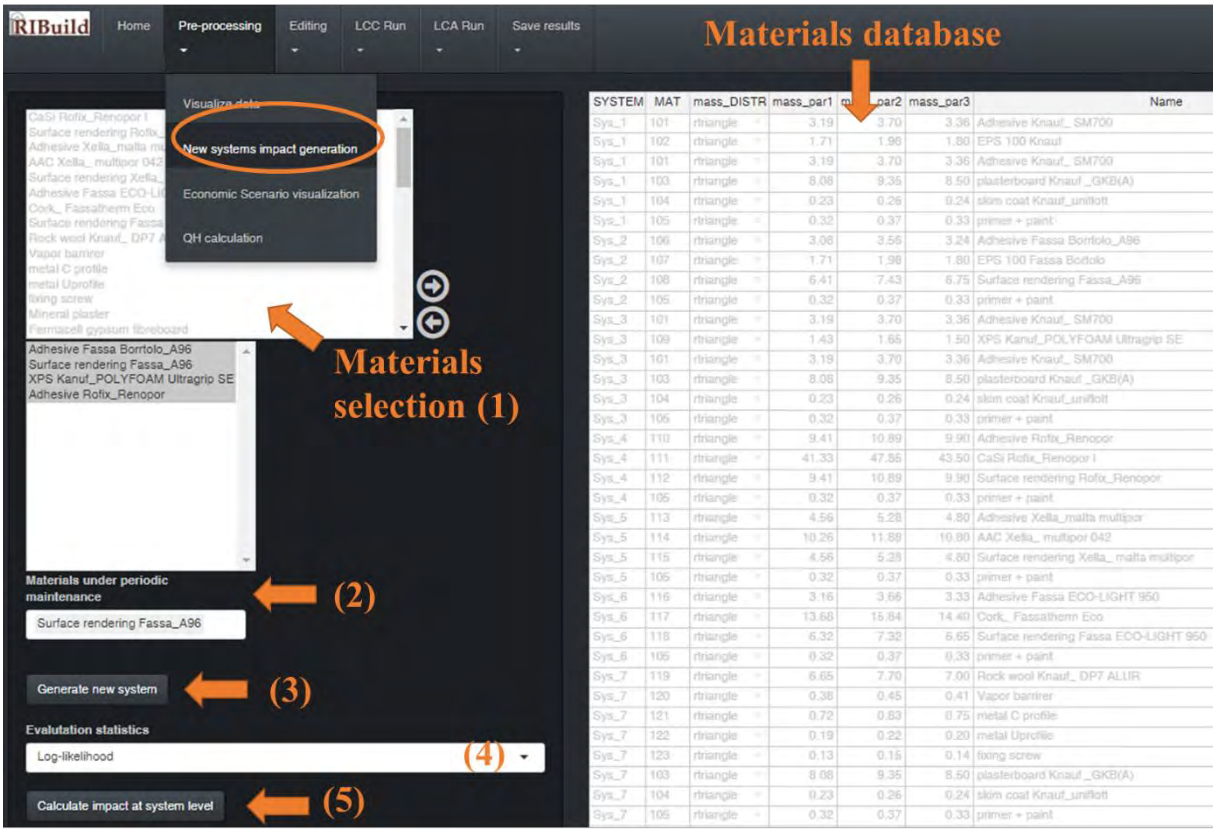


Figure 37 Pre-processing menu → New system impact generation. Procedure for the creation of a new insulation system based on the materials available in the database and calculation of its environmental impact due to production, maintenance and end of life phases

In *QH calculation* (Figure 38), the user can assess the Qh_{post} and Qh_{pre} for a certain case study, based on the simplified HDD methodology (option 3, described in sections 2.2.3.2, 2.4.1 and 2.5.1). At this aim, the user must:

1. select the insulation system among those contained within the tool database;
2. select the EU region for the assessment. As reported in section 2.4.1 and in Appendix 2, the main EU regions and Countries climates are represented through HDD distributions;

3. select the existing wall thermal resistance range [m^2K/W], surfaces resistances excluded.

If the user assesses an eventual new system created under *New system impact generation*, he must also provide a (deterministic) value (*DU*) for the thermal resistance of the insulation system (m^2K/W), surfaces resistances excluded.

Once pushed the *Run* button (4), summary data (5) and PDFs of Qh_{post} and Qh_{pre} for the case study will be represented on the right. The data can be copied (CTRL+c), to be used in the following editing menu, as shown later.

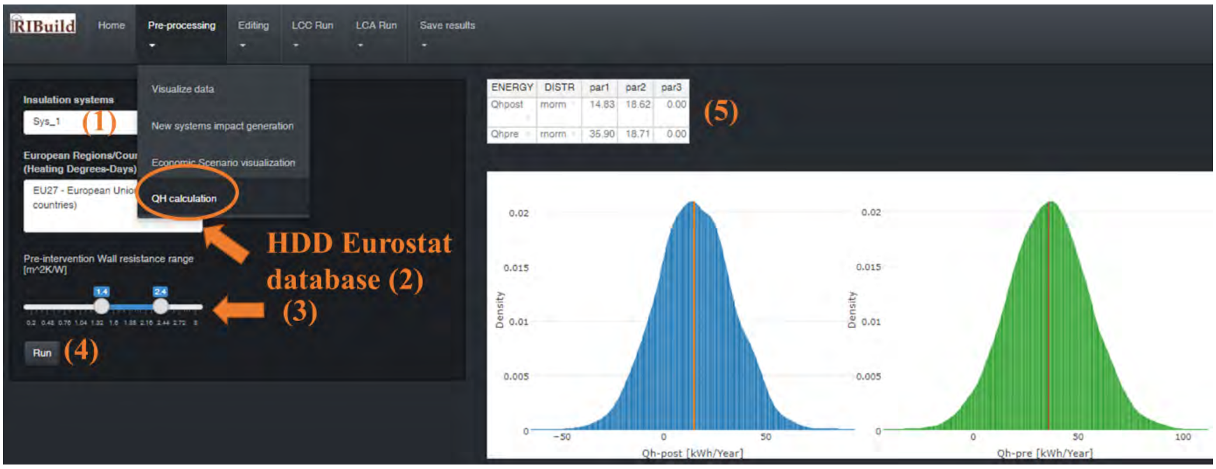


Figure 38 Pre-processing menu → QH calculation. Assessment of the Qh_{post} and Qh_{pre} for a certain case study, based on the simplified HDD methodology (option 3)

Editing

The *Editing* menu contains the following items: *Edit case study*, *Edit Energy Source*.

In *Edit case study*, the user can visualize data of the case studies included into the tool database (those documented in the excel data frame *case_studies.csv*) or create a new case study.

To visualize the summary data of a case study (Figure 39), the user (1) selects the case study name, to which an insulation system is associated (2)[29]. After pushing *Confirm* button (3), summary data inputs on tables will appear on the right (4).

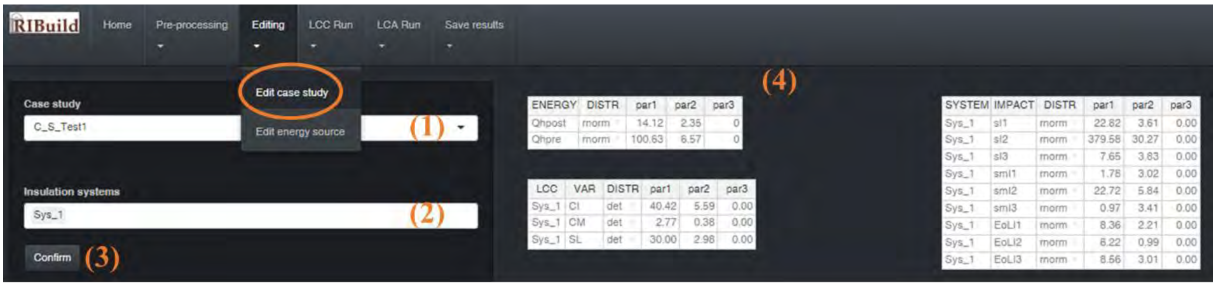


Figure 39 Editing menu → Edit case study. Visualization of the summary data of a case study

To create a new case study (Figure 40), the user selects the *NEW* option from the bar (1) and write a name for the case study (2). Then he selects the insulation system included in the case study from

[29] More renovation measures can be associated to a case study.

the bar (3)[30] and push the *Confirm* button (4). Summary input tables will appear on the right (5), only including data related to the insulation system. Data on Qh_{post}, Qh_{pre} and system Service Life (SL) must be provided (together with those on CI and CM for the LCC assessment, as documented in RIBuild Deliverable 5.2[31]) and then *Save changes* button must be pushed to save the new case study. Notice that this procedure must be applied when the user assesses Qh_{post} and Qh_{pre} through the HDD method included in the tool (as previously described).

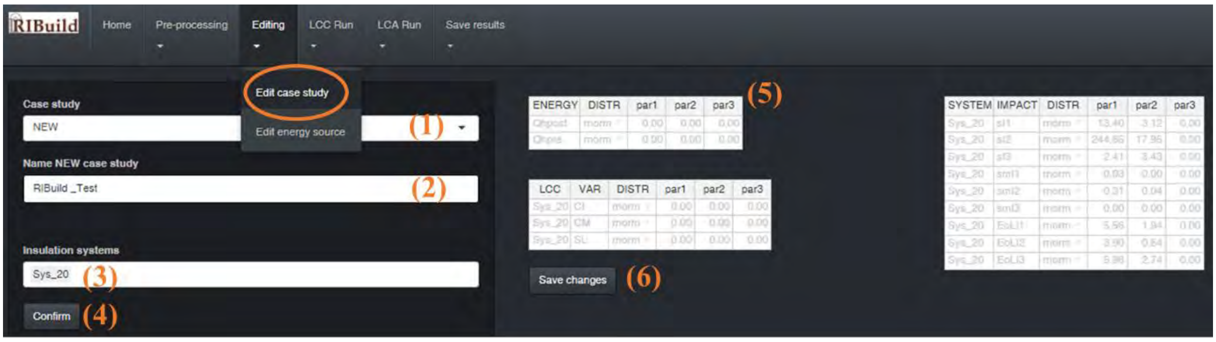


Figure 40 Editing menu → Edit case study. Creation of a new case study

Similarly, in *Edit energy source* (Figure 41), the user can visualize data of the national energy scenarios included into the tool database (documented in the excel data frame *energy_sources.csv* and filtered by Country) or create a new energy scenario, with similar procedure to that just described for a new case-study.

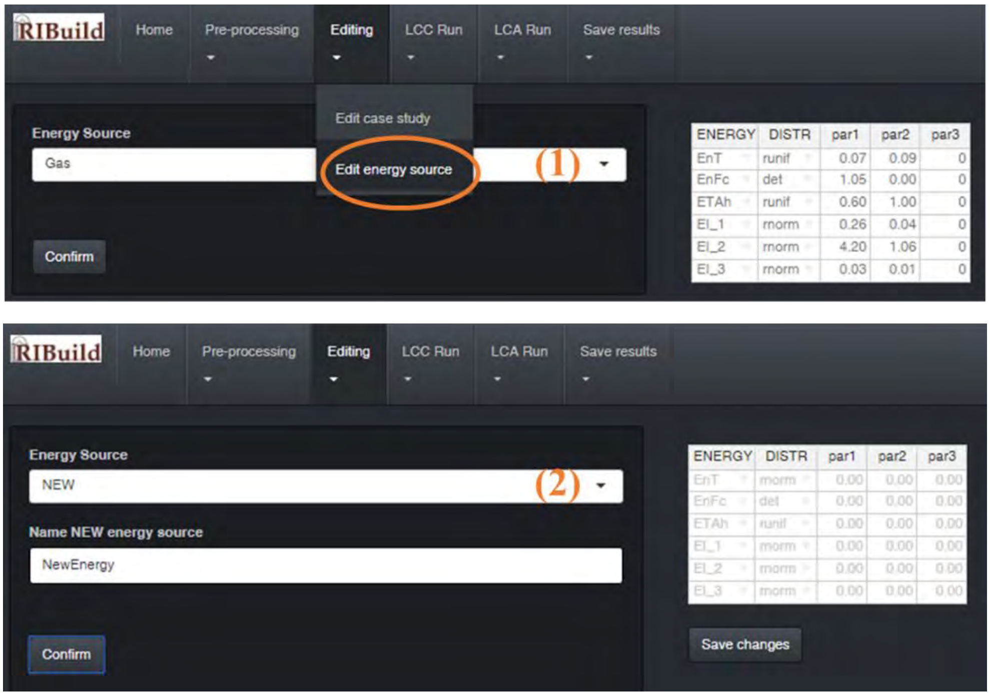


Figure 41 Editing menu → Edit energy source. Visualization of the summary data of an energy source (above) and creation of a new energy source (below)

[30] Multiple selection is allowed, if more renovation measures are associated to a case study.

[31] The LCC section of the software is almost ready at this stage, but will be further developed and documented in D5.2, by June 2018.

LCA Run

The *LCA Run* menu contains the following items: *LCA*, *LCA – Sensitivity analysis*, in order to perform the Monte-Carlo based LCA and the calculation of sensitivity indices according to the method described in section 2.6.

In *LCA* (Figure 42), the user (1) selects the case study to be assessed, among those in the tool database, or among those created or edited during the working session. He must also select the scenarios for the assessment: the energy scenario (2) and the calculation period (4), dragging the specific slider for this last. Finally, he must choose the number of iterations for the Monte Carlo calculation (3) and then push the *Compute* button (5). The calculation may take a few dozen seconds or some minutes depending on the simulations number (a time bar will appear on the right). Once finished, results will appear on the right. They are:

- the output probability and cumulative density functions for the post-renovation and pre-renovation Global Impacts according to the specific environmental indicators;
- the output probability and cumulative density functions for the Global Impacts savings according to the specific environmental indicators;
- Tables for each graph summarizing the simulation number, the mean value, the median value and the standard deviation of the PDF obtained.

Figure 42 LCA Run menu → LCA. Assessment of the environmental impacts results for a certain case study

In *LCA – Sensitivity analysis* (Figure 43), once concluded the LCA assessment, the user can evaluate the sensitivity first and total order Sobol's indices for each Impact indicator (2) by pushing on *Run sensitivity analysis* button (3). The graph and table representing the first order and total order indices for the LCA inputs obtained will appear on the right.

Save results

Once the calculation is performed, results can be saved as *.xlsx* file or *.Rdata* workspace (Figure 44). A file name must be filled and the generation button pushed. In separate sheets, the excel file contains:

- a summary of the input data PDFs;
- the whole samples of input data;

- the whole samples of outputs (global impact pre-renovation and global impact post-renovation, for each environmental indicator)
- The first and total order sensitivity indices for each environmental indicator.

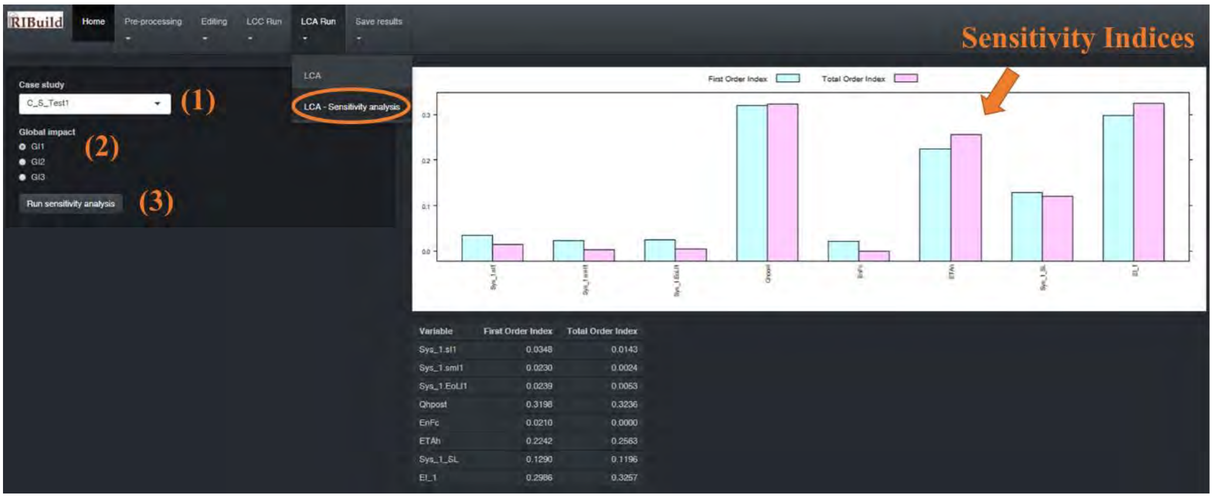


Figure 43 LCA Run menu → LCA – Sensitivity analysis. Calculation of the Sobol first order and total order indices for the LCA inputs

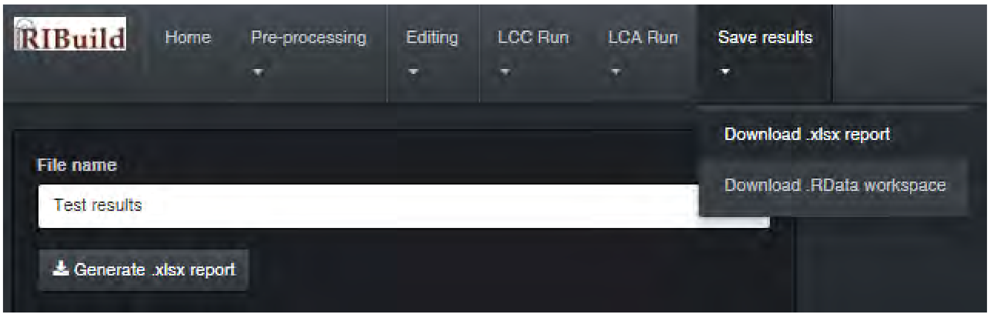


Figure 44 Save results menu

Part 2: Energy saving potential of internal insulation measures

Introduction

Application of internal insulation to external facades of historical buildings offers a possibility to considerably improve energy performance and indoor thermal comfort, without compromising the architectural appearance of the building.

This part of the report includes the assessment of the energy saving potentials related to renovation measures including internal insulation, in some exemplary historic building cases, carried out in Task 5.1 “Evaluation of the energy saving potential of internal insulation solutions depending on building practice”.

Calculation of energy savings in the case buildings is based on a number of scenarios depending on the degree of renovation before implementing internal insulation. Hence, the calculations comprise energy demand in the building for the following situations:

- as it was originally constructed
- with implementation of internal facade insulation on the original building
- as the building was before implementing the facade insulation (if different from 1st)
- as the building is after implementation of internal facade insulation (if different from 2nd)
- with a full package of energy saving measures (if different from 4th), e.g. new windows, roof insulation, insulation under floor, etc.

The aim of the exercise performed in Task 5.1 is then to assess the impact, in terms of energy consumptions, of this intervention when isolated or not from other measures in a renovated building. This can, in most cases, only be done as a desktop calculation exercise or as a dedicated lab test. This study reports on desktop calculations of stand-alone facade insulation solutions and combinations with other energy saving measures on selected case study buildings in Denmark, Latvia, Italy, and Switzerland.

Historic buildings do often have a long list of previous interventions that may have influenced the energy performance of the building. Additionally, detailed information on the building and its constructions which are need for carrying out an energy performance calculation, or even more demanding an energy performance simulation, may not be available. Therefore, energy performance calculations have been performed based on the available material and hence “starting point”.

Calculations of energy savings have been carried out using the preferred energy performance tool of partner countries. In most cases calculations were based on quasi-stationary monthly conditions in accordance with EN ISO 13790 [117]. Only in two cases dynamic simulation was used as detailed thermo-physical and geometric information about material layers in a historic building is difficult or in some cases impossible to obtain.

The effect of internal insulation on facades is challenged by the presence of partition walls and horizontal divisions that makes it impossible to insulate those parts of the facade covered by these constructions. This both limits the available area for application of insulation and creates thermal bridges. Nevertheless, the case studies show that application of internal facade insulation in historic buildings have the potential of considerably reducing the energy need for space heating also when considering insulation of the facades as a single measure.

5 Danish cases

Three Danish cases have been calculated using the Danish compliance checking tool: Buildings energy demand 2015 - Be15 [118]. Be15 is a calculation tool based on quasi-stationary conditions, and programmed according to EN ISO 13790 [117]. Be15 calculates energy demands in primary energy, and to avoid influence of the Danish primary energy factors, which is hard-coded into the tool, direct district heating is selected as heat source. This implies a primary energy factor of 1 and no losses (100 % efficiency) in the heating installation. Additionally, all pipes and pumps used for distribution of heat and hot water internally in building have been removed from the calculation models. Additionally, the net energy demand is being calculated for the habitable parts of the building only. It is estimated that the energy demand is approx. 10-15% higher if losses and efficiencies in the technical installations are included in the calculations.

In the calculations, standard use of the buildings is assumed, i.e. standard load from persons, appliances and consumption of domestic hot water according to Table 25.

Table 25 Standard values for internal loads in Danish case study calculations

System	Internal load
Persons	1.5 W/m² (24 hours/day all year)
Appliances and light	3.5 W/m² (24 hours/day all year)
Domestic hot water	250 l/m² per year, heated from 10 °C to 60 °C

The Danish design reference year [119] is used as climate data in the calculations with the following characteristics given in Table 26.

Table 26 Danish design reference year climate characteristics

Climate information	
Average outdoor temperature	7.75 °C
Minimum outdoor temperature	-21.1 °C
Maximum outdoor temperature	32.1 °C
Heating degree days (base 17 °C)	3940 HDD
Annual solar irradiation on horizontal	1025 kWh/m²

In each case energy savings are calculated based on three different insulation measures, representing the different measures applied in the three case buildings.

5.1 Case: Kildevældsgade 69

Kildevældsgade 69 in Copenhagen is a 4-storey residential building, with three storeys of apartments and shops at the ground floor. The building was constructed in 1905 with facades made of bricks and presumably lime mortar. Facades are solid walls, thickness 1½ brick (350 mm) at 4th floor and 2 brick (470 mm) at lower floors.

Figure 45 Kildevældsgade 69, Copenhagen, Denmark, with indication of renovated apartment

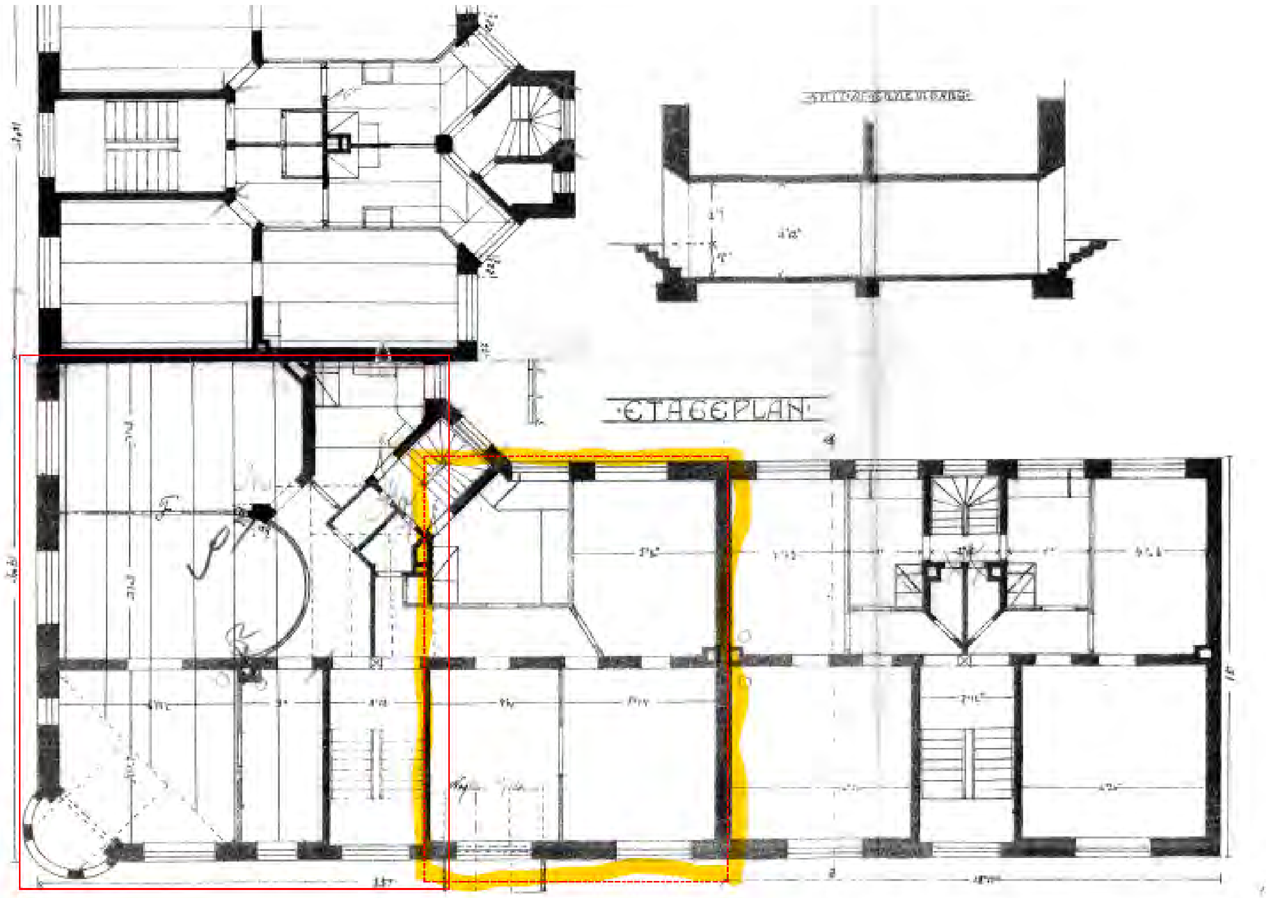


Figure 46 Floor-plan drawing of apartment at upper floor used as test case (yellow and red marking) for internal facade insulation

5.1.1 Description of building before and after renovation

External walls in the selected apartment are insulated using 25 mm *Kingspan K17* insulation material with gypsum enclosure (Figure 47), having a total thermal resistance of 1.32 m²K/W – almost reducing the transmission loss through the insulated parts of the facade to one third of the original value. The U-value of the walls at the upper floor after internal insulation is changed from 1.49 W/m²K to 0.50 W/m²K, at the lower floor from 1.19 W/m²K to 0.46 W/m²K.

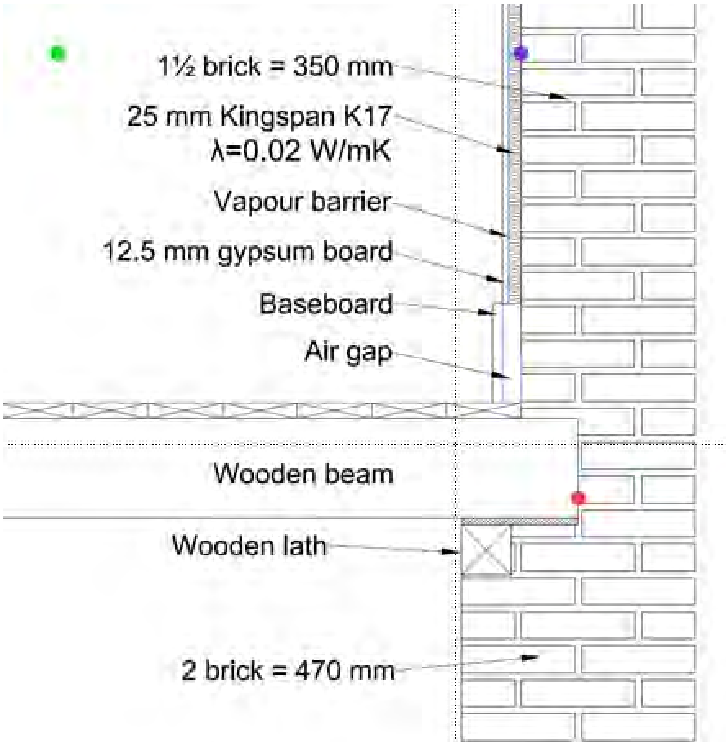


Figure 47 Section of internally insulated facade at Kilidevældsgade 69

5.1.2 Calculation conditions

Calculations are carried out for the upper three residential floors, assuming an adiabatic face between the shops and the apartments.

Due to internal walls and floors meeting the opaque facade, only a fraction of the facade can be insulated. In Kildevældsgade this means that only 47 % of the total facade area can be insulated (see Table 27).

Table 27 Overview of heated floor area and facade areas of Kildevældsgade 69

Kildevældsgade	m²	%
Total heated floor area, 3 floors	314	-
Heated floor area per floor	104.7	-
Total facade	193.9	100%
Opaque facade	135.0	70%
Insulated part of total facade	90.9	47%
Windows	58.9	30%
Not insulated part of total facade	44.1	23%

5.1.3 Energy saving potential – results

Alternative internal insulation systems were investigated by calculations (cf. introduction to Danish cases), i.e. 30 mm *IQ-Therm* and 60 mm *Kingspan* respectively, instead of 25 mm *Kingspan* internal insulation that was installed in the case building (see Table 28). Additionally, energy savings in the building with upgraded windows (U-value for windows changed from 4.4 W/m²K to 2.4 W/m²K) were calculated (see Table 29).

Table 28 Energy demands (and savings) due to selected internal insulation system (green) and two alternative insulation systems in the building without any other energy saving measures

As built	kWh/m²	IQ-therm 30 mm kWh/m²	Kingspan 25 mm kWh/m²	Kingspan 60 mm kWh/m²
Total energy requirement	138.6	118.8	116.8	110.7
Space heating	125.5	105.7	103.7	97.5
Domestic hot water	13.1	13.1	13.1	13.3
Savings (space heating)		15.8 %	17.4 %	22.3 %

Table 29 Energy demands (and savings) due to selected internal insulation system (green) and two alternative insulation systems in the building with replaced windows (U-value for windows changed from 4.4 W/m²K to 2.4 W/m²K)

As built +2 layer windows	kWh/m²	IQ-therm 30 mm kWh/m²	Kingspan 25 mm kWh/m²	Kingspan 60 mm kWh/m²
Total energy requirement	106.4	86.8	84.8	78.8
Space heating	93.3	73.7	71.7	65.7
Domestic hot water	13.1	13.1	13.1	13.1
Savings (space heating)		21.0 %	23.2 %	29.6 %

In the building without additional energy saving measures applied, 25 mm *Kingspan* internal insulations results in 17.4 % savings. In the building with upgraded windows, the energy saving is 23.2 %. Savings are calculated without considering the energy demand for production of domestic hot water as this is independent of the quality of the thermal envelope. Taking the standard consumption of domestic hot water into consideration, energy savings is 15.7 % and 20.3 % respectively.

The two alternative internal insulation systems, 30 mm *IQ-therm* and 60 mm *Kingspan*, demonstrates that there are alternatives to the selected internal insulation system with similar effects. Additionally, a solution with 60 mm *Kingspan* and upgraded windows result in almost 30 % energy savings on the space heating demand.

5.2 Case: Thomas Laubs Gade 5

Thomas Laubs Gade 5 in Copenhagen is a 4-storey residential buildings whereas three storeys are residential apartments while the ground floor contains shops. An apartment on the 4th floor has been internally insulated at the east facing facade towards the street.

Figure 48 Thomas Laubs Gade 5, with indication of renovated apartment

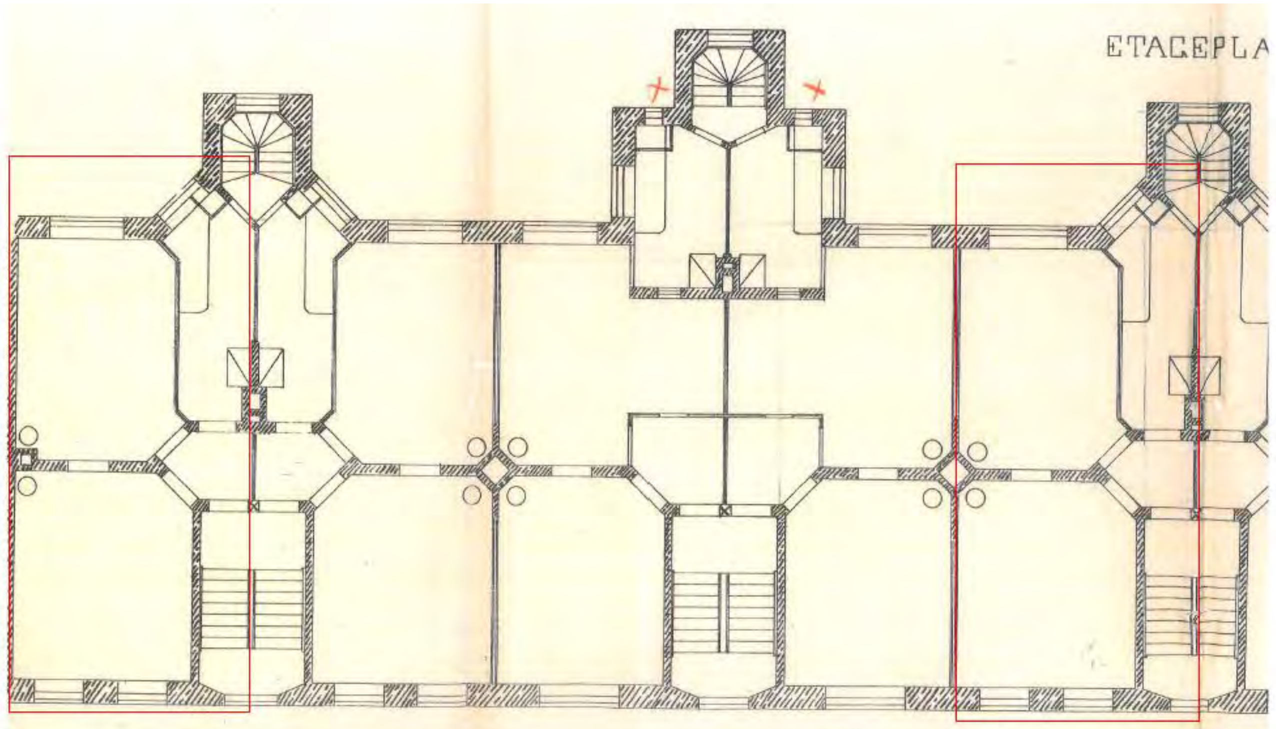


Figure 49 Floor-plan of Thomas Laubs Gade 5 used in the case calculation (red marking plus apartment placed symmetrical around the stair-well

5.2.1 Description of building before and after renovation

The building was constructed in 1899 with facades made of bricks and presumably lime mortar. Facades are solid walls, thickness 1½ brick (350 mm) at 4th floor and 2 brick (470 mm) at lower floors.

In the calculations, the accessible area of the internal facade in the selected apartment is internally insulated with 30 mm *IQ-Therm* and 10 mm gypsum board, having a total thermal resistance equal to 1.04 m²K/W – almost reducing the transmission loss through the insulated parts of the facade by 60 % of the original value. The U-value of the walls at the upper floor after internal insulation is changed from 1.49 W/m²K to 0.59 W/m²K, and at the lower floors from 1.19 W/m²K to 0.53 W/m²K (Figure 50).

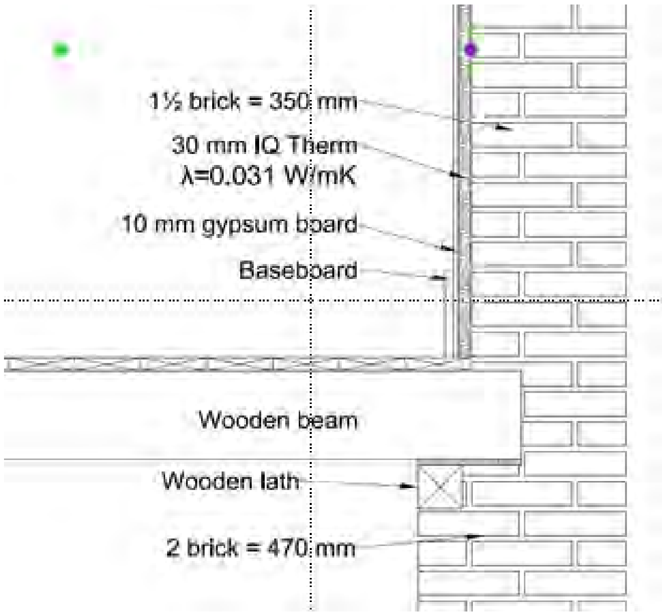


Figure 50 Section of internally insulated facade at Thomas Laubs Gade 5

5.2.2 Calculation conditions

Calculations are only carried out for the upper 3 residential floors, assuming an adiabatic face between the shops and the apartments.

Due to internal walls and floors meeting the opaque facade, only a fraction of the facade can be insulated. In Thomas Laubs Gade 5 this means that only 51 % of the total facade area can be insulated (see Table 30).

Table 30 Overview of heated floor area and facade areas in Thomas Laubs Gade 5

Thomas Laubs Gade	m²	%
Total hated floor area, 3 floors	273	-
Heated floor areas per floor	91	-
Total facade	161.9	100%
Opaque facade	116.7	72%
Insulated part of total facade	83.1	51%
Windows	45.2	28%
Not insulated part of total façade	33.6	21%

5.2.3 Energy saving potential – results

As an experiment, alternative internal insulation systems were investigated in the calculations, i.e. 25 and 60 mm *Kingspan* respectively, instead of the used 30 mm *IQ-Therm* internal insulation (see Table 31).

Additionally, energy savings in the building with upgraded windows (U-value for windows changed from 4.4 W/m²K to 2.4 W/m²K) are calculated (see Table 32).

An often-seen energy saving measure in Denmark is blowing in insulation below the attic floor, which allows for approx. 60 mm insulation. This measure decreases the roof U-value from 0.45 W/m²K to 0.20 W/m²K, or a reduction of the transmission loss by approx. 55 %. Table 33 shows the calculated energy demand and savings in the building with internal facade insulation, 2 layer windows and 60 mm attic floor insulation.

Table 31 Energy demands (and savings) due to selected internal insulation system (green) and two alternative insulation systems in the building without any other energy saving measures

as built	kWh/m²	IQ-therm 30 mm kWh/m²	Kingspan 25 mm kWh/m²	Kingspan 60 mm kWh/m²
Total energy requirement	129.5	108.7	106.6	100.1
Space heating	116.3	95.6	93.4	86.9
Domestic hot water	13.1	13.1	13.1	13.3
Savings (space heating)		17.8 %	19.7 %	25.3 %

Table 32 Energy demands (and savings) due to selected internal insulation system (green) and two alternative insulation systems in the building with replaced windows (windows U-values changed from 4.4 W/m²K to 2.4 W/m²K)

As built +2 layer windows	kWh/m²	IQ-therm 30 mm kWh/m²	Kingspan 25 mm kWh/m²	Kingspan 60 mm kWh/m²
Total energy requirement	101.2	80.8	78.6	72.3
Space heating	88.2	67.6	65.5	59.2
Domestic hot water	13.1	13.3	13.1	13.1
Savings (space heating)		23.4 %	25.7 %	32.9 %

Table 33 Energy demands (and savings) due to selected internal insulation system (green) and two alternative insulation systems in the building with replaced windows (windows U-values changed from 4.4 W/m²K to 2.4 W/m²K) and roof insulation

As built + 2 layer windows + roof insulation	kWh/m²	IQ-therm 30 mm kWh/m²	Kingspan 25 mm kWh/m²	Kingspan 60 mm kWh/m²
Total energy requirement	93,6	73,2	71,1	65
Space heating	80,5	60,1	58	51,9
Domestic hot water	13,1	13,1	13,1	13,1
Savings (space heating)		25,3 %	28,0 %	35,5 %

In the building without additional energy saving measures applied, 30 mm *IQ-Therm* internal insulations results in 17.8 % savings. In the building with upgraded windows, energy saving is 23.4 %, and in the building with upgraded windows and attic floor insulation the total saving amounts to 25.3 %. Savings are calculated without considering the energy demand for production of domestic hot water as this is independent of the quality of the thermal envelope. Taking the standard consumption of domestic hot water into consideration, energy savings drops to 16.1; 20.2 and 21.8 % respectively.

The two alternative internal insulation systems, 25 and 60 mm *Kingspan*, demonstrates that there are relevant alternatives to the selected internal insulation system and that a solution with 60 mm *Kingspan*, upgraded windows and attic floor insulation result in almost 35.5 % energy savings on the space heating demand.

5.3 Case: Klitgården

Klitgården is a detached single-family house located at Klitgårdsvej 4, near Hundested at the Northern shore of the island Zealand in Denmark.

Figure 51 Klitgården, East facade

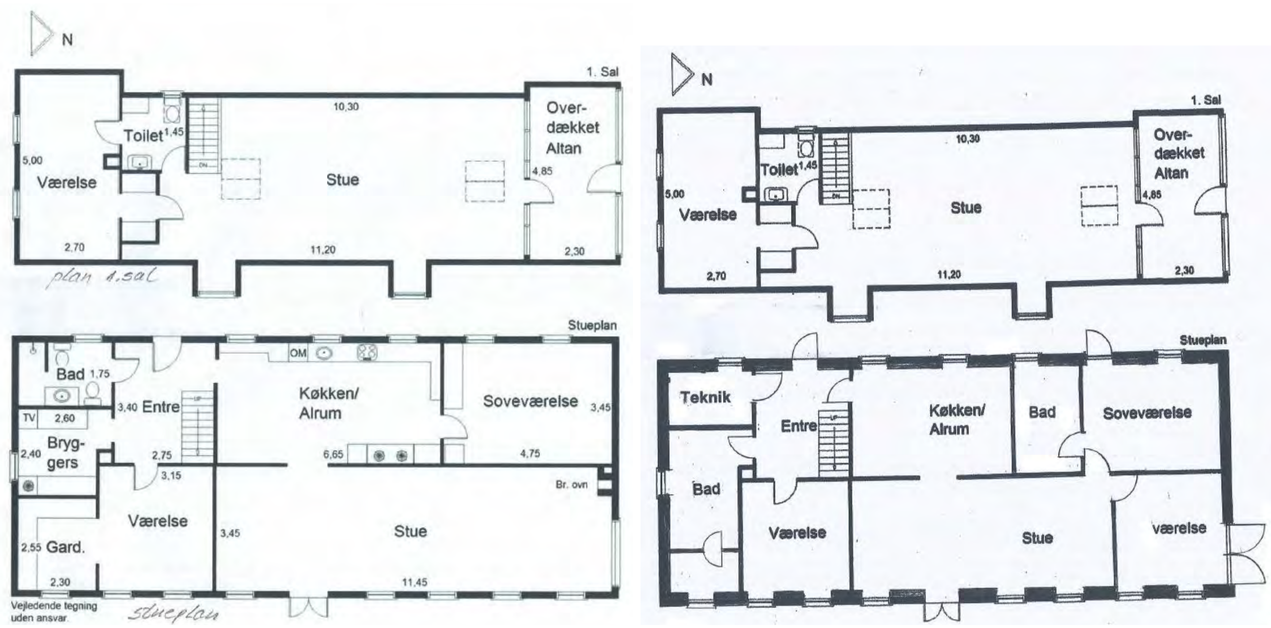


Figure 52 Upper floor plans (top) and lower floor plans (bottom) before (left) and after (right) renovation

5.3.1 Description of building before and after renovation

The house was constructed in 1875 with a total built-up area of 144 m² and two floors of 144 m² and 77 m² respectively. At the first floor, there is an open terrace ("Altan"). The house has a thatched roof and the external walls are made of massive bricks. The original floor was a wooden floor on top of a concrete slab without any insulation.

Facades has been insulated with 80 mm *IQ-therm*; 10 mm *IQ-fix* and 10 mm *IQ top/IQ-Fill*, totalling 100 mm of internal insulation, changing the U-value from 0.62 W/m²K to 0.30 W/m²K. Additionally, the space under the eaves has been insulated with 135 mm glass wool, windows have been upgraded from single pane windows to standard 2-layers glass with an average U-value of 2.8 W/m²K. The floor has also been insulated during the renovation by adding a 230 mm super EPS (Expanded Polystyrene) above which a 100 mm concrete floors with floor heating was placed. Between the floor and the facade, 100 mm polystyrene border insulation has been added.

5.3.2 Calculation conditions

Due to the internal walls only a fraction of the opaque facade can be insulated. In the case of Klitgården, it means that 4.7 % (9.3 m²) of the opaque facade has not been insulated (see Table 34). Windows and doors have been added to the house during the renovation (Table 34), meaning that the total window and door area was increased from 41.3 m² (25.3 % of the total facade area) to 46.7 m² (28.6 % of the total facade area).

Table 34 Overview of heated floor area and facade areas in Klitgården

Klitgården	AsBuilt m²	%	Renovated m²	%
Ground floor heated floor area	144		144	
1st floor heated floor area	77		77	
Total facade	199.5		199.5	
Windows and doors	41.3	25.3	46.7	28.6
Not insulated part of opaque facades	9.3	4.7	9.3	4.7

5.3.3 Energy saving potential – results

Klitgården have been subject to a major renovation including internal insulation of the facades. Additionally, windows and external doors have been replaced, the floor and space under the eaves has been insulated and the floor equipped with floor heating. Table 35 shows the main results of the case study calculations.

Table 35 Calculated energy demands (and savings) due to internal insulation of facades (green) and two alternative renovation solutions

Klitgården	AsBuilt kWh/m²	AsWas kWh/m²	Facade only kWh/m²	Full renovation kWh/m²
Total energy demand	205.9	125.4	110.1	68.7
Space heating	192.8	112.3	97.0	55.6
Domestic hot water	13.1	13.1	13.1	13.1
Savings (space heating) from AsBuild	-	41.8 %	49.7 %	71.2 %
Savings (space heating) from AsWas		-	13.6 %	50.5 %

5.4 Reflections on Danish cases

All Danish case studies are residential building: two multi-family houses and one detached single-family house. In all cases, internal insulation of the facades is made in combination with other energy saving measures. This is a normal procedure to avoid disturbing the residents more the necessary and to have only one circle of intervention. Calculation of the energy savings was performed to make it possible to isolate the savings due to internal facade insulation from the other measures. Additionally, calculations did not consider efficiencies of the heating and domestic hot water production and other equipment installations, even though these may have been upgraded in combination with the renovation. The calculation thus only analyse energy demands and savings for space heating.

The buildings' energy demand for space heating in their initial state (as they were originally constructed), after application of internal facade insulation, is reduced by 13.6 to 17.4 %. A full renovation, i.e. additional measures seen as being cost efficient, will boost the energy savings to somewhere between 23.2 and 50.5 % compared to the buildings' original energy demand for space heating.

6 Latvian cases

The energy performance calculation of two case buildings was performed through the dynamic simulation tool TRNSYS Type 56 (2016) [120], while a steady-state tool was used for another case building. In all three cases, three scenarios were simulated or calculated:

- The building as it was originally constructed;
- The building with implementation of internal facade insulation;
- The building with other energy saving measures (basement and roof insulation, windows replacement).

Latvia is located in the northern part of Europe and has long heating season with 4060 heating degree days (base 20 °C). Average yearly temperature in Riga, Latvia is 6.2 °C, and the average temperature in the heating season is 0 °C (the heating season includes 203 days) [121]. The sun shines in average 1790 hours per year, mostly from May to August, 8-10 hours per day in average.

6.1 Catholic school

The case building was built in 1910 as psychiatric clinic, since 1923 used as Catholic school. It represents an example of *art-nouveau* style. It is three-storey building with basement. Each floor differs. On the north side, the building is partly connected to the new part of the school building (see Figure 53, top right).

The heated floor area of the Catholic school is about 2410 m^2, the volume about 9142 m^3. The total facade area (including windows and doors) is about 2358 m^2.

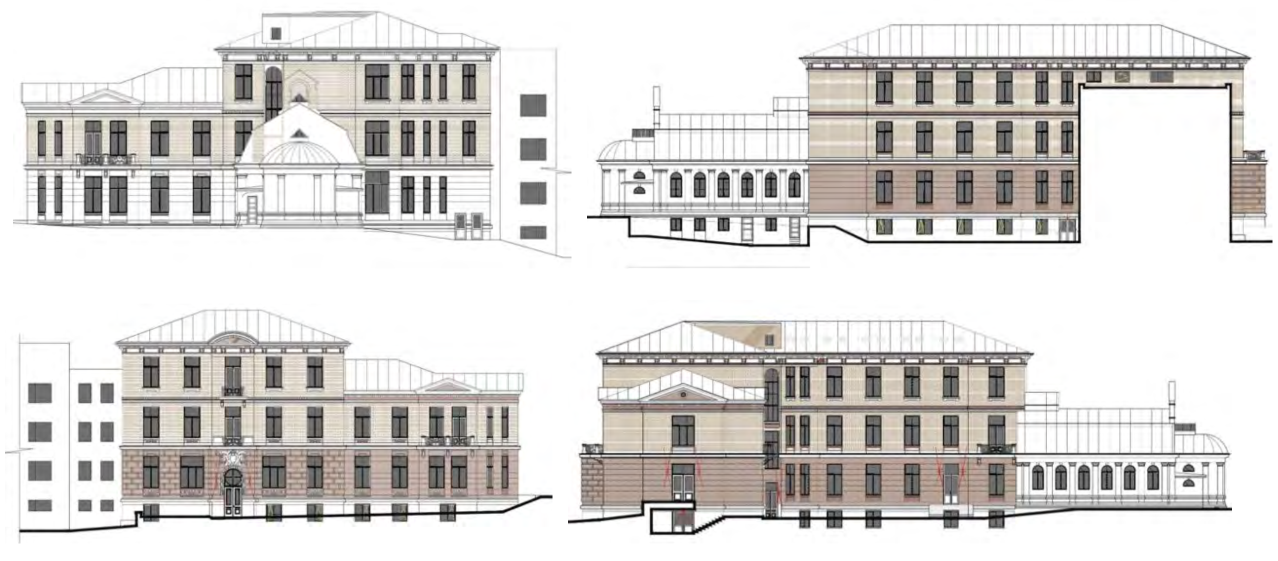


Figure 53 East facade (top left), North facade (top right), West facade (bottom left), and South facade (bottom right) of Catholic school building

Figure 54 Ground floor of catholic school

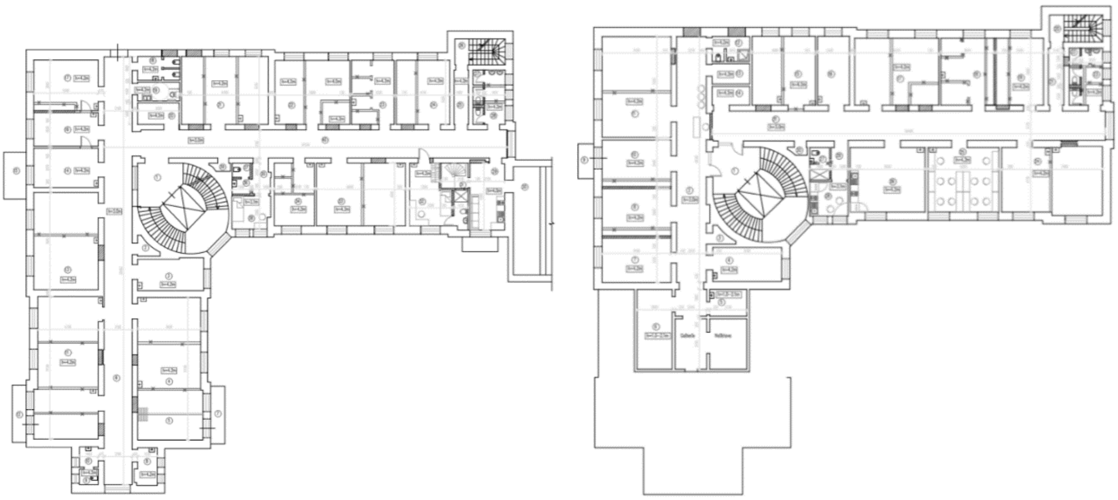


Figure 55 1st and 2nd floor plans in catholic school

6.1.1 Description of Catholic school building before and after renovation

The building has not been used for several years, with exception of few rooms, therefore its actual energy demand is not known. Retrofitting is planned to be carried out in summer 2017. Until now no energy-efficient improvements were done. External walls are made by clay bricks with variable thicknesses: 0.70 m (basement), 0.66 m (ground and 1st floor) and 0.55 m (2nd floor).

Figure 56 shows the planned insulation solution at the basement and over-ground floors. Facade construction after retrofit is described in more details in Table 36 toTable 38. Besides internal insulation, other retrofit measures are planned – windows replacement, basement insulation with 50 mm EPS (λ=0.034 W/mK) from outside, attic insulation with a 300 mm insulation layer (mineral wool λ=0.041 W/mK). The original windows, made with timber frames and single glazing, will be replaced with timber frames and triple glass windows (U ≤ 1.3 W/m²K). After retrofit, the building will be used as a school and youth centre.

Table 36 Facade construction after retrofit (basement)

	Thickness (mm)	Thermal conductivity (λ, W/mK)	Density (kg/m^3)	Area (m^2)	Heat transfer coefficient (U, W/m^{2}K)
Plaster	20	0.87	1800	356.15	0.349
Insulation Tenapors EPS	50	0.034	25		
Waterproofing (2 layers)					
Existing plaster	20	0.87	1800		
Existing masonry	700	0.64	1570		
Restoration render system and silicate paint	20	0.24	1000		

Table 37 Facade construction after retrofit (ground floor)

	Thickness (mm)	Thermal conductivity (λ, W/mK)	Density (kg/m^3)	Area (m^2)	Heat transfer coefficient (U, W/m^{2}K)
Existing plaster	20	0.87	1800	440.07	0.359
Existing masonry	660	0.64	1570		
Levelling mortar layer/existing plaster	10	0.87	1800		
Mineral wool in timber frame	50	0.035	60		
Vapour barrier Asperta					
Plasterboard (2x12.5 mm)	25	0.21	680		
Internal decoration					

Table 38 Facade construction after retrofit (1st and 2nd floor)

	Thickness (mm)	Thermal conductivity (λ, W/mK)	Density (kg/m^3)	Area (m^2)	Heat transfer coefficient (U, W/m^{2}K)
Existing masonry	550-660	0.64	1570	770.85	0.375
Levelling mortar layer/existing plaster	10	0.87	1800		
Mineral wool in timber frame	50	0.035	60		
Vapour barrier Asperta					
Plasterboard (2x12.5 mm)	25	0.21	680		
Internal decoration					

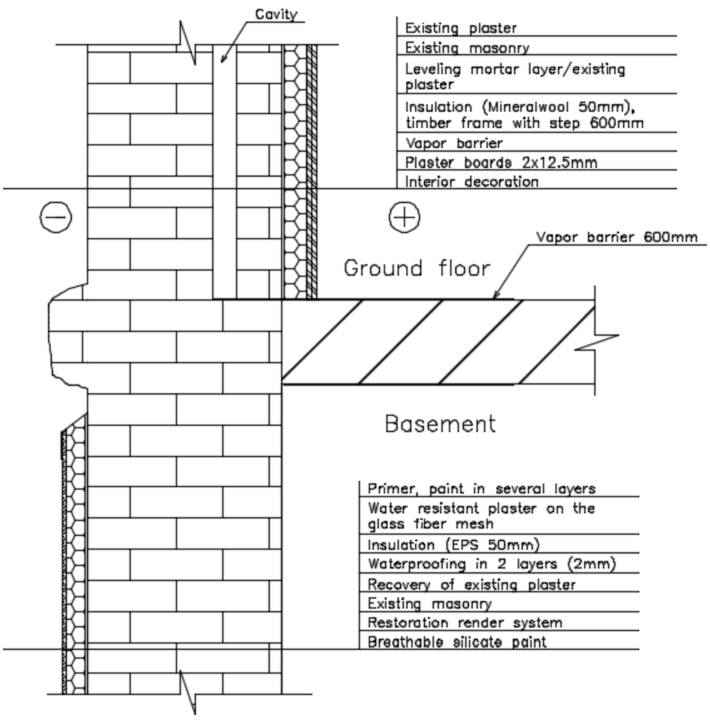


Figure 56 Planned insulation solution at basement and ground floor

6.1.2 Calculation conditions

Calculations were performed for the whole building using dynamic simulation tool TRNSYS Type 56 [120]. The building was divided in two zones: zone A1 – basement, zone A2 – all over-ground floors. The main input data are shown in Table 39. The building has a natural ventilation system.

Table 39 Main input data

	Orientation				**Heat transfer coefficient U, W/m²K**	
	East	**North**	**South**	**West**	**Before renovation**	**After renovation**
Facade walls (m²)						
Basement (masonry)	30.4	25.3	29.2	31.3	0.777	0.349
Basement in contact with soil (masonry)	268.76					
Ground floor (masonry + plaster)	157.0	110.5	154.4	155.2	0.809	0.359
2nd and 3rd floor (masonry)	246.2	215.9	282.4	256.3	0.894	0.375
Windows (m²)						
Basement	4.2	3.5	3.3	2.8	2.83	1.26
Ground floor	37.3	22.4	22.4	30.4	2.83	1.26
2nd and 3rd floor	59.7	41.7	57.2	67.6	2.83	1.26
Doors (m²)						
Basement	-	-	-	15	2.83	2.83
Ground floor	6.1	-	9.4	9	2.83	2.83
2nd and 3rd floor	-	-	-	3.8	2.83	2.83
Floor area	821.1				2.395	2.395
Roof area	821.1				2.241	0.129

Three renovation scenarios were simulated:

1. The building as it was originally constructed,
2. The building with implementation of internal facade insulation only in ground, 1st and 2nd floors,
3. The building with other energy saving measures (basement and roof insulation, windows replacement).

The calculations, for the different scenarios, were made with the following assumptions:

- Climatic data of Riga (Latvia);
- Inside temperature 20 ºC, when the building is used, i.e. workdays from 8 am to 4 pm, and 18 ºC the rest of the time;
- Infiltration 0.05 h^{-1}. Natural ventilation during use of the building (opening of windows) of 0.3 h^{-1} for zone A1 and 0.5 $h^{-1}$for zone A2;
- Heat gains based on values defined in EN ISO 13790 [117] for educational building and in TRNSYS, i.e. area per person (occupancy) 10 m^2/person, average heat flow per person 75 W/person, annual electricity use per conditioned floor area 5 W/m^2. All heat gains are scheduled (use of building in workdays from 8 am to 4 pm).

6.1.3 Energy saving potential - results

Results of the total heat demand are shown in Table 40. Scenarios 2 and 3 are compared to the performance of the building as it was originally constructed (scenario 1). The estimated annual energy needed for heating of the building before renovation (scenario 1) is 413 660 kWh/year. The estimated annual energy needed for heating of the building in scenario 2 is 377 490 kWh/year (8.7 % energy saving), and in scenario 3 is 232 490 kWh/year (43.8 % energy saving).

Table 40 Calculated energy demand in the building

		Total (kWh)	Per heated area (kWh/m^2)	Per facade area (kWh/m^2)	Savings (%)
Scenario 1	As it is originally constructed	413 660	171.6	175.4	
Scenario 2	With implementation of internal facade insulation on the original building	377 490	156.61	160.1	8.7
Scenario 3	With a full package of energy saving measures (e.g. new windows, roof insulations, basement insulation)	232 490	96.5	98.6	43.8

6.2 Spīķeri complex

The case building was built in 1930. It is located in Riga, Latvia, in the Spīķeri complex, included in the UNESCO World Heritage List.

6.2.1 Description of Spīķeri complex before and after renovation

Figure 57 and Figure 58 show the facade of the building after renovation and the floor plan.

Total heated floor area before renovation was 56.3 m^2. During renovation a number of internal walls were removed thereby, the heated floor area of the building increased to 64.8 m^2, the volume is 252.7 m^3. The total facade area (including windows and doors) is 152.6 m^2, windows and doors area is 22.5 m^2.

Figure 57 Facade of Spīķeri complex

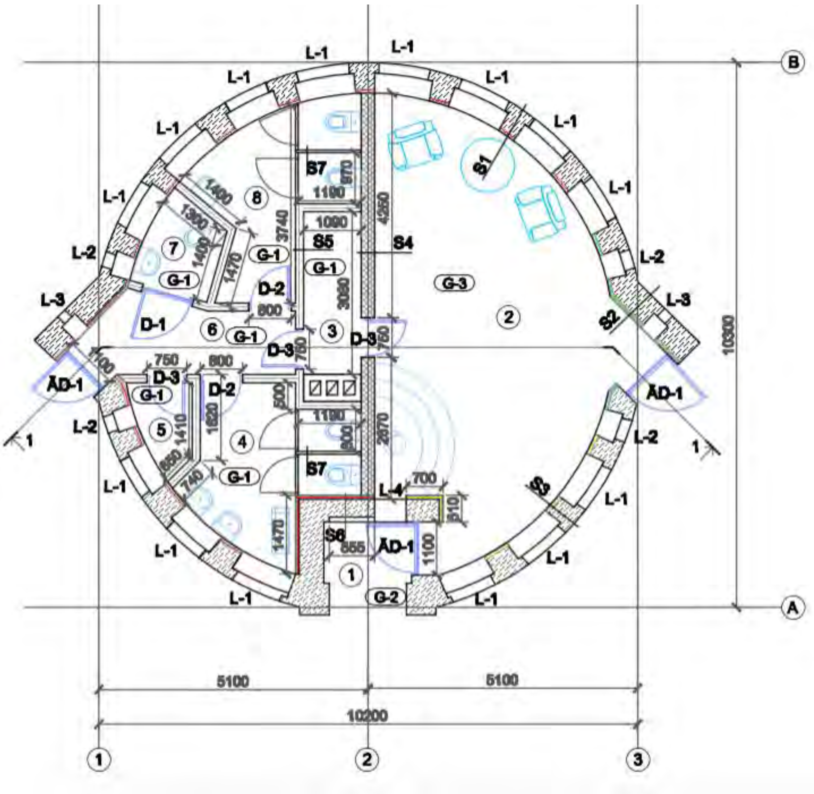


Figure 58 Floor plan of Spīķeri complex

The External walls of the building are made of painted silicate bricks with a thickness of 510 mm. The building was uninhabited for several years and therefore the construction was significantly affected by weather and human factors. Renovation of the building was done in 2012–2013 within the “Co2ol Bricks” project financed by the Baltic Sea Region Programme 2007-2013. Overall renovation included:

- Wall insulation from inside by using 50 mm aerogel, 50 mm and 100 mm respectively of polyisocyanurate (PIR) insulation and 50 mm of vacuum insulation panels (VIP); wall constructions after renovation in more details are described in Table 41 to Table 44 and Figure 59.

- Roof insulation with 300 mm PIR (Figure 61);
- Ground floor insulation with 200 mm PIR (Figure 60);
- Triple glazing with integrated shading (U = 0.82 W/m^{2}K);
- Lighting system with LED luminaries;
- Daylight using system Parans with optical fibres, where sunlight is transferred via optical fibre to rooms;
- Self-cleaning facade paint *Lotusan* for easier maintenance of the building;
- Heat pump for space heating;
- Mechanical ventilation with heat recovery.

Table 41 Facade construction after retrofit with 50 mm aerogel

	Thickness (mm)	Thermal conductivity (λ, W/mK)	Area (m^2)	Heat transfer coefficient (U, W/m^{2}K)
Self-cleaning facade paint Lotusan			4.7	0.27
Silicate bricks	510	0.8		
Aerogel	50	0.018		
Vapour barrier				
Plasterboard	25	0.21		
Internal decoration				

Table 42 Facade construction after retrofit with 50 mm vacuum insulation panel (VIP)

	Thickness (mm)	Thermal conductivity (λ, W/mK)	Area (m^2)	Heat transfer coefficient (U, W/m2K)
Self-cleaning facade paint Lotusan			5.2	0.13
Silicate bricks	510	0.8		
Vacuum insulation panels	50	0.008		
Vapour barrier				
Plasterboard	25	0.21		
Internal decoration				

Table 43 Facade 3 construction after retrofit with 50 mm polyisocyanurate (PIR)

	Thickness (mm)	Thermal conductivity (λ, W/mK)	Area (m^2)	Heat transfer coefficient (U, W/m^{2}K)
Self-cleaning facade paint Lotusan			5.0	0.32
Silicate bricks	510	0.8		
Polyisocyanurate (PIR)	50	0.023		
Vapour barrier				
Plasterboard	25	0.21		
Internal decoration				

Table 44 Facade construction after retrofit with 100 mm PIR

	Thickness (mm)	Thermal conductivity (λ, W/mK)	Area (m^2)	Heat transfer coefficient (U, W/m^2K)
Self-cleaning facade paint Lotusan			114.1	0.19
Silicate bricks	510	0.8		
Polyisocyanurate (PIR)	100	0.023		
Vapour barrier				
Plasterboard	25	0.21		
Internal decoration				

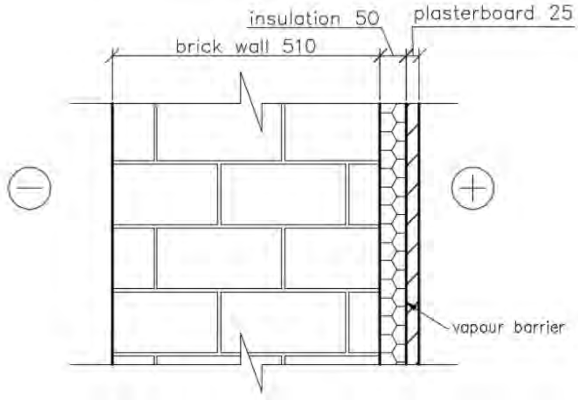


Figure 59 Wall insulation solution

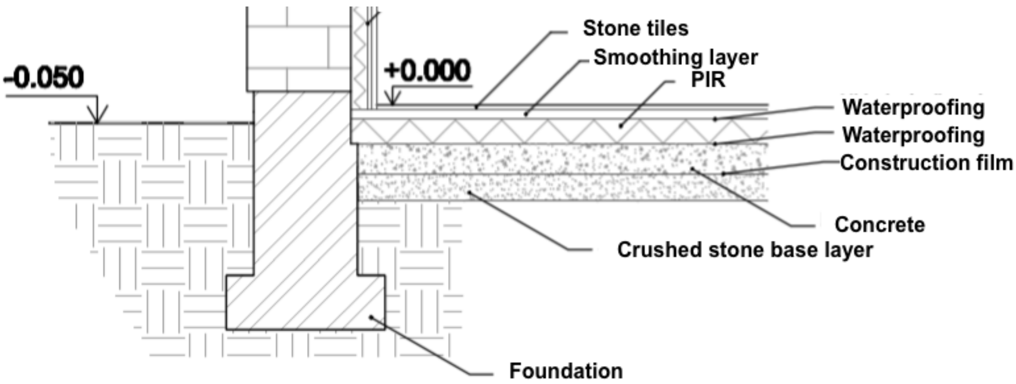


Figure 60 Ground insulation solution

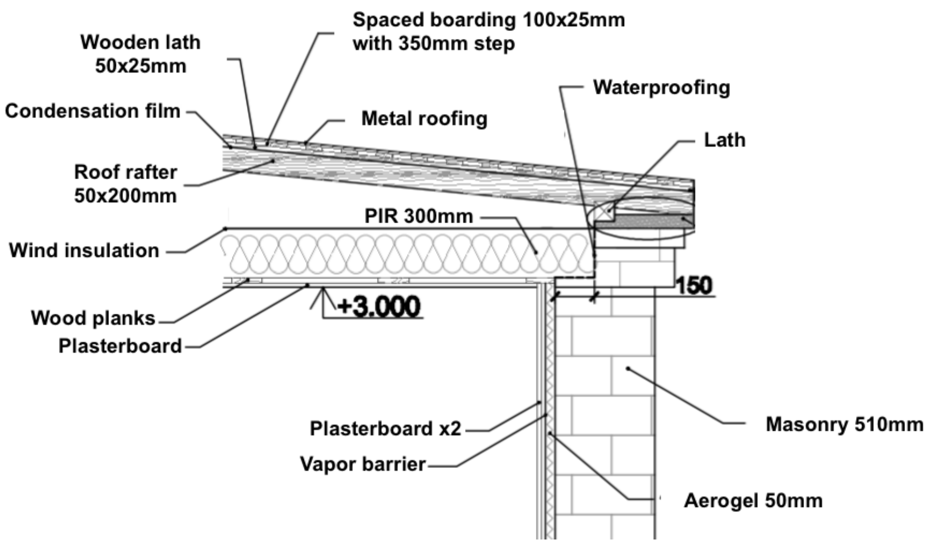


Figure 61 Roof insulation solution

6.2.2 Calculation conditions

Calculations were done according to Regulations of Cabinet of Ministers No 338 "Regulations regarding the Latvian Building Code LBN 003-15 "Construction Climatology" and Regulations of Cabinet of Ministers No 348 "Method for calculating energy performance of buildings" [121]. This method is based on EN ISO 13790 [117]. The calculation is based on the following assumptions:

- Inside temperature 18 ºC;
- Relative humidity 50 %;
- Ventilation system with heat recovery which runs 8 hours/day, providing 1.5 h^{-1} air exchange and 70% heat recovery, during the rest of the time infiltration 0.35 h^{-1}.
- Heat gains based on values defined in EN ISO 13790 [117]. Four persons are expected to be present 8 h per day.

Three renovation scenarios were calculated:

1. The building as it was originally constructed;
2. The building with implementation of internal facade insulation;
3. The building with other energy saving measures (ground and roof insulation, windows replacement).

6.2.3 Energy saving potential - results

Results of total heat demand are shown in Table 45. Scenarios 2 and 3 are compared to the performance of the building as it was originally constructed (scenario 1).

The estimated annual energy need for space heating in the building before renovation (scenario 1) is 36 570 kWh/year or 564.4 kWh/m² per year. This is high large annual energy consumption for space heating compared to the average building in Latvia, which is 150 – 180 kWh/m^2. However, the building cannot be compared to an average building as the heated area is only 64.8 m^2, which is far less than an average building. The height of the building is also higher than an average building. All these factors lead to a very high space heating consumption.

The estimated annual energy need for space heating in the building in scenario 2 is 24 868 kWh/year (32% energy saving), and in scenario 3 it is 8 030 kWh/year (78% energy saving).

Table 45 Calculated energy demand in the building

Scenario		Total (kWh)	Per heated area (kWh/m^2)	Per facade area (kWh/m^2)	Savings (%)
1	As it is originally constructed	36 570	564.35	239.64	
2	With implementation of internal facade insulation on the original building	24 868	383.76	162.96	32
3	With a full package of energy saving measures (e.g. new windows, roof insulations, basement insulation)	8 030	123.92	52.62	78

6.3 Single family house

6.3.1 Description of building before and after renovation

The case building, single family house (Figure 62), was built in 1893. It is a two-story building with pitched roof and basement.

Figure 62 North and west side of the single-family house case building

The heated floor area (ground and 1st floor, Figure 63 and Figure 64) is 339.4 m^2, the volume 870 m^3. The total facade area (including windows and doors, but without basement) is 275 m^2. The basement has an area of 68.7 m^2 and a volume of 130.5 m^3 and is not heated.

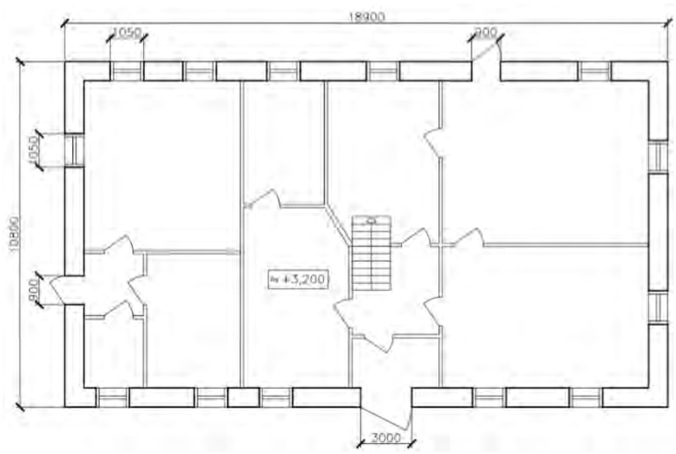


Figure 63 Plan of the ground floor

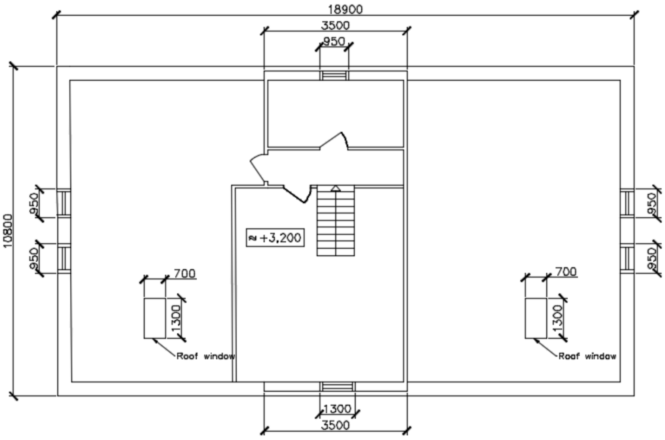


Figure 64 Plan of the 1st floor

External walls are made of dolomite stone embedded in mortar and plastered inside, with a thickness of 0.60 m (ground floor and basement) and 0.45 m (1^{st} floor). Dolomite stone has a density varying between 2060 to 2340 kg/m^3. After the full roof reconstruction two dormers were added on west and east side of the house.

The house was renovated in 2006 with internal wall insulation made of mineral wool and plasterboard. Facade construction in more details is described in Table 46 to Table 48 and in Figure 65. Besides internal facade insulation, roof and basement ceiling was also insulated - roof was insulated with 300 mm mineral wool (λ = 0.035 W/mK), basement ceiling was insulated with expanded clay (250 mm, λ = 0.11 W/mK). Windows were replaced with new ones (U ≤ 1.3 W/m^2K).

Table 46 Facade construction after retrofit (ground floor)

	Thickness (mm)	Thermal conductivity (λ, W/mK)	Density (kg/m^3)	Area (m^2)	Heat transfer coefficient (U, W/m^2K)
Dolomite	600	2.2	2400	149.54	0.208
Existing plaster	20	0.87	1800		
Mineral wool	150	0.035	60		
Vapour barrier					
Plasterboard	12.5	0.21	680		
Internal decoration					

Table 47 Facade construction after renovation (1st floor 1st type)

	Thickness (mm)	Thermal conductivity (λ,W/mK)	Density (kg/m^3)	Area (m^2)	Heat transfer coefficient (U, W/m^2K)
Dolomite	450	2.2	2400	29.62	0.211
Existing plaster	20	0.87	1800		
Mineral wool	150	0.035	60		
Vapour barrier					
Plasterboard	12.5	0.21	680		
Internal decoration					

Table 48 Facade construction after renovation (1st floor 2nd type - dormer)

	Thickness (mm)	Thermal conductivity (λ,W/mK)	Density (kg/m^3)	Area (m^2)	Heat transfer coefficient (U, W/m^2K)
Wood planks	25	0.2		22.78	0.215
Mineral wool	150	0.035	60		
Vapour barrier					
Plasterboard	12.5	0.21	680		
Internal decoration					

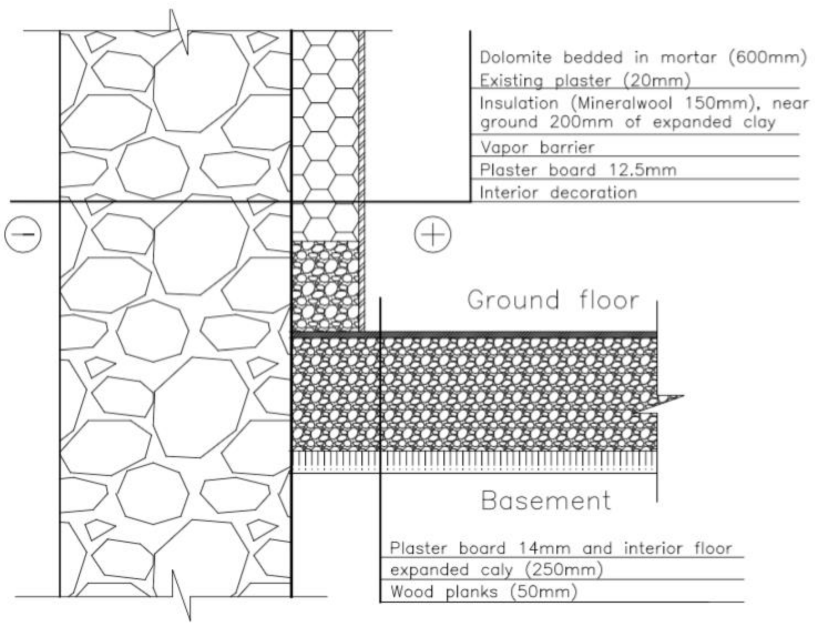


Figure 65. Planned insulation solution at basement and ground floor.

6.3.2 Calculation conditions

Calculations were performed for the whole building using the dynamic simulation tool TRNSYS Type 56 [120]. The house was divided in two zones: zone A1 – basement, and zone A2 – both over-ground floors. Main input data are shown in Table 49. The house has a natural ventilation system with infiltration through the building envelope. Note that 2nd type of 1st floors' wall was constructed only after roof reconstruction.

Table 49 Main input data

	Orientation				**Heat transfer coefficient U, W/m²K**	
	North	**East**	**West**	**South**	**Before renovation**	**After renovation**
Facade walls (m²)						
Basement	9.14	18.9	-	5.08	2.259	2.259
Basement in contact with soil	-	15.12	34.02	4.06		
Ground floor	32.4	56.7	56.7	32.4	2.147	0.208
1st floor (1st type)	17.28	-	-	17,28	2.515	0.211
1st floor (2nd type)	4,32	8,47	8,47	4,32	-	0,215
Windows (m²)						
Basement	-	1.68	-	1.12	2.83	2.83
Ground floor	1.68	8.4	8.4	3.36	2.83	1.26
1st floor (1st type)	2.47	-	-	2.47	2.83	1.26
1st floor (2nd type)	-	1.24	1.57	-	-	1.26
Doors (m²)						
Basement	1.44	-	-	-	2.83	2.83
Ground floor	1.98	1.98	2.86	-	2.83	2.83
Floor area on ground	108.11				2.395	2.395
Basement ceiling	96.01				0.668	0.34
Roof area	-	141.4	141.4	-	1.087	0.110

Three renovation scenarios were simulated:
1. The house as it was before renovation;
2. The house with implementation of internal facade insulation in ground and 1st floors;
3. The building with other energy saving measures (basement ceiling and roof insulation, windows replacement).

The calculation, for the different scenarios, was made with the following assumptions:
- Climatic data of Latvia defined by user as input file in TRNSYS;
- Inside temperature 20 ºC, when the building is used, i.e. workdays in the morning (6 am to 8 am) and in the evening (4 pm to 11 pm) and full weekends, and 18 ºC the rest of the time;
- Relative humidity 50 %;
- Infiltration 0.05 h-1. Natural ventilation during the use of the building for zone A2 0.5 h^{-1}.
- Heat gains based on values defined in EN ISO 13790 [117] for a single family house - 70 W/person (2 persons), annual electricity use per conditioned floor area 5 W/m^2 during the use of building. All heat gains are scheduled.

6.3.3 Energy saving potential - results

Results of total space heating demand are shown in Table 50. Scenarios 2 and 3 are compared to the performance of the house as it was originally constructed (scenario 1). The estimated annual energy need for space heating in the house before renovation (scenario 1) is 66 071 kWh/year or 194 kWh/m² per year. The estimated annual energy needed for space heating of the house in scenario 2 is 42 753 kWh/year or 126 kWh/m² per year (35% energy saving), and in scenario 3 is 18 334 kWh/year or 54 kWh/m² per year (72% energy saving).

Table 50 Calculated energy demand in the building

		Total (kWh)	Per heated area (kWh/m^2)	Per facade area (kWh/m^2)	Savings (%)
Scenario 1	Without insulation	66 071	194.42	240.48	
Scenario 2	With implementation of internal facade insulation on the original building	42 753	125.80	155.61	35
Scenario 3	With a full package of energy saving measures (e.g. new windows, roof insulations, basement insulation)	18 334	53.95	66.73	72

Further results of the building energy simulations are reported in Table 51 to Table 53 that includes: the internal heat gains, the solar heat gains, losses by ventilation and infiltration, and the monthly energy needed for space heating.

Table 51 Energy balance before renovation (Scenario 1)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Heating	13010	10900	9372	5595	0	0	0	0	0	6046	9158	11990
Cooling	0	0	0	0	0	0	0	0	0	0	0	0
Infiltration	-292.4	-254.1	-228.5	-151	0	0	0	0	0	-142.6	-199.5	-263.4
Ventilation	-1922	-1675	-1522	-1014	0	0	0	0	0	-953.7	-1316	-1737
SolarLoad	282.8	492.4	853	1035	0	0	0	0	0	474.6	85.23	112
Internal heat gains	619.7	561.3	623.8	600.2	0	0	0	0	0	619.7	600.2	623.8

Table 52 Energy balance after application of internal facade insulation (Scenario 2)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Heating	8531	7079	5911	3359	0	0	0	0	0	3898	6070	7905
Cooling	0	0	0	0	0	0	0	0	0	0	0	0
Infiltration	-292.4	-254.2	-228.6	-151.7	0	0	0	0	0	-142.8	-199.7	-263.6
Ventilation	-1923	-1676	-1523	-1018	0	0	0	0	0	-954.9	-1317	-1738
SolarLoad	282.8	492.4	853	1035	0	0	0	0	0	474.6	85.23	112
Internal heat gains	619.7	561.3	623.8	600.2	0	0	0	0	0	619.7	600.2	623.8

Table 53 Energy balance after full renovation (Scenario 3)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Heating	3871	3244	2657	1396	0	0	0	0	0	1285	2416	3465
Cooling	0	0	0	0	0	0	0	0	0	0	0	0
Infiltration	-292.3	-254	-228.4	-152.5	0	0	0	0	0	-144	-199.4	-263.3
Ventilation	-1922	-1674	-1521	-1022	0	0	0	0	0	-960.9	-1316	-1737
SolarLoad	174.5	305.9	537	658.6	0	0	0	0	0	297.4	53.59	69.35
Internal heat gains	619.7	561.3	623.8	600.2	0	0	0	0	0	619.7	600.2	623.8

6.4 Reflections on Latvian case studies

All 3 Latvian case buildings are different both for their design and use. In all cases the internal insulation of the facade is made in combination with other energy saving measures. Therefore, for each case the energy saving calculation was performed for three scenarios: building as it was originally constructed; building insulated with internal insulation; building with other energy measures. This made it possible to compare savings due to internal facade insulation and due to other implemented measures. The energy demand for space heating after application of internal facade insulation is reduced by 9 to 35%. A full renovation offers energy savings from 44 to 78% compared to the buildings' original demand for space heating.

7 Italian case

7.1 Graziosi House

The Italian building case-study is the ”Graziosi House” (Figure 66), a three-storey single-family detached house for 3 people, built in 1935 in Cattolica (RM), a coastal town in the centre of Italy (average heating degree-days: 2165 with a base temperature of 19°C). The building has a base area of 96 m^2 and 3 floors (ground floor, first floor plus an attic), for a total volume of 690 m^3.

Figure 66 View of the facades (a); Building plans (b)

Energy performance is calculated using standard conditions for loads and indoor conditions in residential buildings, with the Italian software Termo Namirial, 3.3 version [122], a tool used to perform the quasi-stationary energy calculation according to the Italian technical specifications [123], which represent the national application procedure of EN ISO 13790 [117].

The calculation provides the energy demands in energy needed and in primary energy. The climatic data of the city of Cattolica, included in the climatic zone “E” (Figure 66) one of the most representative in Italy, are used in order to perform the energy calculation (Table 54).

Table 54 Cattolica, climate zone “E”, reference climate characteristics

Climate information	
Average outdoor temperature	8.8 °C
Heating degree days (base 19 °C)	2165 °C
Heating period	183 days
Annual solar irradiation on horizontal	2403 kWh/m²
Building natural ventilation rate:	0.5 h^{-1}

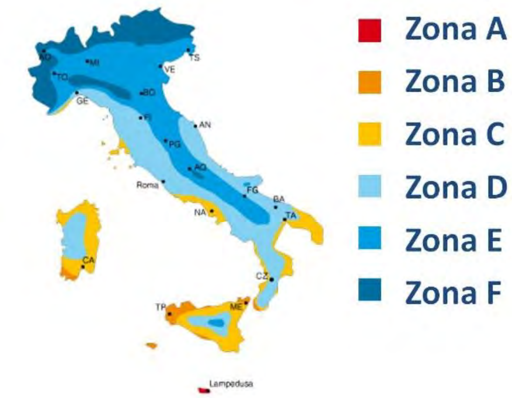


Figure 67 Map with the Italian climate zones

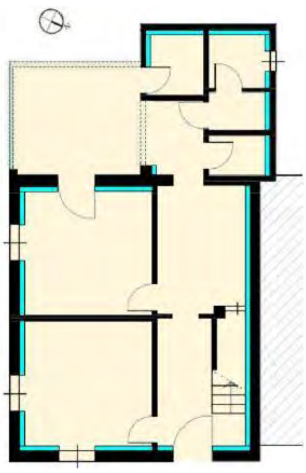
Finally, the following assumptions, also, are made:

- simplified approach for the calculation of internal heat gains, depending on the building use (residential building) with a value of 2.64 W/m² (24 hours/day all year).
- thermal bridges calculated based on CENED national database of thermal bridges through the simplified approach of standard [124];
- conversion coefficient to primary energy fixed at 1.05 for fossil fuels and 2.42 for electricity.

7.1.1 Description of Graziosi House before and after renovation

External, original walls (before the building renovation) are in plastered brick masonry with variable thicknesses, from 29 cm (U=1.76 W/m²K) to 16 cm (U= 2.58 W/m²K). The material layers of the original walls are: 2 cm external plaster (lime and cement based plaster, 25 or 12 cm brick masonry and 2 cm internal plaster (lime and gypsum based plaster).

Original floors and roof, before renovation, consisted on wooden slabs without insulation, with respectively floor tiles (U=1.29 W/m²K-first floor slab) or clay tiles (U=1.68 W/m²K).



Layer	S (m)		U [W/m2K]
External plaster	0,02		0,48
Brick	0,25		
Adhesive	0,01		
EPS insulation	0,06		
Internal plaster	0,006		

Layer	S (m)		U [W/m2K]
External plaster	0,02		0,53
Brick	0,12		
Adhesive	0,01		
EPS insulation	0,06		
Internal plaster	0,006		

Figure 68 House floor plan with internal insulation (left). Material layers of the insulated walls (right)

This house is designed in Art Nouveau style (Modern Style). It is not a nationally listed building but shows interesting architectural elements that should be preserved. For this reason, in order to preserve the facade elements and, at the same time, improve the building heating energy performance and the indoor thermal comfort, an internal insulation system was selected for the envelope. In particular, walls have been insulated with 6 cm EPS (Expanded Polystyrene) and finished with plaster (ETICS technique) to obtain a U-value of 0.48 W/m²K (for the existing wall thickness 29 cm) and a U-value of 0.53 W/m²K (for the existing wall thickness 16 cm), as shown in Figure 68.

Building renovation included other energy retrofit measures, i.e. replacement of windows, insulation of roof and renewal of the equipment for heating and domestic hot water. In particular, the renovation of the roof was obtained by including an insulation layer consisting of 8 cm of wood fibre insulation board. With regards to windows, the original ones with timber frame and 4 mm single glazing (U = 5.7 W/m²K), were replaced with double glass 4-16-4 mm and timber frame windows (U = 2.98 W/m²K).

Finally, concerning the building equipment, the old heating system was a conventional natural gas equipment (23 kW peak power) with radiators. This was renewed with a new natural gas equipment (29.8 kW peak power) and radiant floor for a total area of 153 m².

7.1.2 Calculation conditions

The building performance simulation for the assessment of the energy consumption was calculated based on the Italian technical specifications UNI/TS 11300:2014, which represent the national application procedure of EN ISO 13790 [117] in 4 renovation scenarios:

1. The building, as it was originally constructed, before energy efficiency improvements.
2. The building with implementation of internal facade insulation as a single intervention to improve the building space heating energy performance.
3. The building with other energy saving measures i.e. new windows and roof insulation, but only related to the thermal envelope.
4. The building subject to a global renovation, including the envelope renovation measures (both opaque and transparent components) and the renewal of equipment for heating and domestic hot water.

The net heated floor area (calculated on the insulated building, considering 6 cm of insulation) is 170.3 m². The facade area covered by internal insulation (excluding slabs and windows) is 184.26 m².

7.1.3 Energy saving potential - results

Scenarios 2, 3 and 4 are compared to the performance of the building before renovation (scenario 1). The estimated annual energy needed for space heating in the house before renovation (scenario 1) is 36277.5 kWh/year or 213.0 kWh/m² per year. The estimated annual energy needed for space heating in the house in scenario 2 is 24102 kWh/year or 141.5 kWh/m² per year (34 % energy saving), and in scenario 3 is 19032 kWh/year or 111.7 kWh/m² per year (48 % energy saving). The estimated annual energy needed for space heating of the house in scenario 4 is the same of scenario 3 because no other measures are applied to the building envelope; the only retrofit intervention is the renewal of the equipment for heating and domestic hot water, which only affects the efficiency of producing the needed heating and hence the total primary energy demand for heating the house.

The estimated annual primary energy for space heating of the house before implementation of energy efficiency measures (scenario 1) is 50777 kWh/year or 298.2 kWh/m² (net heated floor area) per year. The estimated annual primary energy for space heating of the house in scenario 2 is 32546 kWh/year or 191.1 kWh/m² per year (36 % energy saving), in scenario 3 is 26015 kWh/year or 152.7 kWh/m² per year (49 % energy saving), and in scenario 4 is 24776 kWh/year or 145.5 kWh/m² per year (51% energy saving). These results are reported in Table 55 and shown also in Figure 68 to Figure 70.

Table 55 Annual energy needed and primary energy for heating in scenarios 1, 2, 3 and 4, per net heated floor area

Scenario	Qh,nd (Annual Energy Needed for heating) [kWh/m²]	Saving of the energy consumption of the building before renovation expressed as energy needed [%]
1	213.0	
2	141.5	-34%
3	111.7	-48%
	Qp,TOT,H (Annual Primary Energy for heating) [kWh/m²]	**Saving of the energy consumption of the building before renovation expressed as primary energy [%]**
1	298.2	
2	191.1	-36%
3	152.7	-49%
4	145.5	-51%
	Qd,TOT,H (Annual delivered energy for heating) [kWh/m²]	**Saving of the energy consumption of the building before renovation expressed as primary energy [%]**
1	284.0	
2	182.0	-36%
3	145.4	-49%
4	138.5	-51%

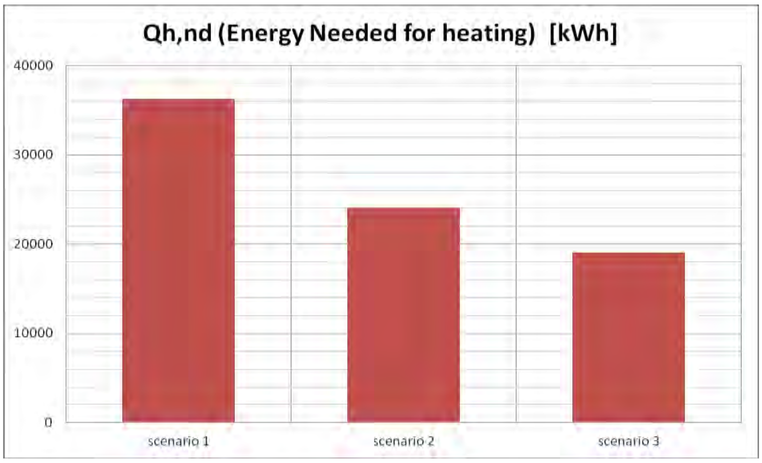


Figure 69 Annual energy needed for heating in scenarios 1, 2 and 3

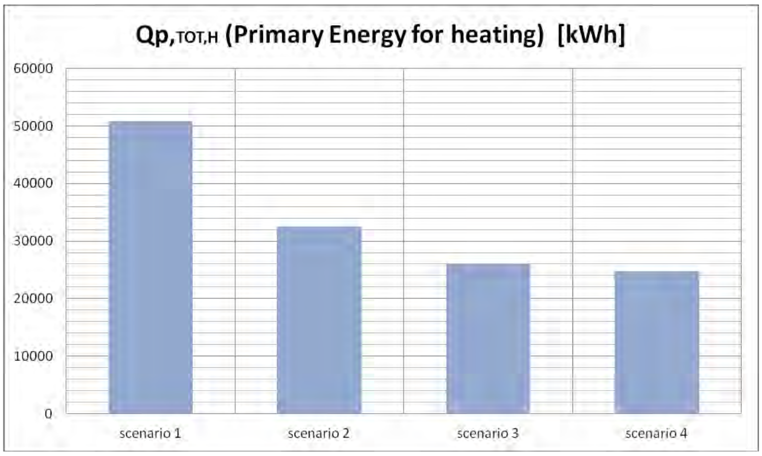
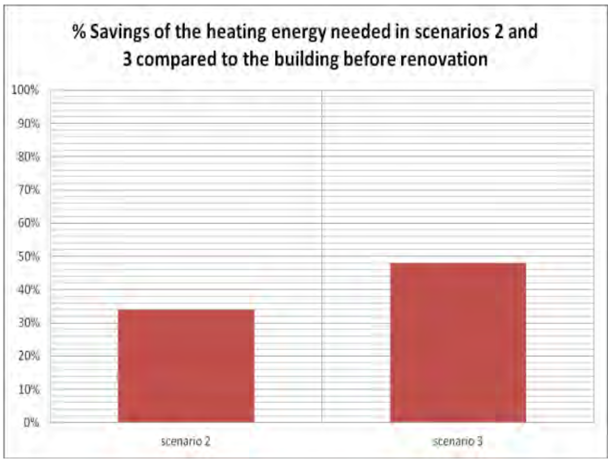


Figure 70 Annual Primary energy for heating in scenarios 1, 2, 3 and 4



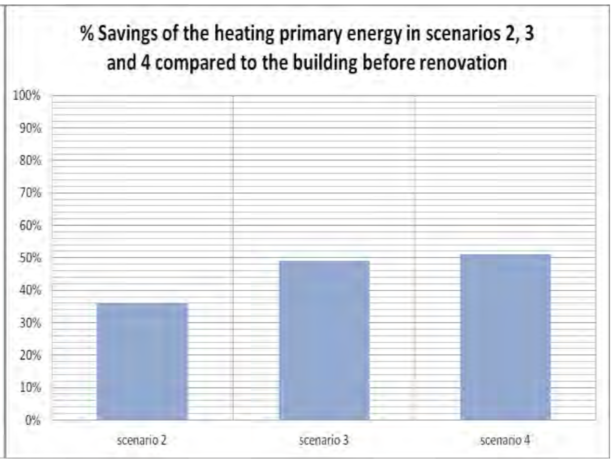


Figure 71 Heating energy savings (%) compared to the building before renovation: energy needed (left) and primary energy (right)

Further results of the building energy simulations are reported in Table 56 and include: the heat transfer by transmission, the heat transfer by ventilation, the internal heat gains, the solar heat gains, the monthly energy needed for space heating and the monthly primary energy for space heating.

Table 56 Main results of the energy performance assessment for the original building and renovation scenarios

QH,tr (Heat Transfer by Transmission) [kWh]													
Scenario	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	Total
1	8070	7044	6187	2446	-	-	-	-	-	2077	5426	7436	38685
2	5501	4820	4267	1694	-	-	-	-	-	1470	3745	5070	26567
3	4422	3891	3472	1395	-	-	-	-	-	1190	3009	4068	21447
4	4422	3891	3472	1395	-	-	-	-	-	1190	3009	4068	21447
QH,ve (Heat Transfer by Ventilation) [kWh]													
Scenario	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	Total
1	575	513	468	193	-	-	-	-	-	163	396	526	2832
2	552	492	449	185	-	-	-	-	-	156	380	505	2718
3	555	496	452	186	-	-	-	-	-	157	383	509	2738
4	555	496	452	186	-	-	-	-	-	157	383	509	2738
QH,int (Internal Heat Gains) [kWh]													
Scenario	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	Total
1, 2, 3, 4	335	302	335	162	-	-	-	-	-	184	324	335	1976
QH,sol (Solar Heat Gains, through transparent and opaque parts of the envelope) [kWh]													
Scenario	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	Total
1	1106	1262	1739	931	-	-	-	-	-	887	1193	1007	8125
2	771	886	1234	666	-	-	-	-	-	622	833	700	5711
3	672	753	1010	526	-	-	-	-	-	527	723	615	4827
4	672	753	1010	526	-	-	-	-	-	527	723	615	4827
Qh,nd (Energy Needed for space heating) [kWh]													
Scenario	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	Total
1	7839	6740	5658	2148	-	-	-	-	-	1704	4995	7193	36278
2	5250	4500	3732	1396	-	-	-	-	-	1106	3307	4810	24102
3	4179	3582	2951	1105	-	-	-	-	-	825	2576	3814	19032
4	4179	3582	2951	1105	-	-	-	-	-	825	2576	3814	19032
Qp,TOT,H (Primary Energy for space heating) [kWh]													
Scenario	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	Total
1	10807	9307	7905	3204	-	-	-	-	-	2597	7012	9946	50777
2	6928	5956	5028	2079	-	-	-	-	-	1697	4480	6379	32546
3	5579	4798	4030	1665	-	-	-	-	-	1282	3540	5120	26015
4	5379	4617	3833	1511	-	-	-	-	-	1161	3356	4920	24776

7.2 Reflections on Italian cases

The Italian case building is a historic single family-house located in a coastal town in the centre of Italy, in the climatic area “E”, one of the most representative in Italy (average heating degree-days: 2165, 19°C temperature basis).

The building performance simulations were performed in 4 progressive scenarios: (1) pre-renovation; (2) facades internal insulation; (3) facades internal insulation, roof insulation, windows replacement; (4) whole envelope and heating equipment renovation.

Scenario 4 represents the real renovation intervention realized in the building, while scenarios 2 and 3 represent two intermediate calculation steps. Renovation was realized according to the previous national requirements [125] for building energy efficiency, before the actual regulation [126].

The scenarios 2-4 entail a significant reduction of the estimated annual energy needed compared to pre-renovation scenario - respectively of 34 % for scenario 2 and 48 % for scenarios 3 and 4 - and of annual primary and delivered energy for heating - respectively of 36 % for scenario 2 and 49 % for scenario 3 and 51 % for scenario 4.

Although very rarely in the Italian context energy efficiency measures are limited to the insulation of the building envelope, while most often they also include interventions on the heating equipment, results underline the great benefits solely deriving from application of internal insulation.

The recent European Guidelines for the promotion of nearly Zero Energy Buildings [127] provide the benchmarks for energy performance of nZEBs, classified by several climatic zones in Europe. Targets for a new residential building in Continental climate (as for this case study) are: consumption of total primary energy of 50–70 kWh/(m^2 year), of which 30 kWh/(m^2 year) should come from on-site renewable sources and 20–40 kWh/(m^2 year) from net primary energy. The case building presents higher values but this is justified by the fact that this target is set for new buildings and that the renovation was realized according to a previous Italian energy efficiency regulation.

Results obtained from energy simulations cannot be compared with measured data on the building energy consumption before/after renovation, since these data are not available. Finally, it should be considered that calculation according to Italian technical specifications UNI/TS 11300: 2014 [123] which represent the national application procedure of EN ISO 13790 [117], include some relevant simplifications and assumptions, including the length of the heating hours/periods and the building's internal gains compared to the real situation.

8 Swiss case

8.1 Lausanne residential building

This building, from 1910 situated in the centre of Lausanne (CH), is part of a group of four buildings grouped together. It is made of five regular storeys containing each four apartments, with three additional apartments just below the mansard roof. The building provides a heated gross floor area of 1563 m² and is not insulated at all.

Figure 72 east, west and south-oriented facades

8.1.1 Description of Lausanne building before and after renovation

The external walls are made of limestone masonry, 60 cm thick on the ground floor and 50 cm thick on the top floor. The limestones are visible on the ground floor and covered with a mineral coat on higher floors. They are responsible for around 75 % of the thermal losses of the building as shown in Figure 73.

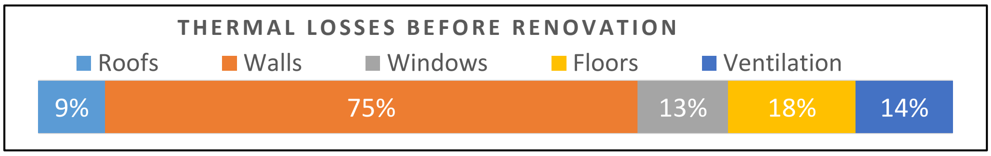


Figure 73 Repartition of thermal losses, before renovation

Windows were replaced during a previous renovation and now use a double-glazing system with a low emissivity layer. The ground floor is facing an unheated cellar and the 6th floor's ceiling is facing an unheated attic.

In order to not change the visual aspect of the external facade, an intervention from the inside was decided. Two different renovation scenarios are described in this section. The first one consists of using standard mineral wool insulation in addition to a vapour barrier in order to prevent condensation inside the construction. However, the characteristics of the walls and wooden floors make the installation of a vapour barrier a challenge. As a result, an alternative scenario which avoids using a vapour barrier was also analysed (cf. scenario 2).

Scenario 1

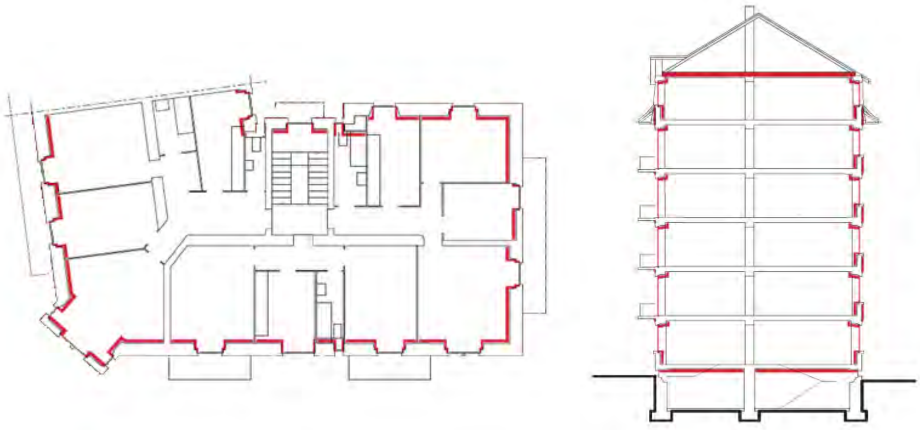
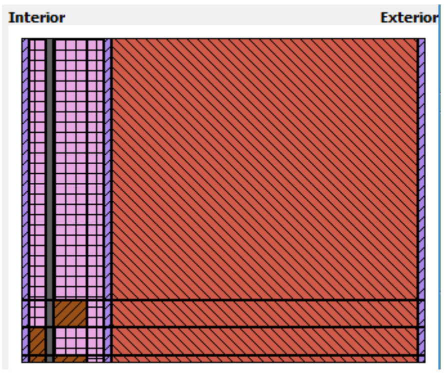


Figure 74 Renovation scenario 1, insulation added shown in red

Three layers of glass wool insulation panels are added on the inside, between wood lathing. A vapour barrier with variable vapour diffusion resistance is added before the last glass-wool panel (see Table 57) in order to avoid condensation issues inside the construction.

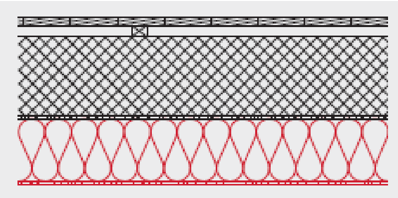
Table 57 Facade renovation, scenario 1. U-value before = 1.60 W/(m²K). U-value after = 0.40 W/(m²K)



Material	Thickness [cm]	Thermal conductivity [W/(mK)]
Gypsum plasterboard	1.25	0.21
Glass wool Wood	6 + 3	0.032 0.14
Vapour barrier	0.03	0.2
Glass wool Wood	6 + 3	0.032 0.14
Internal plaster	1	0.7
Limestone masonry	50-60	1.3
Lime plaster	0 (ground floor) 1.5 (upper floors)	0.87

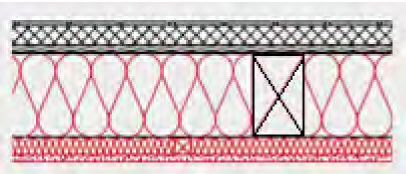
Additional renovation measures were required in order to comply with the thermal performance required by the Swiss standard SIA 380/1 [128]. The floor against the cellar was insulated from below with a Rockwool insulation. The ceiling between the last floor and attic was insulated between the beams with cellulose and below the beams with additional Rockwool placed on the internal face.

Table 58 Renovation of floor against basement. U-value before (black) = 0.98 W/(m²K). U-value after = 0.18 W/(m²K)



Material	Thickness [cm]	Thermal conductivity [W/(mK)]
Wooden floor	2.2	0.13
Air layer	3	0.025
Reinforced concrete	20	1.8
Plaster	0.5	0.7
Rockwool	16	0.034
Plaster	0.5	0.7

Table 59 Renovation of ceiling against attic. U-value before (black) = 1.35 W/(m²K). U-value after = 0.19 W/(m²K)



Material	Thickness [cm]	Thermal conductivity [W/(mK)]
Ceramic floor tiles	1.2	1.3
Cement cast flor	5	1.2
Wood	2	0.13
Cellulose / wood	21	0.038 / 0.13
Rockwool	4	0.034
Wood-cement fibreboard	1.5	0.4
Plaster	0.5	0.7

All windows were already replaced during a previous renovation. However, to comply with the SIA380/1 global renovation limit on building energy needs, it was necessary to upgrade the current windows to a triple glazing and improve the insulation of the frames. A glazing offering a high solar energy transmittance value has been chosen in order not to reduce the solar gains more than necessary.

Scenario 2

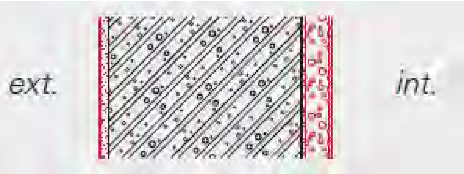
The implementation of scenario 1 requires great care while laying the vapour barrier in order to provide air-tightness. As it is difficult to verify the quality of the implementation, a second scenario using a Multipor mineral insulation panel with a good vapour diffusion property instead of a standard vapour barrier was considered.

An external lime mortar layer already covers the stones on the last four storeys[32]. In this new scenario, the mortar is removed and replaced by an insulating cover coat. This practice, which does not change the building architectural aspect, is quite common for Swiss historic building renovation.

[32] Several historic buildings in Switzerland built before 1945 (some of them being protected) have an external rendering as part of their external architecture. This situation allows the application of external rendering such as mineral or aerogel rendering with a high insulation value. By doing so, the internal surface of the facade has a higher temperature as without the external rendering.

Two possibilities exist on the local market: a mineral insulating layer or an aerogel one, which is more efficient as well as more expensive. Given the insulation placed on the inside, the mineral one was sufficient to provide adequate thermal resistance.

Table 60 Facade renovation, scenario 2. U-value before = 1.6 W/(m²K). U-value after = 0.25 W/(m²K)



Material	Thickness [cm]	Thermal conductivity [W/(mK)]
Light mortar	0.3	0.18
Multipor insulation	6	0.042
Light mortar	0.5	0.18
Limestone masonry	50-60	1.3
Hagatherm mineral insulating plaster	2	0.054

Additional renovation measures such as insulating the floor and ceiling against the unheated cellar and attic were required in order to comply with the performance required by the Swiss SIA 380/1 renovation standard. The same measures used for the first scenario were considered. However, it was not necessary to change the windows. The existing double glazing and frames were sufficient.

8.1.2 Calculation conditions

A monthly energy calculation according to the Swiss SIA 380/1 was performed using the Lesosai software [129]. The following assumptions were made:

- Internal temperature is considered constant at 20 °C,
- Monthly average external temperatures and radiation come from the SIA 2028 "Payerne" climate station. The sum of heating degree days 20/20 (20 °C inside temp. and, 20 °C reference temperature) over the whole year is 3854.

Month	Te_Mth [°C]	GH_Mth [MJ/...	GS_Mth [MJ/m²]	GE_Mth [MJ/m²]	GN_Mth [MJ/m²]	GW_Mth [MJ/...
January	0.3	107	166	70	46	75
February	1.6	174	230	109	63	119
March	5.5	340	340	201	96	214
April	8.3	435	298	251	122	244
May	13.4	562	297	308	163	303
June	16.4	614	283	342	187	321
July	18.7	640	313	359	182	346
August	18.6	552	351	321	147	308
September	14.1	376	329	213	101	231
October	9.9	222	257	123	70	145
November	4.2	114	161	67	41	73
December	1.7	86	137	54	35	56

Figure 75 Payerne SIA2028 Climate Data (external temperature and solar irradiation (horizontal, S/E/N/W)

- U values are calculated using an internal surface resistance of 0.13 m²K/W when thermal flow is horizontal, 0.1 m²K/W when the flow goes upwards, and 0.17 m²K/W when the flow goes downwards. The external surface resistance is 0.04 m²K/W. These values are compliant with EN ISO 6946 [112].

- For construction elements against non-heated zones, thermal losses are evaluated using reduction factors. Factors of respectively 0.9 and 0.7 were used to evaluate losses through the ceiling and floor,
- Internal gains from users, devices and lightning are defined by the SIA 380/1 standard [128] and depend on the building type. For multi-family dwelling, there are 40 m² of floor area by occupant and each occupant provides 70W for 12 hours a day. Overall, a value of 27.1 kWh/m² is used for internal gains,
- SIA380/1 defines a fixed air flow value of 0.7 m³/(h.m²), which is equivalent to approx. 0.3 air-changes per hour given the gross floor area and volume of the building.

When renovating the building from the inside, thermal bridges can have a substantial influence on the building heat losses. It is therefore important to take them into account as accurately as possible. For each renovation scenario, all relevant thermal bridges were analysed using Flixo Energy [130] to reach "psi" values to use in the thermal calculation. This software also helped us take the necessary measures to avoid surface condensation on the inside.

8.1.3 Energy saving potential – results

The following table presents the building energy demand for space heating calculated with Lesosai software for the building in its current condition and for the two renovation scenarios.

Table 61 Calculated space heating demand before and after renovation

Scenario	Heating energy demand [kWh/(m²year)]	Energy saving potential	Compliant with CH standards
Current state	141.3	-	No
Scenario 1 – facade only	73.4	48 %	No
Scenario 1 – Full	36.8	74 %	Yes
Scenario 2 – facade only	79.8	43 %	No
Scenario 2 - Full	35.7	75 %	Yes

8.2 Reflections on Swiss case

The internal insulation of the facade reduces thermal losses significantly. Between 43 % and 48 % of energy can be saved. However, those renovation measures are not sufficient for the building to comply with the Swiss SIA380/1 renovation standard. Only a global renovation scenario that also includes insulating the roof and the slab as well as changing the windows will be able to reach the requirements. In both scenarios, condensation inside the external walls was evaluated using the Glaser method and it shows that there is no moisture left inside the construction after the summer. Therefore, they comply with the requirement of the SIA 180 standard [131].

9 Conclusions

This document reports the main results of the work carried out in RIBuild WP5, Tasks 5.1 "*Evaluation of the energy saving potential of internal insulation solutions depending on building practice*" and Task 5.2 "*Probabilistic Life Cycle Impact Assessment of the environmental impact of internal insulation solutions*", presented in the two parts of the report.

Part 1 described the probabilistic LCA methodology and the software tool developed within Task 5.2 in the field of internal insulation solution of historic buildings, also providing exemplary cases of the methodology application and potential.

Part 2 reported the results of the analyses on the potential energy savings in historic buildings when considering internal facade insulation only or coupled with other renovation measures, carried out on selected case buildings in Denmark, Latvia, Italy, and Switzerland, within Task 5.1 activities.

The document accompanies the *WP5 software tool* developed for the probabilistic LCA of renovation strategies, especially internal insulation solutions, in historic buildings.

As shown in detail in the report, the work performed is an important contribution in the field of building LCA and energy saving potential of internal insulation, for several reasons summarized below.

(1) As seen in *Section 1*, probabilistic approaches in LCA, especially in building LCA are still rarely used, both in research and in practice. Nevertheless, assessments including uncertainty and sensitivity analysis allow improving the credibility of results.

→ *Task 5.2 developed a probabilistic approach to LCA that considerably improves the reliability of decision making in building renovation and allows overcoming the current limits of traditional LCA deterministic approaches.*

(2) As documented in *Section 2 and Section 3*, the LCA probabilistic methodology can be applied to assess the environmental performance of several design options (internal insulation solutions) in several possible scenarios (original wall applications, climatic contexts, energy sources, reference study periods). Furthermore, the methodology is based on a flexible approach, tailored to the user needs, in relation to (a) its connection to different possible methods to assess the heat transmission losses through the building wall before and after the renovation measure; (b) the user level of knowledge and information on inputs data related to the design options and possible assessment scenarios.

→ The LCA probabilistic methodology can be then effectively applied in further developments of the RIBuild project in WP6, i.e. *to assess the environmental impact of several insulation solutions, in several existing walls configurations and in different climates, in order to realize the RIBuild web tool on internal insulation.*

(3) The methodology has been implemented into the *WP5 software tool* described in *Section 4,* that will be further updated, including the Life Cycle Costing part, as defined for WP5 task 5.3 (D5.2[33]).

[33] The LCC section of the software is almost ready at this stage, but will be further developed within WP5 task 5.3 activities, as part of D5.2, by June 2018.

→ *WP5 software can be effectively used for the realization of the RIBuild web tool on internal insulation solutions within WP6, to calculate the distributions of environmental impacts of insulation systems applied to wall case studies under possible scenarios. The tool already includes a database of data inputs on the exemplary national case studies performed within RIBuild Task 5.2 that can be edited or enriched at user's choice, e.g. during RIBuild WP6 activities. Furthermore, the tool has a high exploitation potential outside the project, as it has been conceived to be applied also to other possible renovation measures than internal insulation.*

(4) *Part 2* reports exemplary calculations of the energy performance improvements due to the installation of internal facade insulation for selected historic case buildings in 4 participating countries, i.e. Denmark (*section 5*), Latvia (*section 6*), Italy (*section 7*) and Switzerland (*section 8*).

→ *The results obtained focus on the energy savings that relates to the facade insulation – in some cases alternative solutions – and energy savings from facade insulation in combination with other energy saving measures, thus providing interesting suggestions for RIBuild web tool developments in WP6. Furthermore, the results of the assessments performed, can be used as target points to perform further LCA "at building scale", providing useful reference values to building designers, owners, stakeholders.*

These achievements constitute an effective starting point for future developments, not only within RIBuild project WP6, but in further projects in the field of building LCA and energy saving potential of renovation measures.

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Appendix 1: Examples of building components Service Life data

Table 62 Building components SL values coming from a service lives database of building components developed by HES-SO (Switzerland). The database is structured according to the cost calculation method for Switzerland [132]. Sources relevant for internal insulation systems come from various data types and countries (Switzerland, Germany, France, UK, and Belgium). The values in black are found directly in the reference database. The values in blue are mean values of different types of materials for the same type of component (as an example, different insulation materials) statistically averaged in the HES-SO database. The databases used are: SIA 2032 Korrigenda C1 zu SIA 2032:2010 [22]; SIA 480:2016 [133]; ASLOCA 2007 (association of tenants in Western Switzerland [134]; Haefliger I.F., 2014 [135], Wagner F., 2014 [136]; Mayer P., 2005 [137]; BBSR, 2011 [138]; IBGE, 2010 [139].

Building element lifetime database (value expressed in years)			**Service life used for LCA in Switzerland**	**Service life used for LCC in Switzerland**			**Amortisation time used in CH to prevent conflicts between landlords and tenants**	**Service life of building components referring to many international sources**	**Service life of building components in CH used by the Department of Defense and Swiss Army**	**Expected service life used in the UK to evaluation the sensitivity of maintenance phase in LCC and LCA**	**Service life used for LCA in Germany**	**Service life of building materials in Belgium**
Facade and wall cladding		***Source:***	*[22]*	*[133]*			*[134]*	*[135]*	*[136]*	*[137]*	*[138]*	*[139]*
Type of system	**Layers of materials**	**Type of material**		Minimum	Medium	Maximum		Mean value				
Internal insulation maintained with wood lathing. Vapour barrier on internal position	Decorative finish		30				19.1	35	19	7	25.5	
		Painting					8 - 15		10 - 15		10 - 18	
		Wallpaper					10 - 20		15		10 - 15	
		Rendering					20 - 30	35	40		50	
		Panelling					20 - 30		15		50	
	Internal cladding		30	20	40	80	30	44.5	35	60	50	50
		Gypsum plasterboard						47				
		Wood fibreboard						42	35			
	Technical space											
	Vapour barrier			20	40	80		42		60	50	
	Insulation		30	20	40	80	27.5	37.7	35	60	50	50
		Wood fiber										
		Cellulose						42				
		Rockwool						42				

Building element lifetime database (value expressed in years)			**Service life used for LCA in Switzerland**	**Service life used for LCC in Switzerland**			**Amortisation time used in CH to prevent conflicts between landlords and tenants**	**Service life of building components referring to many international sources**	**Service life of building components in CH used by the Department of Defense and Swiss Army**	**Expected service life used in the UK to evaluation the sensitivity of maintenance phase in LCC and LCA**	**Service life used for LCA in Germany**	**Service life of building materials in Belgium**
Facade and wall cladding		***Source:***	*[22]*	*[133]*			*[134]*	*[135]*	*[136]*	*[137]*	*[138]*	*[139]*
Type of system	**Layers of materials**	**Type of material**		Minimum	Medium	Maximum		Mean value				
		Glasswool					30					
		PIR										
		EPS					25	29				
	possibly air profness									60	50	
	possibly adhesive	Fixing mortar as clay or rendering							40		50	
	wall											
	possibly insulating plaster								25			
Internal insulation maintained with wood lathing. Vapour barrier on medium position	Decorative finish		30				19.1	35	19	7	25.5	
		Painting					8 - 15		10 - 15		10 - 18	
		Wallpaper					10 - 20		15		10 - 15	
		Rendering					20 - 30	35	40		50	
		Panelling					20 - 30		15		50	
	Internal cladding		30	20	40	80	30	44.5	35	60	50	50
		Gypsum plasterboard						47				
		Wood fibreboard						42	35			
	Technical space											
	Insulation		30	20	40	80	30	42	35	60	50	50
		Rockwool						42				
		Glasswool					30					
	Vapour barrier			20	40	80		42		60	50	

Building element lifetime database (value expressed in years)			Service life used for LCA in Switzerland	Service life used for LCC in Switzerland			Amortisation time used in CH to prevent conflicts between landlords and tenants	Service life of building components referring to many international sources	Service life of building components in CH used by the Department of Defense and Swiss Army	Expected service life used in the UK to evaluation the sensitivity of maintenance phase in LCC and LCA	Service life used for LCA in Germany	Service life of building materials in Belgium
Facade and wall cladding		***Source:***	*[22]*	*[133]*			*[134]*	*[135]*	*[136]*	*[137]*	*[138]*	*[139]*
Type of system	**Layers of materials**	**Type of material**		Minimum	Medium	Maximum		Mean value				
	Insulation		30	20	40	80	30	42	35		50	50
		Rockwool						42		60		
		Glasswool					30			60		
	wall											
	possibly insulating plaster								25			
Internal insulation fixed with mortar	Decorative finish		30				19.1	30	21.25	7	20.6	
		Painting					8 - 15		10 - 15		10 - 18	
		Wallpaper					10 - 20		15		10 - 15	
		Tiles					30 - 40	30	45		50	
	Surface rendering	Plaster	30	20	40	80	20 - 30	35	40	60	50	50
	Insulation		30	20	40	80		42	35	60	50	50
		Wood fiber										
		CaSi										
		XPS						42				
	Adhesive	Fixing mortar as clay or rendering		20	40	80			40		50	100
	wall											
	possibly insulating plaster								25			
Internal insulation with VP included fixed with mortar	Decorative finish		30				19.1	30	21.25	7	20.6	
		Painting					8 - 15		10 - 15		10 - 18	
		Wallpaper					10 - 20		15		10 - 15	
		Tiles					30 - 40	30	45		50	
	Internal	Massive	30				20 - 30	30	40	60	50	50

Building element lifetime database (value expressed in years)			Service life used for LCA in Switzerland	Service life used for LCC in Switzerland			Amortisation time used in CH to prevent conflicts between landlords and tenants	Service life of building components referring to many international sources	Service life of building components in CH used by the Department of Defense and Swiss Army	Expected service life used in the UK to evaluation the sensitivity of maintenance phase in LCC and LCA	Service life used for LCA in Germany	Service life of building materials in Belgium
Facade and wall cladding		***Source:***	*[22]*	*[133]*			*[134]*	*[135]*	*[136]*	*[137]*	*[138]*	*[139]*
Type of system	**Layers of materials**	**Type of material**		Minimum	Medium	Maximum		Mean value				
	cladding	plaster tiles										
	Insulation integrating VB	Glasswool	30	20	40	80	30		35	60	50	50
	wall											
	possibly insulating plaster								25			

Table 63 RSL data of insulation materials from other literature sources

Insulation materials	**Reference Service Life (years)**	**Location**	**Reference**
Wood wool (internal walls); Cork slab (external walls)	70	Italy	[92]
Glass wool	[min, max] [20, 60]	France	[66]
Rock wool	[min, max] [20, 60]	France	[66]
14 cm expanded polystyrene slabs in concrete roof (U-value: 0.3 W/m^2 K)	25	Swiss	[24]
12 cm 2 layers glass wool in wooden roof (U-value: 0.25 W/m^2 K)	40	Swiss	[24]
12 cm external glass wool insulation in sandstone wall (U-value: 0.28 W/m^2 K)	30	Swiss	[24]
8 cm intermediate glass wool insulation in masonry wall (U-value: 0.25 W/m^2 K)	80	Swiss	[24]
10 cm expanded polystyrene in plastered masonry wall (U-value: 0.27 W/m^2 K)	25	Swiss	[24]
Mineral wool as insulation material	60	Denmark	[140]
Foam plastic as insulation material	60	Denmark	[140]
Insulation in other structures	60	Denmark	[140]

Appendix 2: HDD data from Eurostat database and data-fitting results

Table 64 Heating Degree Days based on the Eurostat methodology calculated by the Joint Research Centre (Institute for Environment and Sustainability - IES/MARS Eurostat, Joint Research Center (IES/MARS Unit). Source: http://ec.europa.eu/eurostat/web/energy/data

GEO/TIME	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
EU27 - European Union (27 countries)	2 926.2	3 164.4	3 013.2	3 172.2	3 163.2	3 162.3	3 038.3	2 943.2	3 007.7	3 076.3	3 472.8	3 119.0	3 420.0	3 217.6	2 809.0	2 904.0	3 025.0
EU25 - European Union (25 countries)	2 949.5	3 195.2	3 036.6	3 175.2	3 191.3	3 177.2	3 047.9	2 971.5	3 038.0	3 113.7							
EU15 - European Union (15 countries)	2 911.4	3 116.3	2 966.7	3 077.5	3 115.0	3 085.4	2 957.2	2 913.0	3 009.6	3 046.9							
EA - Euro area (EA11-2000, EA12-2006, EA13-2007, EA15-2008, EA16-2010, EA17-2013, EA18-2014, EA19)	2 540.9	2 707.2	2 582.6	2 712.6	2 758.9	2 748.3	2 612.0	2 538.8	2 639.8	2 651.0							
BE - Belgium	2 521.5	2 729.8	2 535.4	2 696.1	2 797.8	2 668.9	2 590.6	2 436.7	2 706.9	2 696.0	3 174.0	2 399.1	2 772.3	3 023.6	2 315.0	2 633.0	2 689.0
BE10 - Région de Bruxelles-Capitale / Brussels Hoofdstedelijk Gewest	2 381.9	2 571.5	2 368.5	2 521.8	2 548.2	2 457.8	2 430.5	2 236.7	2 513.8	2 487.2							
BE21 - Prov. Antwerpen	2 326.1	2 519.0	2 369.5	2 528.0	2 668.2	2 501.7	2 463.2	2 289.6	2 569.1	2 559.6							
BE22 - Prov. Limburg (BE)	2 392.5	2 599.7	2 431.8	2 607.6	2 679.0	2 561.1	2 495.8	2 345.9	2 613.9	2 584.1							
BE23 - Prov. Oost-Vlaanderen	2 276.4	2 438.9	2 295.3	2 446.8	2 568.2	2 446.0	2 396.9	2 250.5	2 516.4	2 504.9							
BE24 - Prov. Vlaams-Brabant	2 383.5	2 574.3	2 385.4	2 543.3	2 561.3	2 475.2	2 434.7	2 269.0	2 540.0	2 485.5							
BE25 - Prov. West-Vlaanderen	2 328.4	2 491.7	2 319.8	2 503.4	2 494.5	2 374.0	2 411.7	2 273.0	2 512.6	2 547.9							
BE31 - Prov. Brabant Wallon	2 420.6	2 609.9	2 421.3	2 587.6	2 598.9	2 513.6	2 450.3	2 279.5	2 563.5	2 519.0							
BE32 - Prov. Hainaut	2 506.4	2 690.9	2 487.8	2 673.9	2 722.2	2 623.1	2 502.1	2 329.2	2 622.5	2 616.8							
BE33 - Prov. Liège	2 700.9	2 947.3	2 716.1	2 870.8	3 040.2	2 883.4	2 781.2	2 633.6	2 894.8	2 898.8							
BE34 - Prov. Luxembourg (BE)	2 834.7	3 084.8	2 868.5	2 990.4	3 212.1	3 078.1	2 931.0	2 774.9	3 039.2	3 010.6							
BE35 - Prov. Namur	2 689.9	2 938.0	2 699.5	2 866.7	2 955.0	2 800.4	2 683.0	2 552.4	2 834.4	2 831.2							
DK - Denmark	3 106.1	3 470.0	3 166.8	3 315.4	3 305.2	3 262.1	3 074.0	2 988.2	3 016.9	3 235.4	3 971.3	3 150.4	3 422.9	3 402.2	2 855.0	3 114.0	3 136.0

DK001 - København og Frederiksberg Kommuner (NUTS 1999)	3 286.3	3 711.1	3 467.1	3 613.1	3 476.5	3 326.7	3 151.9	2 984.9	2 984.2	3 192.9							
DK002 - Københavns amt (NUTS 1999)	3 276.6	3 696.6	3 444.7	3 598.2	3 466.4	3 319.2	3 144.8	2 980.4	2 979.7	3 193.3							
DK003 - Frederiksborg amt (NUTS 1999)	3 205.8	3 591.0	3 333.3	3 430.9	3 366.9	3 288.4	3 135.2	2 978.4	3 001.7	3 245.1							
DK004 - Roskilde amt (NUTS 1999)	3 098.7	3 419.2	3 163.9	3 318.1	3 300.5	3 300.7	3 128.9	2 967.8	3 023.1	3 253.7							
DK005 - Vestsjællands amt (NUTS 1999)	3 042.5	3 370.6	3 092.7	3 249.6	3 247.4	3 271.9	3 114.0	2 976.2	2 993.0	3 226.7							
DK006 - Storstrøms amt (NUTS 1999)	2 999.4	3 293.1	3 077.3	3 239.5	3 227.1	3 190.4	3 036.1	2 901.3	2 882.7	3 119.2							
DK007 - Bornholms amt (NUTS 1999)	3 034.1	3 398.9	3 203.0	3 412.3	3 457.7	3 308.4	3 191.3	3 084.1	3 062.3	3 389.5							
DK008 - Fyns amt (NUTS 1999)	2 964.8	3 352.0	3 067.6	3 221.0	3 217.6	3 177.3	2 969.1	2 817.8	2 854.8	3 115.8							
DK009 - Sønderjyllands amt (NUTS 1999)	3 020.5	3 394.8	3 114.0	3 237.5	3 270.2	3 244.2	2 981.7	2 875.8	2 968.1	3 151.9							
DK00A - Ribe amt (NUTS 1999)	3 027.7	3 429.1	3 127.1	3 273.2	3 247.7	3 228.7	2 987.7	2 903.1	2 979.7	3 218.6							
DK00B - Vejle amt (NUTS 1999)	3 148.8	3 586.1	3 254.4	3 408.8	3 419.6	3 430.2	3 132.0	3 057.4	3 126.7	3 333.2							
DK00C - Ringkøbing amt (NUTS 1999)	3 012.2	3 378.4	3 103.9	3 257.2	3 231.8	3 178.6	3 002.8	2 943.8	2 976.9	3 228.3							
DK00D - Århus amt (NUTS 1999)	3 209.2	3 640.3	3 337.9	3 505.9	3 544.6	3 449.2	3 237.5	3 200.8	3 197.0	3 330.7							
DK00E - Viborg amt (NUTS 1999)	3 126.6	3 483.8	3 162.9	3 302.9	3 281.8	3 199.0	3 072.1	3 009.0	3 014.0	3 218.9							
DK00F - Nordjyllands amt (NUTS 1999)	3 301.9	3 595.9	3 177.5	3 318.1	3 275.0	3 239.9	3 106.5	3 079.4	3 092.7	3 315.9							
DE - Germany (until 1990 former territory of the FRG)	2 781.5	3 119.0	2 960.9	3 124.4	3 186.0	3 136.9	3 012.4	2 798.4	2 971.1	3 063.2	3 610.8	2 868.1	3 126.3	3 288.1	2 661.0	2 908.0	3 005.0
DE11 - Stuttgart	2 734.2	2 984.6	2 807.6	2 979.2	3 161.5	3 135.5	2 980.2	2 798.6	2 957.6	3 021.4							
DE12 - Karlsruhe	2 567.7	2 841.5	2 680.0	2 858.9	2 962.0	2 940.1	2 802.5	2 626.8	2 830.5	2 881.0							

DE13 - Freiburg	2 740.3	3 035.6	2 837.0	3 029.9	3 091.7	3 101.3	2 996.5	2 858.7	3 043.6	3 005.0
DE14 - Tübingen	3 046.3	3 322.5	3 091.2	3 313.2	3 424.0	3 406.8	3 310.2	3 062.4	3 265.1	3 276.8
DE21 - Oberbayern	2 928.5	3 247.8	3 011.4	3 279.2	3 400.5	3 490.1	3 303.3	2 997.5	3 137.3	3 186.7
DE22 - Niederbayern	3 017.9	3 342.6	3 106.3	3 366.0	3 489.5	3 568.5	3 405.6	3 041.1	3 172.5	3 239.8
DE23 - Oberpfalz	3 126.2	3 473.5	3 272.8	3 450.0	3 477.7	3 512.8	3 332.8	3 076.3	3 224.5	3 301.5
DE24 - Oberfranken	3 097.3	3 470.6	3 277.7	3 432.6	3 550.9	3 504.3	3 350.8	3 112.5	3 290.2	3 389.6
DE25 - Mittelfranken	2 952.0	3 258.1	3 084.7	3 258.8	3 303.6	3 356.7	3 157.9	2 931.7	3 089.5	3 188.9
DE26 - Unterfranken	2 767.7	3 052.0	2 908.6	3 055.9	3 161.7	3 169.2	3 028.8	2 803.0	2 989.8	3 050.5
DE27 - Schwaben	3 049.3	3 356.5	3 114.9	3 354.2	3 539.6	3 563.4	3 383.3	3 132.9	3 310.9	3 353.4
DE30 - Berlin	2 641.4	3 098.8	2 967.1	3 079.3	3 052.5	3 043.4	2 941.8	2 702.4	2 803.9	2 997.5
DE41 - Brandenburg - Nordost (NUTS 2006)	2 706.3	3 151.1	3 012.3	3 138.9	3 140.5	3 129.3	3 017.8	2 772.2	2 888.1	3 090.1
DE42 - Brandenburg - Südwest (NUTS 2006)	2 607.7	3 047.6	2 938.6	3 068.7	3 090.3	3 101.6	2 961.3	2 718.5	2 846.7	3 034.3
DE50 - Bremen	2 696.5	3 053.0	2 913.7	3 116.1	3 005.1	2 905.1	2 824.9	2 639.8	2 839.9	2 905.5
DE60 - Hamburg	2 766.5	3 162.4	3 020.2	3 141.4	3 157.0	3 113.7	2 934.1	2 723.2	2 873.9	3 013.4
DE71 - Darmstadt	2 574.2	2 842.8	2 682.5	2 818.5	2 922.7	2 851.0	2 802.8	2 615.5	2 828.6	2 864.0
DE72 - Gießen	2 825.2	3 072.1	2 946.5	3 072.5	3 245.0	3 109.1	3 092.7	2 917.3	3 097.9	3 148.8
DE73 - Kassel	2 909.1	3 234.4	3 081.9	3 212.7	3 391.3	3 256.0	3 151.4	2 964.9	3 119.3	3 210.1
DE80 - Mecklenburg-Vorpommern	2 822.9	3 212.3	3 053.2	3 182.9	3 142.4	3 075.3	3 000.6	2 768.4	2 914.3	3 138.0
DE91 - Braunschweig	2 700.0	3 092.7	2 988.9	3 110.4	3 149.3	3 092.0	2 956.0	2 746.1	2 894.0	3 041.0
DE92 - Hannover	2 621.9	2 986.6	2 894.4	3 061.0	2 995.7	2 962.5	2 831.3	2 645.2	2 843.7	2 911.4
DE93 - Lüneburg	2 706.3	3 094.6	2 948.3	3 126.0	3 077.6	3 014.9	2 874.7	2 686.6	2 873.4	2 974.8
DE94 - Weser-Ems	2 657.1	2 967.5	2 830.7	3 017.3	2 911.6	2 789.8	2 716.2	2 546.9	2 786.0	2 822.9
DEA1 - Düsseldorf	2 380.2	2 629.4	2 493.9	2 655.3	2 793.9	2 623.6	2 568.3	2 370.4	2 647.3	2 650.5
DEA2 - Köln	2 595.1	2 854.5	2 683.1	2 838.8	3 033.8	2 835.9	2 750.1	2 571.8	2 817.9	2 834.0
DEA3 - Münster	2 516.1	2 774.7	2 665.4	2 834.1	2 907.0	2 745.6	2 636.7	2 464.8	2 738.8	2 764.7
DEA4 - Detmold	2 625.5	2 971.1	2 852.2	3 004.5	3 048.0	2 963.0	2 838.0	2 652.2	2 867.5	2 960.9
DEA5 - Arnsberg	2 759.3	3 063.2	2 932.8	3 059.0	3 226.1	3 050.4	2 933.1	2 765.7	2 978.0	3 002.3
DEB1 - Koblenz	2 856.9	2 979.1	2 879.6	3 033.9	3 183.0	2 998.8	2 920.7	2 738.4	2 953.5	2 953.3
DEB2 - Trier	2 802.3	3 044.9	2 878.0	2 997.4	3 234.5	3 067.9	2 951.8	2 768.0	3 011.8	2 977.9

DEB3 - Rheinhessen-Pfalz	2 529.1	2 788.7	2 643.8	2 797.6	2 875.2	2 822.9	2 718.4	2 540.5	2 764.0	2 783.5							
DEC0 - Saarland	2 653.0	2 930.2	2 764.0	2 888.7	3 060.0	2 932.9	2 798.1	2 657.2	2 898.2	2 849.1							
DED1 - Chemnitz (NUTS 2006)	3 048.5	3 492.8	3 252.4	3 398.7	3 550.3	3 507.7	3 321.0	3 126.8	3 253.5	3 354.9							
DED2 - Dresden	2 806.7	3 270.7	3 088.3	3 234.6	3 231.0	3 243.2	3 100.8	2 873.4	2 986.1	3 139.3							
DED3 - Leipzig (NUTS 2006)	2 645.1	3 057.4	2 957.5	3 100.4	3 074.7	3 055.2	2 952.1	2 732.4	2 839.6	2 975.0							
DEE1 - Dessau (NUTS 1999)	2 614.0	3 024.8	2 935.8	3 057.7	3 076.8	3 049.1	2 899.8	2 657.0	2 801.5	3 001.9							
DEE2 - Halle (NUTS 2003)	2 674.8	3 028.3	2 967.1	3 108.1	3 073.8	3 033.5	2 929.0	2 716.6	2 880.5	3 011.9							
DEE3 - Magdeburg (NUTS 2003)	2 649.4	3 044.6	2 951.8	3 085.0	3 095.7	3 054.8	2 921.5	2 686.8	2 843.9	3 000.4							
DEF0 - Schleswig-Holstein	2 837.5	3 189.5	2 978.9	3 137.5	3 171.3	3 067.3	2 938.0	2 760.5	2 912.4	3 072.9							
DEG0 - Thüringen	2 925.4	3 284.3	3 161.5	3 305.9	3 383.6	3 297.9	3 168.4	2 976.6	3 120.9	3 231.3							
IT - Italy	1 694.9	1 767.1	1 710.7	1 913.5	1 882.8	2 050.7	1 824.3	1 715.0	1 775.9	1 829.0	1 992.3	1 861.0	1 968.1	1 933.4	1 632.0	1 810.0	1 762.0
ITC1 - Piemonte	2 112.3	2 203.4	2 161.2	2 336.2	2 282.7	2 378.0	2 228.4	2 114.2	2 266.7	2 266.3							
ITC2 - Valle d'Aosta/Vallée d'Aoste	2 823.0	2 874.7	2 853.7	2 891.5	3 123.8	3 277.8	3 206.6	3 024.7	3 286.6	3 164.4							
ITC3 - Liguria	1 702.0	1 738.8	1 653.9	1 831.9	1 786.5	1 858.8	1 715.2	1 727.4	1 813.9	1 823.2							
ITC4 - Lombardia	2 226.6	2 352.9	2 244.0	2 378.8	2 364.3	2 510.6	2 246.9	2 051.6	2 181.2	2 288.3							
ITD1 - Provincia Autonoma Bolzano/Bozen (NUTS 2006)	3 965.6	4 095.8	4 006.6	4 102.5	4 202.2	4 274.0	3 993.6	3 838.1	3 880.1	3 867.6							
ITD2 - Provincia Autonoma Trento (NUTS 2006)	3 349.6	3 496.1	3 296.2	3 437.8	3 635.6	3 701.7	3 489.4	3 208.7	3 376.4	3 403.8							
ITD3 - Veneto (NUTS 2006)	2 160.8	2 254.7	2 142.9	2 350.4	2 322.8	2 560.8	2 228.1	2 043.1	2 203.9	2 232.4							
ITD4 - Friuli-Venezia Giulia (NUTS 2006)	2 119.7	2 265.7	2 128.8	2 407.8	2 418.4	2 675.8	2 360.4	2 109.3	2 255.5	2 243.5							
ITD5 - Emilia-Romagna (NUTS 2006)	1 889.5	1 993.3	1 919.4	2 148.6	2 088.4	2 288.8	1 999.8	1 867.3	1 924.1	2 007.6							
ITE1 - Toscana (NUTS 2006)	1 574.8	1 678.1	1 619.8	1 853.1	1 748.8	2 016.1	1 743.2	1 623.5	1 711.6	1 762.9							
ITE2 - Umbria (NUTS 2006)	1 701.8	1 811.9	1 726.3	2 076.0	1 919.1	2 143.0	2 030.1	1 916.4	1 973.8	1 980.8							
ITE3 - Marche (NUTS 2006)	1 671.2	1 765.4	1 785.1	2 066.8	1 985.2	2 212.8	1 898.9	1 626.2	1 734.1	1 819.9							
ITE4 - Lazio (NUTS 2006)	1 402.5	1 462.0	1 372.2	1 664.8	1 641.8	1 790.5	1 654.6	1 531.6	1 565.6	1 625.0							
ITF1 - Abruzzo	1 625.9	1 624.8	1 690.3	1 994.4	1 962.0	2 140.5	1 913.8	1 747.2	1 710.9	1 849.5							
ITF2 - Molise	1 583.6	1 575.2	1 618.6	1 851.5	1 814.8	1 958.0	1 746.9	1 630.7	1 639.5	1 744.3							

ITF3 - Campania	1 278.2	1 326.8	1 244.4	1 507.6	1 510.4	1 645.7	1 467.3	1 408.8	1 397.2	1 433.2							
ITF4 - Puglia	1 254.5	1 283.6	1 279.2	1 516.7	1 445.1	1 590.6	1 456.0	1 373.8	1 312.2	1 414.8							
ITF5 - Basilicata	1 440.4	1 481.0	1 424.4	1 629.0	1 620.1	1 736.9	1 563.6	1 527.5	1 470.8	1 561.4							
ITF6 - Calabria	1 081.3	1 098.3	1 067.3	1 193.1	1 156.5	1 312.5	1 163.3	1 111.0	1 122.8	1 171.4							
ITG1 - Sicilia	975.0	964.6	950.9	1 106.3	1 060.3	1 247.3	1 020.2	1 041.4	1 023.9	1 092.8							
ITG2 - Sardegna	1 022.3	1 114.6	1 070.5	1 200.7	1 215.6	1 367.3	1 039.3	1 042.1	1 117.1	1 138.7							
LV - Latvia	3 742.1	4 155.0	4 039.8	4 243.6	4 195.9	4 183.9	4 009.9	3 888.6	3 724.9	4 160.7	4 622.3	3 939.9	4 320.1	4 037.4	3 948.0	3 658.0	4 003.0
LV00 - Latvija	3 742.1	4 155.0	4 039.8	4 243.6	4 195.9	4 183.9	4 009.9	3 888.6	3 724.9	4 160.7							
SE - Sweden	4 940.0	5 402.3	5 156.4	5 230.1	5 240.4	5 097.1	4 982.2	5 068.3	5 075.7	5 291.2	5 873.9	4 926.8	5 503.8	5 185.5	4 887.0	4 910.0	5 125.0
SE11 - Stockholm	3 602.1	4 012.2	3 946.2	4 029.0	3 966.5	3 900.9	3 820.7	3 807.9	3 718.9	4 016.6							
SE12 - Östra Mellansverige	3 749.2	4 218.9	4 070.2	4 148.9	4 069.7	3 989.0	3 900.9	3 879.6	3 791.8	4 120.6							
SE21 - Småland med öarna	3 585.8	4 073.0	3 842.4	3 953.5	3 972.3	3 846.0	3 685.4	3 621.0	3 619.2	3 922.1							
SE22 - Sydsverige	3 271.7	3 658.2	3 396.6	3 492.9	3 548.4	3 439.6	3 304.4	3 153.2	3 192.6	3 481.3							
SE23 - Västsverige	3 560.4	4 028.5	3 798.9	3 891.2	3 903.9	3 775.8	3 650.9	3 596.2	3 571.7	3 845.9							
SE31 - Norra Mellansverige	4 505.7	5 050.4	4 810.3	4 813.4	4 800.7	4 682.0	4 587.4	4 707.0	4 650.8	4 957.1							
SE32 - Mellersta Norrland	5 217.3	5 635.7	5 273.8	5 453.2	5 415.5	5 345.3	5 189.7	5 406.0	5 426.8	5 669.1							
SE33 - Övre Norrland	6 039.7	6 488.1	6 257.5	6 296.4	6 357.9	6 141.7	6 042.7	6 164.0	6 224.9	6 321.8							
EEA18 - European Economic Area (EU-15 plus IS, LI, NO)	5 025.3	5 547.7	5 276.7	5 238.2	5 093.5	5 075.7	4 955.4	5 087.3	5 159.7	5 212.5							
CH - Switzerland	3 232.1	3 458.7	3 213.0	3 357.6	3 470.1	3 584.9	3 364.3	3 166.5	3 398.4	3 320.1							
CH01 - Région lémanique	3 279.3	3 497.1	3 256.9	3 333.0	3 570.5	3 729.7	3 486.6	3 313.0	3 513.8	3 435.5							
CH02 - Espace Mittelland	3 077.8	3 306.2	3 104.3	3 262.7	3 361.7	3 485.4	3 317.5	3 097.8	3 321.2	3 212.2							
CH03 - Nordwestschweiz	2 872.7	3 098.4	2 894.3	3 171.7	3 141.3	3 147.0	3 017.0	2 824.5	3 054.2	2 965.9							
CH04 - Zürich	2 890.8	3 123.9	2 888.4	3 192.6	3 055.6	3 196.3	2 973.1	2 787.1	3 040.3	2 948.1							
CH05 - Ostschweiz	3 337.9	3 573.1	3 295.8	3 439.0	3 557.4	3 640.3	3 390.1	3 173.4	3 419.7	3 357.2							
CH06 - Zentralschweiz	3 313.2	3 543.3	3 285.1	3 430.7	3 597.7	3 709.1	3 460.6	3 325.2	3 524.6	3 477.6							
CH07 - Ticino	3 539.3	3 741.4	3 437.7	3 553.0	3 480.3	3 628.4	3 388.9	3 166.1	3 503.0	3 435.9							

Table 65 Parameters of the normal distribution (mean and standard deviation) obtained on the Eurostat HDD data (data-fitting and Shapiro test)

Climate	HDD - Mean	HDD - SD	test_shapiro	Climate	HDD - Mean	HDD - SD	test_shapiro
EU27 - European Union (27 countries)	3096.153	167.413	pvalue= 0.40	DEA2 - Köln	2781.496	129.891	pvalue= 0.39
EU25 - European Union (25 countries)	3089.603	88.251	pvalue= 0.16	DEA3 - Münster	2704.769	129.737	pvalue= 0.69
EU15 - European Union (15 countries)	3019.888	75.327	pvalue= 0.25	DEA4 - Detmold	2878.313	135.923	pvalue= 0.14
EA - Euro area (EA11-2000, EA12-2006, EA13-2007, EA15-2008, EA16-2010, EA17-2013, EA18-2014, EA19)	2649.208	76.855	pvalue= 0.45	DEA5 - Arnsberg	2976.983	133.477	pvalue= 0.49
BE - Belgium	2669.746	204.963	pvalue= 0.36	DEB1 - Koblenz	2949.721	111.275	pvalue= 0.86
BE10 - Région de Bruxelles-Capitale / Brussels Hoofdstedelijk Gewest	2451.785	96.032	pvalue= 0.43	DEB2 - Trier	2973.461	128.584	pvalue= 0.81
BE21 - Prov. Antwerpen	2479.399	112.429	pvalue= 0.67	DEB3 - Rheinhessen-Pfalz	2726.371	112.000	pvalue= 0.16
BE22 - Prov. Limburg (BE)	2531.140	103.736	pvalue= 0.39	DEC0 - Saarland	2843.136	121.180	pvalue= 0.68
BE23 - Prov. Oost-Vlaanderen	2414.034	102.619	pvalue= 0.42	DED1 - Chemnitz (NUTS 2006)	3330.653	156.359	pvalue= 0.76
BE24 - Prov. Vlaams-Brabant	2465.226	92.645	pvalue= 0.35	DED2 - Dresden	3097.411	153.923	pvalue= 0.18
BE25 - Prov. West-Vlaanderen	2425.708	91.910	pvalue= 0.25	DED3 - Leipzig (NUTS 2006)	2938.925	145.849	pvalue= 0.15
BE31 - Prov. Brabant Wallon	2496.419	98.780	pvalue= 0.28	DEE1 - Dessau (NUTS 1999)	2911.832	159.615	pvalue= 0.078
BE32 - Prov. Hainaut	2577.477	113.672	pvalue= 0.31	DEE2 - Halle (NUTS 2003)	2942.352	138.723	pvalue= 0.15
BE33 - Prov. Liège	2836.721	118.967	pvalue= 0.74	DEE3 - Magdeburg (NUTS 2003)	2933.391	151.949	pvalue= 0.11
BE34 - Prov. Luxembourg (BE)	2982.424	125.278	pvalue= 0.96	DEF0 - Schleswig-Holstein	3006.573	137.597	pvalue= 0.68
BE35 - Prov. Namur	2785.063	120.268	pvalue= 0.66	DEG0 - Thüringen	3185.572	139.477	pvalue= 0.51
DK - Denmark	3188.784	163.578	pvalue= 0.96	IT - Italy	1830.746	111.770	pvalue= 0.97
DK001 - København og Frederiksberg Kommuner (NUTS 1999)	3319.465	235.717	pvalue= 0.73	ITC1 - Piemonte	2234.930	84.315	pvalue= 0.74
DK002 - Københavns amt (NUTS 1999)	3309.993	231.311	pvalue= 0.76	ITC2 - Valle d'Aosta/Vallée d'Aoste	3052.684	172.471	pvalue= 0.16
DK003 - Frederiksborg amt (NUTS 1999)	3257.689	179.182	pvalue= 0.94	ITC3 - Liguria	1765.165	63.582	pvalue= 0.67
DK004 - Roskilde amt (NUTS 1999)	3197.451	136.721	pvalue= 0.81	ITC4 - Lombardia	2284.519	119.333	pvalue= 0.94
DK005 - Vestsjællands amt (NUTS 1999)	3158.456	126.134	pvalue= 0.51	ITD1 - Provincia Autonoma Bolzano/Bozen (NUTS 2006)	4022.602	137.796	pvalue= 0.64
DK006 - Storstrøms amt (NUTS 1999)	3096.618	135.202	pvalue= 0.64	ITD2 - Provincia Autonoma Trento (NUTS 2006)	3439.545	141.438	pvalue= 0.91

DK007 - Bornholms amt (NUTS 1999)	3254.165	151.439	pvalue= 0.21	ITD3 - Veneto (NUTS 2006)	2249.986	133.084	pvalue= 0.47
DK008 - Fyns amt (NUTS 1999)	3075.777	163.879	pvalue= 0.82	ITD4 - Friuli-Venezia Giulia (NUTS 2006)	2298.501	165.836	pvalue= 0.22
DK009 - Sønderjyllands amt (NUTS 1999)	3125.877	154.847	pvalue= 0.86	ITD5 - Emilia-Romagna (NUTS 2006)	2012.679	124.055	pvalue= 0.26
DK00A - Ribe amt (NUTS 1999)	3142.258	156.440	pvalue= 0.68	ITE1 - Toscana (NUTS 2006)	1733.183	122.116	pvalue= 0.33
DK00B - Vejle amt (NUTS 1999)	3289.733	163.411	pvalue= 0.51	ITE2 - Umbria (NUTS 2006)	1927.916	137.457	pvalue= 0.73
DK00C - Ringkøbing amt (NUTS 1999)	3131.393	137.528	pvalue= 0.48	ITE3 - Marche (NUTS 2006)	1856.540	175.107	pvalue= 0.61
DK00D - Århus amt (NUTS 1999)	3365.327	152.511	pvalue= 0.21	ITE4 - Lazio (NUTS 2006)	1571.071	123.812	pvalue= 0.77
DK00E - Viborg amt (NUTS 1999)	3187.100	138.093	pvalue= 0.64	ITF1 - Abruzzo	1825.914	165.054	pvalue= 0.48
DK00F - Nordjyllands amt (NUTS 1999)	3250.294	145.517	pvalue= 0.13	ITF2 - Molise	1716.303	121.815	pvalue= 0.31
DE - Germany (until 1990 former territory of the FRG)	3036.543	212.548	pvalue= 0.44	ITF3 - Campania	1421.976	113.770	pvalue= 0.92
DE11 - Stuttgart	2956.042	132.904	pvalue= 0.43	ITF4 - Puglia	1392.643	106.065	pvalue= 0.59
DE12 - Karlsruhe	2799.102	125.264	pvalue= 0.34	ITF5 - Basilicata	1545.505	92.485	pvalue= 0.65
DE13 - Freiburg	2973.947	113.998	pvalue= 0.10	ITF6 - Calabria	1147.755	67.371	pvalue= 0.16
DE14 - Tübingen	3251.861	130.586	pvalue= 0.12	ITG1 - Sicilia	1048.303	82.700	pvalue= 0.19
DE21 - Oberbayern	3198.235	172.609	pvalue= 0.87	ITG2 - Sardegna	1132.830	100.077	pvalue= 0.16
DE22 - Niederbayern	3274.969	179.742	pvalue= 0.72	LV - Latvia	4051.362	231.013	pvalue= 0.70
DE23 - Oberpfalz	3324.813	145.278	pvalue= 0.42	LV00 - Latvija	4034.446	180.502	pvalue= 0.11
DE24 - Oberfranken	3347.644	147.003	pvalue= 0.49	SE - Sweden	5126.354	173.234	pvalue= 0.56
DE25 - Mittelfranken	3158.170	136.201	pvalue= 0.61	SE11 - Stockholm	3882.094	135.098	pvalue= 0.24
DE26 - Unterfranken	2998.735	128.534	pvalue= 0.30	SE12 - Östra Mellansverige	3993.884	149.903	pvalue= 0.69
DE27 - Schwaben	3315.836	162.902	pvalue= 0.35	SE21 - Småland med öarna	3812.076	163.981	pvalue= 0.32
DE30 - Berlin	2932.811	153.508	pvalue= 0.10	SE22 - Sydsverige	3393.894	153.198	pvalue= 0.91
DE41 - Brandenburg - Nordost (NUTS 2006)	3023.641	124.649	pvalue= 0.12	SE23 - Västsverige	3762.355	152.692	pvalue= 0.46
DE42 - Brandenburg - Südwest (NUTS 2006)	2941.538	159.470	pvalue= 0.091	SE31 - Norra Mellansverige	4756.472	156.657	pvalue= 0.91
DE50 - Bremen	2889.974	140.994	pvalue= 0.85	SE32 - Mellersta Norrland	5403.231	151.077	pvalue= 0.48
DE60 - Hamburg	2990.572	153.300	pvalue= 0.22	SE33 - Övre Norrland	6233.463	134.128	pvalue= 0.86
DE71 - Darmstadt	2780.267	109.396	pvalue= 0.10	EEA18 - European Economic Area (EU-15 plus IS, LI, NO)	5167.224	157.834	pvalue= 0.26
DE72 - Gießen	3052.724	116.280	pvalue= 0.52	CH - Switzerland	3356.566	122.826	pvalue= 0.91
DE73 - Kassel	3153.116	134.861	pvalue= 0.83	CH01 - Région lémanique	3441.540	140.999	pvalue= 0.55

DE80 - Mecklenburg-Vorpommern	3031.022	144.599	pvalue= 0.4	CH02 - Espace Mittelland	3254.682	124.927	pvalue= 0.48
DE91 - Braunschweig	2977.041	146.863	pvalue= 0.18	CH03 - Nordwestschweiz	3018.697	118.238	pvalue= 0.42
DE92 - Hannover	2875.367	138.122	pvalue= 0.25	CH04 - Zürich	3009.618	129.579	pvalue= 0.74
DE93 - Lüneburg	2937.717	145.514	pvalue= 0.37	CH05 - Ostschweiz	3418.393	133.781	pvalue= 0.91
DE94 - Weser-Ems	2804.605	134.446	pvalue= 0.95	CH06 - Zentralschweiz	3466.717	127.728	pvalue= 0.78
DEA1 - Düsseldorf	2581.282	125.146	pvalue= 0.26	CH07 - Ticino	3487.395	144.820	pvalue= 0.71

Appendix 3: LCA inputs for the case studies included in the software tool database

Table 66 materials.csv data frame

ID	Name	Country	de	sl_DISTR	sl_1	sl_2	sl_3	UI_1_DISTR	UI_1_1	UI_1_2	UI_1_3	UI_2_DISTR	UI_2_1	UI_2_2	UI_2_3	UI_3_DISTR	UI_3_1	UI_3_2	UI_3_3	EOL_1_DISTR	EOL_1_1	EOL_1_2	EOL_1_3	EOL_2_DISTR	EOL_2_1	EOL_2_2	EOL_2_3	EOL_3_DISTR	EOL_3_1	EOL_3_2	EOL_3_3
101	Adhesive Knauf_ SM700	Italy	1400	det	30	0	0	rnorm	1.376	0.366	0	rnorm	19.833	4.968	0	rnorm	0.765	0.341	0	rnorm	0.515	0.22	0	rnorm	0.361	0.109	0	rnorm	0.431	0.241	0
102	EPS 100 Knauf	Italy	18	det	50	0	0	rnorm	4.457	0.344	0	rnorm	99.751	8.068	0	rnorm	0.332	0.211	0	rnorm	0.118	0.064	0	rnorm	0.272	0.103	0	rnorm	0.243	0.131	0
103	plasterboard Knauf _GKB(A)	Italy	680	det	50	0	0	rnorm	0.399	0.055	0	rnorm	4.515	0.653	0	rnorm	0.097	0.057	0	rnorm	0.518	0.223	0	rnorm	0.355	0.094	0	rnorm	0.451	0.301	0
104	skim coat Knauf_uniflott	Italy	1200	det	10	0	0	rnorm	0.103	0.012	0	rnorm	1.29	0.167	0	rnorm	0.02	0.012	0	rnorm	0.504	0.22	0	rnorm	0.35	0.099	0	rnorm	0.442	0.278	0
105	primer + paint	Italy	1200	det	10	0	0	rnorm	5.257	8.93	0	rnorm	66.797	17.025	0	rnorm	2.911	10.09	0	rnorm	0.089	0.049	0	rnorm	0.272	0.103	0	rnorm	3.442	2.142	0
106	Adhesive Fassa Borrtolo_A96	Italy	1350	det	30	0	0	rnorm	1.376	0.366	0	rnorm	19.833	4.968	0	rnorm	0.765	0.341	0	rnorm	0.515	0.22	0	rnorm	0.361	0.109	0	rnorm	0.431	0.241	0
107	EPS 100 Fassa Bortolo	Italy	18	det	50	0	0	rnorm	4.457	0.344	0	rnorm	99.751	8.068	0	rnorm	0.332	0.211	0	rnorm	0.515	0.22	0	rnorm	0.361	0.109	0	rnorm	0.431	0.241	0
108	Surface rendering Fassa_A96	Italy	1350	det	30	0	0	rnorm	1.376	0.366	0	rnorm	19.833	4.968	0	rnorm	0.765	0.341	0	rnorm	0.515	0.22	0	rnorm	0.361	0.109	0	rnorm	0.431	0.241	0
109	XPS Kanuf_POLYFOAM Ultragrip SE	Italy	15	det	50	0	0	rnorm	3.903	0.441	0	rnorm	89.646	11.942	0	rnorm	0.508	0.338	0	rnorm	0.118	0.068	0	rnorm	0.259	0.097	0	rnorm	0.247	0.133	0
110	Adhesive Rofix_Renopor	Italy	1650	det	30	0	0	rnorm	1.376	0.366	0	rnorm	19.833	4.968	0	rnorm	0.765	0.341	0	rnorm	0.515	0.22	0	rnorm	0.361	0.109	0	rnorm	0.431	0.241	0
111	CaSi Rofix_Renopor I	Italy	290	det	80	0	0	det	2.039	0	0	det	0	0	0	rnorm	0	0	0	det	0	0	0	det	0	0	0	det	0	0	0
112	Surface rendering Rofix_Renopor	Italy	1650	det	30	0	0	rnorm	1.376	0.366	0	rnorm	19.833	4.968	0	rnorm	0.765	0.341	0	rnorm	0.515	0.22	0	rnorm	0.361	0.109	0	rnorm	0.431	0.241	0
113	Adhesive Xella_malta multipor	Italy	800	det	30	0	0	rnorm	1.376	0.366	0	rnorm	19.833	4.968	0	rnorm	0.765	0.341	0	rnorm	0.515	0.22	0	rnorm	0.361	0.109	0	rnorm	0.431	0.241	0
114	AAC Xella_ multipor 042	Italy	90	det	80	0	0	det	0.878	0	0	det	0	0	0	rnorm	0	0	0	det	0	0	0	det	0	0	0	det	0	0	0
115	Surface rendering Xella_ malta multipor	Italy	800	det	30	0	0	rnorm	1.376	0.366	0	rnorm	19.833	4.968	0	rnorm	0.765	0.341	0	rnorm	0.515	0.22	0	rnorm	0.361	0.109	0	rnorm	0.431	0.241	0
116	Adhesive DOMUS PAN HD	Italy	950	det	30	0	0	rnorm	1.376	0.366	0	rnorm	19.833	4.968	0	rnorm	0.765	0.341	0	rnorm	0.515	0.22	0	rnorm	0.361	0.109	0	rnorm	0.431	0.241	0
117	Cork_ Sugherite	Italy	120	det	30	0	0	rnorm	1.58	0.163	0	rnorm	23.771	2.71	0	rnorm	0.581	0.468	0	rnorm	0.502	0.202	0	rnorm	0.35	0.099	0	rnorm	0.434	0.247	0
118	Surface rendering DOMUS PAN HD	Italy	950	det	30	0	0	rnorm	1.376	0.366	0	rnorm	19.833	4.968	0	rnorm	0.765	0.341	0	rnorm	0.515	0.22	0	rnorm	0.361	0.109	0	rnorm	0.431	0.241	0
119	Rock wool Knauf_ DP7 ALUR	Italy	70	det	37.5	0	0	rnorm	1.452	0.142	0	rnorm	18.108	1.77	0	rnorm	0.464	0.295	0	rnorm	0.496	0.208	0	rnorm	0.353	0.102	0	rnorm	0.433	0.242	0
120	Vapor barrirer	Italy	2700	det	30	0	0	rnorm	4.965	0.946	0	rnorm	51.671	9.779	0	rnorm	2.475	1.083	0	rnorm	0.505	0.212	0	rnorm	0.357	0.104	0	rnorm	0.433	0.227	0
121	metal C profile	Italy	7800	det	100	0	0	rnorm	2.029	0.446	0	rnorm	23.433	4.708	0	rnorm	2.618	1.429	0	rnorm	0.005	0.002	0	rnorm	0.157	0.067	0	rnorm	0.001	0.001	0

122	metal Uprofile	Italy	7800	det	100	0	0	rnorm	2.029	0.446	0	rnorm	23.433	4.708	0	rnorm	2.618	1.429	0	rnorm	0.005	0.002	0	rnorm	0.157	0.067	0	rnorm	0.001	0.001	0
123	fixing screw	Italy	7800	det	100	0	0	rnorm	2.029	0.446	0	rnorm	23.433	4.708	0	rnorm	2.618	1.429	0	rnorm	0.005	0.002	0	rnorm	0.157	0.067	0	rnorm	0.001	0.001	0
201	Mineral plaster	Switzerland	1200	det	30	0	0	det	0.0806	0	0	det	1.53	0	0	det	147	0	0	det	0.00485	0	0	det	0.111	0	0	det	19.2	0	0
202	Fermacell gypsum fibreboard	Switzerland	1150	det	30	0	0	det	0.291	0	0	det	4.61	0	0	det	349	0	0	det	0.0291	0	0	det	0.287	0	0	det	48.1	0	0
203	GYSO VS 80 R vapour barrier	Switzerland	875	det	30	0	0	det	2.76	0	0	det	88.8	0	0	det	2240	0	0	det	2.58	0	0	det	0.479	0	0	det	1360	0	0
204	Glasswool Isover PB M 032	Switzerland	29	det	30	0	0	det	0.84	0	0	det	17.2	0	0	det	1280	0	0	det	0.0101	0	0	det	0.244	0	0	det	29.1	0	0
205	Softwood	Switzerland	480	det	30	0	0	det	0.105	0	0	det	2.59	0	0	det	364	0	0	det	0.00927	0	0	det	0.113	0	0	det	24.7	0	0
206	Rockwool Flumroc 1	Switzerland	38	det	30	0	0	det	1.02	0	0	det	13.9	0	0	det	1000	0	0	det	0.0101	0	0	det	0.244	0	0	det	29.1	0	0
207	Multipor WI insulation	Switzerland	115	det	30	0	0	det	0.41	0	0	det	3.17	0	0	det	321	0	0	det	0.00903	0	0	det	0.182	0	0	det	25.4	0	0
208	Isofloc LM	Switzerland	50	det	30	0	0	det	0.163	0	0	det	2.5	0	0	det	264	0	0	det	0.0406	0	0	det	0.366	0	0	det	85.9	0	0
209	Multipor light mortar	Switzerland	450	det	30	0	0	det	0.191	0	0	det	1.34	0	0	det	178	0	0	det	0.00959	0	0	det	0.19	0	0	det	26.2	0	0
301	Isover glasswool rolls (lambda 37)	Denmark	15	det	60	0	0	det	0.71	0	0	det	11.23	0	0	det	0	0	0	det	0.03	0	0	det	0.3	0	0	det	0	0	0
302	Isover Steel frame (stud)	Denmark	7840	det	100	0	0	rnorm	2.029	0.446	0	rnorm	23.433	4.708	0	rnorm	2.618	1.429	0	rnorm	0.005	0.002	0	rnorm	0.157	0.067	0	rnorm	0.001	0.001	0
303	Flexibatts 37 rockwool	Denmark	29	det	60	0	0	det	1.18	0	0	det	0.0894	0	0	det	0	0	0	det	0	0	0	det	0	0	0	det	0	0	0
304	OSB-3 board	Denmark	600	det	50	0	0	det	0	0	0	det	8.95	0	0	det	0	0	0	det	0.602833	0	0	det	-19.8	0	0	det	0	0	0
305	Rockwool vapour barrier (plastic PE foil)	Denmark	920	det	40	0	0	det	3.57	0	0	det	88.77	0	0	det	0	0	0	det	0	0	0	det	0	0	0	det	0	0	0
306	Gypsum plasterboard	Denmark	668	det	60	0	0	det	0.251	0	0	det	4.19	0	0	det	0	0	0	det	0.002	0	0	det	0.0275	0	0	det	0	0	0
307	PROMALUX-V calsium silicate boards	Denmark	500	det	100	0	0	det	2.039	0	0	det	26.054	0	0	det	0	0	0	det	0	0	0	det	0	0	0	det	0	0	0
308	Micro dispers (acrylic primer+paint)	Denmark	1295	det	100	0	0	rnorm	5.257	8.93	0	rnorm	66.797	17.025	0	rnorm	2.911	10.09	0	rnorm	0.089	0.049	0	rnorm	0.272	0.103	0	det	0	0	0
309	Sodium Silicate - Inorganic adhesive plaster	Denmark	1350	det	100	0	0	rnorm	1.376	0.366	0	rnorm	19.833	4.968	0	rnorm	0.765	0.341	0	rnorm	0.515	0.22	0	rnorm	0.361	0.109	0	rnorm	0.431	0.241	0
310	DalaPro Nova sandspartel (putty)	Denmark	1400	det	100	0	0	rnorm	1.376	0.366	0	rnorm	19.833	4.968	0	rnorm	0.765	0.341	0	rnorm	0.515	0.22	0	rnorm	0.361	0.109	0	rnorm	0.431	0.241	0
311	CalsiTherm climate board (replaced by promalux-v)	Denmark	185	det	80	0	0	det	2.039	0	0	det	26.054	0	0	det	0	0	0	det	0	0	0	det	0	0	0	det	0	0	0
312	Adhesive mortar	Denmark	1600	det	60	0	0	det	0.638	0	0	det	6.8	0	0	det	0	0	0	det	-0.0369	0	0	det	0	0	0	det	0	0	0
313	Ytong multipor board	Denmark	115	det	100	0	0	det	1.1	0	0	det	12.3	0	0	det	0	0	0	det	0	0	0	det	0	0	0	det	0	0	0
314	Ytong lightmortar	Denm	770	det	100	0	0	det	0.4475	0	0	det	3.56	0	0	det	0	0	0	det	0	0	0	det	0	0	0	det	0	0	0

		ark																													
315	Kingspan KoolTherm K118 plaster board (replaced by foam board)	Denmark	35	det	100	0	0	det	2.9	0	0	det	67.7	0	0	det	0	0	0	det	16.4	0	0	det	205	0	0	det	0	0	0
316	iQ-Therm board (replaced by foam board)	Denmark	45	det	100	0	0	det	2.9	0	0	det	67.7	0	0	det	0	0	0	det	16.4	0	0	det	0	0	0	det	0	0	0
317	iQ-Fix adhesive (replaced by inorganic adhesives)	Denmark	1500	det	100	0	0	rnorm	1.376	0.366	0	rnorm	19.833	4.968	0	rnorm	0.765	0.341	0	rnorm	0.515	0.22	0	rnorm	0.361	0.109	0	rnorm	0.431	0.241	0
318	iQ-Top (replaced by gypsum plaster)	Denmark	630	det	100	0	0	det	0.251	0	0	det	4.19	0	0	det	0	0	0	det	0.002	0	0	det	0.0275	0	0	det	0	0	0
319	iQ-Fill (putty) (inorganic adhesive)	Denmark	1200	det	100	0	0	rnorm	1.376	0.366	0	rnorm	19.833	4.968	0	rnorm	0.765	0.341	0	rnorm	0.515	0.22	0	rnorm	0.361	0.109	0	rnorm	0.431	0.241	0
320	Primer + Paint	Denmark	1200	det	60	0	0	rnorm	5.257	8.93	0	rnorm	66.797	17.025	0	rnorm	2.911	10.09	0	rnorm	0.089	0.049	0	rnorm	0.272	0.103	0	det	0	0	0

Table 67 insulation_system.csv dataframe

ID	Name	Country	CI_DISTR	CI_1	CI_2	CI_3	CM_DISTR	CM_1	CM_2	CM_3	SL_DISTR	SL_1	SL_2	SL_3	n_mater	materials	m_mater_DISTR	m_mater_1	m_mater_2	m_mater_3	M_selection	DU
1	Comp_1	Italy	rnorm	40.42	5.5896	0	rnorm	2.7681	0.38329	0	rnorm	30	2.98	0	6	101 102 101 103 104 000	rtriangle rtriangle rtriangle rtriangle rtriangle rtriangle	9.31 1.71 9.31 8.075 4.56 2.28	10.78 1.98 10.78 9.35 5.28 2.64	9.8 1.8 9.8 8.5 4.8 2.4	105	2.94
2	Comp_2	Italy	rnorm	45.62	6.3209	0	rnorm	2.7681	0.38329	0	rnorm	30	2.98	0	4	106 107 108 105	rtriangle rtriangle rtriangle rtriangle	7.695 1.71 7.695 2.28	8.91 1.98 8.91 2.64	8.1 1.8 8.1 2.4	105	2.794
3	Comp_3	Italy	rnorm	67.18	9.186	0	rnorm	2.7681	0.38329	0	rnorm	30	2.98	0	6	101 109 101 103 104 000	rtriangle rtriangle rtriangle rtriangle rtriangle rtriangle	9.31 1.425 9.31 8.075 4.56 2.28	10.78 1.65 10.78 9.35 5.28 2.64	9.8 1.5 9.8 8.5 4.8 2.4	105	2.94
4	Comp_4	Italy	rnorm	213.63	29.1827	0	rnorm	2.7681	0.38329	0	rnorm	30	2.98	0	4	110 111 112 105	rtriangle rtriangle rtriangle rtriangle	10.9725 41.325 9.405 2.28	12.705 47.85 10.89 2.64	11.55 43.5 9.9 2.4	105	2.84
5	Comp_5	Italy	rnorm	92.99	12.7991	0	rnorm	2.7681	0.38329	0	rnorm	30	2.98	0	4	113 114 115 105	rtriangle rtriangle rtriangle rtriangle	4.56 10.26 4.56 2.28	5.28 11.88 5.28 2.64	4.8 10.8 4.8 2.4	105	2.87
6	Comp_6	Italy	rnorm	79.01	10.9115	0	rnorm	2.7681	0.38329	0	rnorm	30	2.98	0	4	116 117 118 105	rtriangle rtriangle rtriangle rtriangle	9.025 13.68 9.025 2.28	10.45 15.84 10.45 2.64	9.5 14.4 9.5 2.4	105	3.022
7	Comp_7	Italy	rnorm	52.33	7.1218	0	rnorm	2.7681	0.38329	0	rnorm	30	2.98	0	8	119 120 121 122 123 000 000 000	rtriangle rtriangle rtriangle rtriangle rtriangle rtriangle rtriangle rtriangle	6.65 0.38475 0.7163 0.1881 0.1311 8.075 4.56 2.28	7.7 0.4455 0.8294 0.2178 0.1518 9.35 5.28 2.64	7 0.405 0.754 0.198 0.138 8.5 4.8 2.4	105	2.92
8	Comp_8	Switzerland	det	1	0	0	det	0	0	0	det	30	0	0	7	201 202 206 205 203 000 000	det det det det det det det	6 14.3751 1.9924 2.6729 0.21 2.7594 3.5447	0 0 0 0 0 0 0	0 0 0 0 0 0 0	0	3.509
9	Comp_9	Switzerland	det	1	0	0	det	0	0	0	det	30	0	0	6	201 202 205 203 208 000	det det det det det det	6 14.375 1.7452 0.21 6.5628 7.5569	0 0 0 0 0 0	0 0 0 0 0 0	0	3.472
10	Comp_10	Switzerland	det	1	0	0	det	0	0	0	det	30	0	0	8	201 202 204 205 203 000 000 000	det det det det det det det det	6 14.3751 0.8127 1.4286 0.21 1.58 2.6585 0.87	0 0 0 0 0 0 0 0	0 0 0 0 0 0 0 0	0	3.509
11	Comp_11	Switzerland	det	1	0	0	det	0	0	0	det	30	0	0	3	201 207 209	det det det	6 17.25 2.25	0 0 0	0 0 0	0	3.533
12	Comp_12	Switzerland	det	1	0	0	det	0	0	0	det	30	0	0	6	201 202 205 203 207 000	det det det det det det	6 14.375 1.7472 0.21 17.25 2.25	0 0 0 0 0 0	0 0 0 0 0 0	0	3.774
13	Comp_13	Denmark	det	0	0	0	det	0	0	0	det	60	0	0	2	301 302	rtriangle rtriangle	1.4 268.1	1.7 310.5	1.5 282.2	0	2.7
14	Comp_14	Denmark	det	0	0	0	det	0	0	0	det	50	0	0	6	302 302 303 304 305 000	rtriangle rtriangle rtriangle rtriangle rtriangle rtriangle	268.0900 268.0900 3.3250 10.2600 0.1900 7.9	310.5 310.5 3.8 11.9 0.2 9.2	282.2 282.2 3.5 10.8 0.2 8.4	0	3.24
15	Comp_15	Denmark	det	0	0	0	det	0	0	0	det	80	0	0	3	307 309 310	rtriangle rtriangle rtriangle	71.3 6.4 6.7	82.5 7.4 7.7	75 6.8 7	0	2.31
16	Comp_16	Denmark	det	0	0	0	det	0	0	0	det	60	0	0	3	307 312 312	rtriangle rtriangle rtriangle	47.5 7.6 7.6	55 8.8 8.8	50 8 8	0	1.61
17	Comp_17	Denmark	det	0	0	0	det	0	0	0	det	60	0	0	3	312 313 314	rtriangle rtriangle rtriangle	7.6 10.9 3.7	8.8 12.7 4.2	8 11.5 3.9	0	2.5
18	Comp_18	Denmark	det	0	0	0	det	0	0	0	det	60	0	0	3	306 312 315	rtriangle rtriangle rtriangle	7.9 7.6 3.3	9.2 8.8 3.9	8.4 8 3.5	0	3.5
19	Comp_19	Denmark	det	0	0	0	det	0	0	0	det	60	0	0	5	316 317 318 319 320	rtriangle rtriangle rtriangle rtriangle rtriangle	3.4 7.1 3 3.4 3.4	4 8.3 3.5 4 4	3.6 7.5 3.2 3.6 3.6	0	2.6

Table 68 case_studies.csv dataframe

ID	Name	Country	Qhpost_DISTR	Qhpost_1	Qhpost_2	Qhpost_3	Qhpre_DISTR	Qhpre_1	Qhpre_2	Qhpre_3	CN	C1	sur
1	C_S_Test1	Italy	rnorm	14.12	2.35	0	rnorm	100.63	6.57	0	1	1	1
2	C_S_Test2	Italy	rnorm	14.75	2.36	0	rnorm	100.63	6.57	0	1	2	1
3	C_S_Test3	Italy	rnorm	14.12	2.35	0	rnorm	100.63	6.57	0	1	3	1
4	C_S_Test4	Italy	rnorm	14.55	2.36	0	rnorm	100.63	6.57	0	1	4	1
5	C_S_Test5	Italy	rnorm	14.42	2.35	0	rnorm	100.63	6.57	0	1	5	1
6	C_S_Test6	Italy	rnorm	13.79	2.34	0	rnorm	100.63	6.57	0	1	6	1
7	C_S_Test7	Italy	rnorm	14.21	2.35	0	rnorm	100.63	6.57	0	1	7	1
8	C_S_Test8	Switzerland	det	19.61	0	0	det	128.39	0	0	1	8	1
9	C_S_Test9	Switzerland	det	19.61	0	0	det	128.39	0	0	1	9	1
10	C_S_Test10	Switzerland	det	19.61	0	0	det	128.39	0	0	1	10	1
11	C_S_Test11	Switzerland	det	19.61	0	0	det	128.39	0	0	1	11	1
12	C_S_Test12	Switzerland	det	18.52	0	0	det	128.39	0	0	1	12	1
13	C_S_Test13	Denmark	det	26.7894	0	0	det	120	0	0	1	13	1
14	C_S_Test14	Denmark	det	22.243	0	0	det	120	0	0	1	14	1
15	C_S_Test15	Denmark	det	29.0751	0	0	det	120	0	0	1	15	1
16	C_S_Test16	Denmark	det	37.6672	0	0	det	120	0	0	1	16	1
17	C_S_Test17	Denmark	det	27.3484	0	0	det	120	0	0	1	17	1
18	C_S_Test18	Denmark	det	20.8956	0	0	det	120	0	0	1	18	1
19	C_S_Test19	Denmark	det	26.6839	0	0	det	120	0	0	1	19	1

Table 69 energy_sources.csv dataframe

ID	Name	Country	En_S	EnT_DISTR	EnT_1	EnT_2	EnT_3	EnFc_DISTR	EnFc_1	EnFc_2	EnFc_3	ETAh_DISTR	ETAh_1	ETAh_2	ETAh_3	EI_1_DISTR	EI_1_1	EI_1_2	EI_1_3	EI_2_DISTR	EI_2_1	EI_2_2	EI_2_3	EI_3_DISTR	EI_3_1	EI_3_2	EI_3_3
1	Tar_1	Italy	Gas	runif	0.065	0.085	0	det	1.05	0	0	runif	0.6	1	0	rnorm	0.2605	0.0429	0	rnorm	4.196	1.055	0	rnorm	0.0252	0.0126	0
2	Tar_2	Italy	electricity	runif	0.1584	0.2143	0	det	2.42	0	0	runif	2.5	4	0	rnorm	0.1228	0.009	0	rnorm	1.495	0.163	0	rnorm	0.07065	0.0895	0
3	Tar_3	Italy	oil	runif	0.115	0.1354	0	det	1.07	0	0	runif	0.4	0.8	0	rnorm	0.3183	0.0577	0	rnorm	4.923	1.448	0	rnorm	0.01528	0.0084	0
4	Tar_4	Switzerland	Gas	det	0.252174	0	0	det	1	0	0	det	0.9	0	0	det	0.017583	0	0	det	0.294444	0	0	det	17.05556	0	0
5	Tar_5	Switzerland	electricity	det	0.191304	0	0	det	1	0	0	det	1	0	0	det	0.057778	0	0	det	0.941667	0	0	det	34.44444	0	0
6	Tar_6	Switzerland	oil	det	0.321739	0	0	det	1	0	0	det	0.9	0	0	det	0.022972	0	0	det	0.338889	0	0	det	10.55556	0	0
7	Tar_7	Denmark	oil	det	0.132887	0	0	det	1	0	0	det	0.9	0	0	rnorm	0.3183	0.0577	0	rnorm	4.923	1.448	0	rnorm	0.01528	0.0084	0
8	Tar_8	Denmark	Gas	det	0.084527	0	0	det	1	0	0	det	0.9	0	0	rnorm	0.2605	0.0429	0	rnorm	4.196	1.055	0	rnorm	0.0252	0.0126	0
9	Tar_9	Denmark	Renewable energy	det	0	0	0	det	0	0	0	det	0.9	0	0	det	0	0	0	det	0	0	0	det	0	0	0
10	Tar_10	Denmark	electricity	det	0.222311	0	0	det	2.5	0	0	det	0.9	0	0	rnorm	0.1228	0.009	0	rnorm	1.495	0.163	0	rnorm	0.07065	0.0895	0
11	Tar_11	Denmark	District heating	det	0.065563	0	0	det	1	0	0	det	0.95	0	0	det	0.0756	0	0	det	0.6264	0	0	det	0	0	0

Appendix 4: Preliminary national case studies of "deterministic" LCA of internal insulation systems applied in historic buildings renovation interventions

This Appendix reports the national examples of "deterministic" life cycle assessment (LCA) of internal insulation solutions realized on historic buildings, performed by the countries partners at the early stage of Task 5.2. The aim of these preliminary LCA analysis is having a picture on the environmental hotspots, the share of materials, the energy saving, the impact of different phases in the case of LCA of insulation interventions in historic buildings, in order to start the discussion among partners on the following LCA "probabilistic approach" development, e.g. on the life cycle phases to include, the environmental impact indicators to consider, the input parameters (inventory) necessary to perform a complete life cycle analysis.

For these reasons, the case-studies presented in this appendix do not claim to be consistent with each other, but rather opened the preliminary discussion on Task 5.2 topics.

Swiss case study

This section presents the analysis of various renovation measures applied to the facade of a multi-family building built in 1910. Internal insulation reduces the thermal losses through the envelope but might also induce hygrothermal problems. Insulation systems used in this study are based on examples and recommendations provided by manufacturers. Their hygrothermal performances have not been verified with simulation tools. This study only evaluates the performance of internal renovation measures from an environmental (LCA) point of view. The deterministic Life cycle assessment (LCA) performed takes into account the environmental impacts of the renovation materials as well as the impacts of the energy consumption related to the thermal losses through the facade. The LCA is conducted according to the technical book SIA 2032 [22]. The description of the wall for LCA is the same and modelled in the Eco-sai tool [37] developed by HES-SO.

Case building description

Figure 76 North-east view of the building

This study is based on a 1910 building situated in Lausanne, Switzerland. Seventeen apartments are distributed among the six storeys. The external walls are made of natural stone. They are between 50 and 60 cm thick, without any additional thermal insulation. On the first floor, the stones are visible from the outside while and on upper storeys they are covered by mineral roughcast. The internal side is coated with one centimetre of plaster. This study focuses only on the renovation of the external walls. The rather good state of the facades as well as the architectural characteristics (e.g., stone windows embrasures, visible stone on the first floor and mansard roof on the highest floor) explain why the owner would like to avoid an external insulation solution. The complexity of the facade (high number of decorations, balconies) would also make the external insulation tricky.

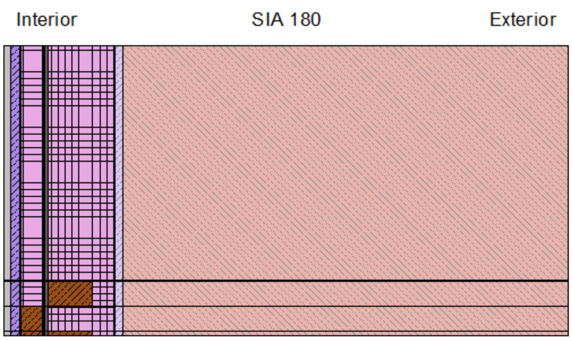
Different internal insulation materials can be used for historic building renovations. We can cite the following ones:

- System with mineral wool (e.g. Rockwool, Isover)
- System with cellular fibre
- System with PUR or System with PUR with calcium silicate tubes (e.g. IQ-Therm)
- System with calcium silicate (e.g. SkamolPlus, MicroTherm or Multipor from Ytong)
- System with vacuum insulation (VIP)

In this deterministic LCA, only the two first ones and the Multipor are considered based on systems currently implemented by the manufacturers. For comparability purposes, each system's insulation thickness was adjusted to comply with thermal resistance limit of the SIA 380/1 [128] renovation standard punctual requirements (U_{val} = 0.25 W/(m²K)). Whenever possible, the thermal and physical properties of insulation products currently available in the Swiss market were taken into account. The existing natural stone wall and internal coating are displayed in blue in the tables below. Their thermal resistance was obtained by performing in situ heat flux measurements.

Glasswool

When insulating this construction element from the inside, the manufacturer (ISOVER) suggests using three layers of glasswool with wooden beams offering support for the insulation panels. Around twelve centimetres of glasswool is required to reach a U-value of 0.25 W/(m²K). A membrane with high vapour permeability is used to prevent moisture damage. On the internal side, gypsum fibreboards are smoothed and coated with mineral roughcast.

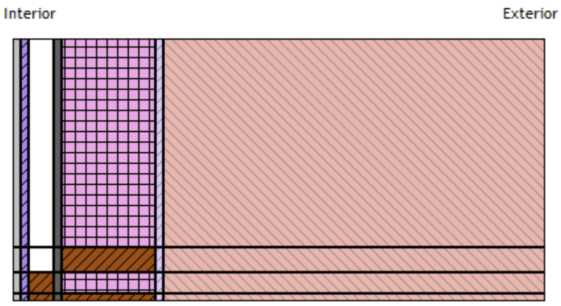


Material	Thickness [cm]	Conductivity [W/(m.K)]	Density [kg/m³]
Natural Stone	60	1.3	2000
Mineral coating	1	0.7	1400
Glasswool	3	0.032	29
Glasswool / Wood	6	0.032 / 0.14	29 / 480
Vapour barrier	0.024	0.2	875
Glasswool / Wood	3.1	0.032 / 0.14	29 / 480
Gypsum plasterboard	1.25	0.32	1150
Mineral cover coat	0.5	0.7	1200

Figure 77 renovated facade using glasswool

Rockwool

This construction element is quite similar to the glasswool variant above. The manufacturer (Flumroc) suggests using two panels of rockwool, separated by a vapour barrier. As the thermal conductivity of the rockwool is higher than the glasswool, a slightly higher insulation thickness is required (around 14 cm).

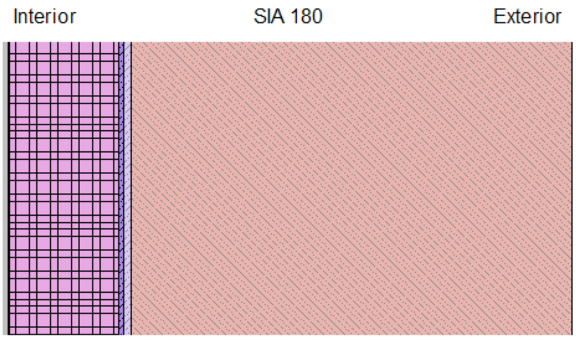


Material	Thickness [cm]	Conductivity [W/(m.K)]	Density [kg/m³]
Natural Stone	60	1.3	2000
Mineral coating	1	0.7	1400
Glasswool / Wood	8	0.035 / 0.14	38 / 480
Vapour barrier	0.024	0.2	875
Glasswool / Wood	5.8	0.035 / 0.14	38 / 480
Gypsum plasterboard	1.25	0.32	1150
Mineral cover coat	0.5	0.7	1200

Figure 78 renovated facade using rockwool

Multipor

Multipor is a porous mineral material made of calcium silicate, lime, sand, cement and water. It offers adequate thermal insulation while its vapour diffusion properties also help regulating hygrometry within the building. Multipor is provided as rigid panels that can be glued to the existing wall using a light mortar provided by the same manufacturer. No additional fixings are required. The internal side is then also coated with mineral roughcast. Fifteen centimetres of Multipor are required to reach the required thermal performance.

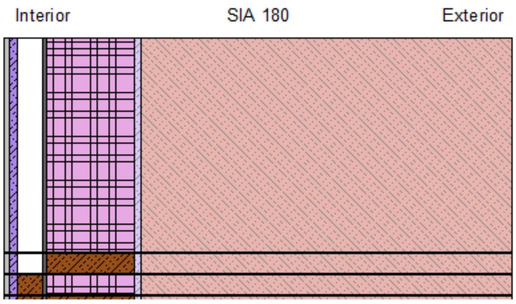


Material	Thickness [cm]	Conductivity [W/(m.K)]	Density [kg/m³]
Natural Stone	60	1.3	2000
Mineral coating	1	0.7	1400
Light mortar	0.5	0.18	450
Multipor WI	15	0.045	115
Mineral cover coat	0.5	0.7	1200

Figure 79 renovated facade using multipor (before the hygrothermal assessment)

Cellulose fibre

The cellulose fibre manufacturer (Isofloc[34]) suggest the following solution for internal insulation of historic building: a vertical wooden structure is installed against the existing wall and a vapour barrier is then put in place. Smaller wooden beams are then placed against the vapour barrier horizontally every forty centimetres. Cellulose fibre can then be blown between the existing wall and the vapour barrier through cavities that will later be sealed. The thickness of the horizontal wooden laths offers a small technical space for pipes installation. On the internal side, gypsum plasterboards are then laid, smoothed and coated with a mineral finishing.



Material	Thickness [cm]	Conductivity [W/(m.K)]	Density [kg/m³]
Natural Stone	60	1.3	2000
Mineral coating	1	0.7	1400
Cellulose / Wood	14.7	0.038 / 0.14	50 / 480
Vapour barrier	0.024	0.2	875
Air / Wood	4	- / 0.14	- / 480
Gypsum plasterboard	1.25	0.32	1150
Mineral cover coat	0.5	0.7	1200

Figure 80 renovated facade using cellulose fibre

LCA assumptions (goal and scope, reference study period, System boundaries, functional unit, data and tools, indicators)

The methodology used in this study is compliant with ISO 14040 [2] as well as with the Swiss SIA 2032 technical book [22] and the IEA Annex 56 recommendations for LCA of energy-related renovation [141]. It takes into account materials and energy flows as well as emissions coming in and out of a system during a pre-defined study period.

Reference study period

IEA Annex 56 recommendations suggest to either take into account the lifespan between two renovations (typically 30 years) or the number of years between the current renovation and the end of the building life (typically 60 years). The second option was chosen and therefore, a reference study period of 60 years is considered in this study.

System boundaries

Table 70 presents the life cycle stages occurring during the building lifetime from cradle to grave based on EN 15978 standard modules' name.

[34] http://isofloc.ch/assets/Produkte/20160321-Sanierungsbroschuere-BUeT-fr-mail.pdf

Table 70 Building life cycle stages according to EN 15978 standard and LCA assumptions considered

LCA step	Choice for the determininistic LCA
Goal definition	1) Deterministic LCA of four interior insulation measures of a historic building facade located in Lausanne (Switzerland)
Functional unit	"Insulation measure needed to cover 1 m2 of a historic facade, providing no risk of condensation (based on Glaser method), for thermal resistance of 0.25 m2.K/W over a reference study period of 60 years"
System boundaries for the LCA	SIA 2032, EN 15978 and Eco-sai system boundaries restricted here to Production stage (module A1-A3) and Operational energy use (B6)
A1-A3: Production Stage	X
A4: Transport	X
A5: Construction / installation	Not considered (low contribution in the environmental impacts)
B1: Use	Not considered due to lack of data and scope of RIBuild
B2: Maintenance	Not considered (to be discussed in relation to module B4 and the use of appropriate service lives for materials)
B3: Repair	Not considered according to EeBGuide guidance document
B4: Replacement	X
B5: Refurbishment	Not considered as this module is related to a full building encompassing a refurbishment
B6: Operational energy use	X
B7: Operational water use	Not considered as not relevant within the scope of RIBuild
C1: Deconstruction	Not considered as not relevant within the scope of RIBuild (we do not look at the structural elements)
C2-C4: End-of-life (except. C1 Deconstruction)	X
Databases	KBOB/2009:2014 (based on ecoinvent v2.2 data and product-specific data)
Service life of construction materials	as in SIA 2032
LCIA indicators	greenhouse gases emissions, cumulative energy demand non renewable, total environmental impacts (Ecological scarcity 2013)
Reference study period for the LCA	60 years
Software used to implement the deterministic / probabilistic LCA	Eco-sai

According to the SIA 2032 and IEA Annex 56 project, some of these stages have generally little influence on the global environmental performance of a building in Switzerland and are therefore neglected (e.g., A5). Others are very specific stage and available guidance (e.g., the EeBGuide) recommend not considering it as a mandatory element (e.g., the B3 Repair module). Others cannot be reliably evaluated due to a clear lack of data (e.g., B1 Use for the release of hazardous substances from construction products during the operational phase of a building). Finally, others are not relevant in the context of the internal insulation measures renovation e.g., the C1 Deconstruction stage as the deconstruction of the building is not a scenario in the RIBuild project. These different elements explain why stages A5, B1, B2, B3, B5, B7 and C1 were not considered in the deterministic LCA.

This study does not consider a global renovation of the building (walls, floor, roof and technical systems). Only the external walls are renovated. In order to keep results within a range of small readable values, an area of one square meter of facade is considered.

Materials

Only the construction materials added during the renovation of the facade are taken into account in this study. For each renovation scenario, all existing materials remain in place. The lifespans of some replacement materials might be lower than the reference study period. These materials will have to be substituted at some point. In the absence of reliable product-specific data on materials lifespans, the values used in this study are compliant with IEA Annex 56 recommendations as well as with the SIA 2032 technical book. Both suggest lifespans of 30 years for internal insulations and coatings. No partial replacements are considered. If at least half the new material lifespan is left until the building end-of-life, the material is fully replaced. If not, then the replacement is not considered.

Operational energy

According to IEA Annex 56, the environmental balance of a renovation project is obtained through subtracting the impacts of the energy saved during the reference study period to the impacts of the materials added during the renovation. A negative balance means that the renovation was effective from an environmental perspective.

$$EI_{reno} = EI_{mat} - (EI_{energy,before} - Ei_{nenergy,after})$$

Eq. 13

Where:

- EI_{reno}: Environmental impact of the renovation
- EI_{mat}: Environmental impact of the materials added during the renovation
- $EI_{energy,\ before}$: Environmental impact of the energy consumed before the renovation
- $EI_{energy,after}$: Environmental impact of the energy consumed after the renovation

The only kind of operational energy directly linked to the renovated wall is the heating energy used to compensate the thermal losses through the wall. Therefore, only the heating energy will be included in the calculation. It is evaluated using a monthly approach from the SIA 380/1 standard:

$$Qt = U * s * dt * T$$

Eq. 14

Where:

- Qt: Energy lost by transmission through the construction element [Ws] during a particular month
- U: U-Value of the construction element [W/(m².K)]
- S: Surface of the construction element [m²]
- dt: Average temperature difference between indoor and outdoor climates [K] during a particular month
- T: Number of seconds in said month [s]

In agreement with SIA380/1 standard, a constant indoor temperature of 20°C is considered. Monthly meteorological data are extracted from the SIA 2028 technical book in order to evaluate average monthly temperature differences. As discussed in [142], in a real building the energy lost by heat transmission (Qt) through the wall is compensated by the energy provided by the heating system (Qh), but also by the internal and solar gains. Therefore, there are two approaches to evaluate Qh:

- When the context is clearly defined (all building parameters known), Qh = Qt * K, where K is a factor depending on solar & internal gains, thermal and ventilation performance. It can be calculated by performing a full SIA380/1 thermal balance of the building;

- When a single construction element is analysed and not all detailed information about the building is known, the hypothesis that the heating energy equals the energy lost (Qh = Qt) can be made but should be clearly documented.

In a previous study, the whole building was analysed in detail, in its current state as well as in various renovation scenarios. From this result, K factors between 0.73 (full renovation scenario, including floor, roof & windows) and 0.9 (current state) were observed. Therefore, a K factor of 0.85 (renovation of external walls) and 0.9 (current state) were considered to evaluate the energy provided by the heating system.

The building is heated using natural gas burnt in a modern condensing boiler with a 95% efficiency rate.

Functional unit

As different internal insulation measures will be compared, it is essential that all scenarios have the same thermal performance as well as provide adequate protection against internal moisture. The SIA 380/1 standard offers two ways to evaluate if a building complies with the Swiss thermal performance requirements. The first assesses the global performance of the building envelope. The second method requires that the thermal conductivity of all the construction elements be lower than limit values specific to the element types (wall, floor, roof, window) and their situations (against external, ground). The U-value of walls against the external should be lower or equal than 0.25 (W/m^2*K).

Therefore, the functional unit is the use of materials and energy, over a reference study period of 60 years, related to $1m^2$ of renovated wall, which offers a thermal resistance equivalent to a U-value of 0.25 $W/(m^2*K)$.

Data and tools

Materials and energy LCA data comes from the KBOB LCA recommendations list [31], provided by the Swiss Federal Office of Construction and Logistics. It regroups data coming from the ecoinvent database as well as from various studies performed by LCA experts in Switzerland. In order to be included in the KBOB list, new data must comply with quality requirements, which include independent third-party peer-review by LCA reviewers. The KBOB list contains impacts values for manufacturing and eliminating numerous construction materials and technical systems. Material data is usually valid for Europe. In some cases, data comes from studies where Swiss hypotheses were made. Energy data is also provided for the main energy vectors. The scope of energy data is mainly a European scope.

Regarding the insulation products used in this study, manufacturers with Swiss production plants (e.g., Flumroc for Rockwool, Isover for glasswool and Isofloc for cellulose fibre) have commissioned Swiss LCA experts to analyses their production chain in order to determine product-specific LCA data of their products.

The LCA tool used in this study is the Swiss Eco-Sai tool. It includes a user-friendly construction element editor as well as a comprehensive database of construction materials. All insulation products used in this study are directly available in Eco-Sai because their manufacturers are part of the *materialsDB* project [143]. As Eco-Sai includes *materialsDB*, thermal and physical data for these products comes directly from the manufacturers.

Indicators

The following indicators are used in this study. The first two are taken into account in most of the environmental standards available in Switzerland.

- CED_{NRE} [MJ]: non-renewable primary energy. Includes fossil and nuclear energy as well as biomass from primary forests;
- GWP [kg CO2-eq]: global warming potential during a span of 100 years (IPCC 2013 characterization factors). Includes all greenhouse gases emissions (CO2, CH4, N2O, etc.);
- Ecological scarcity 2006 [UBP]: global indicator that quantifies ecological loads resulting from polluting emissions (GHG, heavy metals, carcinogenic or radioactive substances) as well as depletion of energetic and mining resources.

LCA Results

Materials added vs Energy saved

As each variant of the construction elements has the same thermal resistance, the heating energy saved by renovating the facade is also the same. Figure 81 shows the materials related impacts for each renovation solution as well as the impacts of the energy saved.

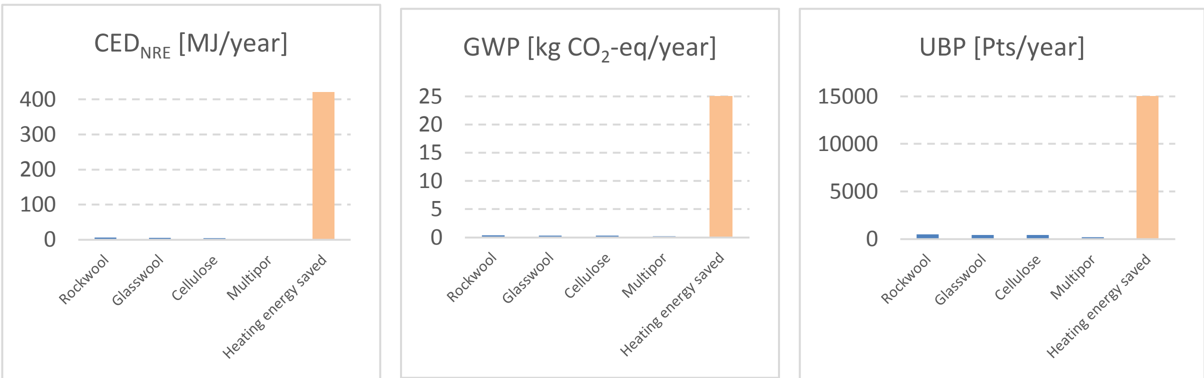


Figure 81 LCA balance of the facade renovation over 30 years

Results presented above are equivocal. Over a reference study period of 60 years, for all three indicators, the heating impacts saved through improving the thermal performance of the facade are much higher than the impacts of the added materials.

The heating system (natural gas boiler) is a fossil fuel-based system and its combustion generates greenhouse gases emissions. It is therefore not the best option from an environmental point of view but it is chosen as this system is still currently found in historic buildings. The heating energy required to compensate losses through the external walls is divided by a factor six after the renovation (from 130 to 20 kWh/year).

Elements comparison

Figure 82 shows the distribution of environmental impacts by material in each construction element.

Globally, in this comparative deterministic LCA, the Multipor variant seems to be the most interesting. CED_{NRE} is between 50% and 61% lower than the other variants. GWP is 31% lower than the rockwool construction, 14% lower than the glasswool variant and only 5% lower than the cellulose one. Among the three other solutions, cellulose offers lower NRE and GWP impacts. Although cellulose insulation has to be thicker (15 cm vs. 12 cm glasswool and 13 cm rockwool) and is slightly denser, manufacturing and elimination impacts per kg for this material are much lower than for the glass/rockwool.

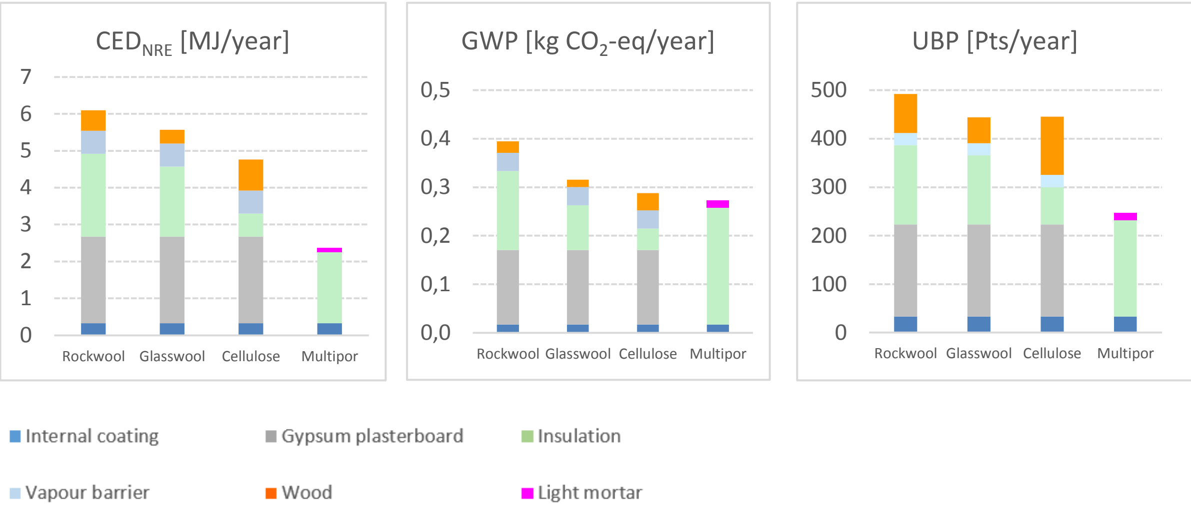


Figure 82 Elements comparison of the four internal insulation solutions for the same functional equivalent

Looking only at the insulation products (green bars), to offer the same thermal resistance, cellulose requires almost three times less non-renewable primary energy than the other insulation materials. It also generates between two and five times less greenhouse gases emissions. The rockwool element's impacts are slightly higher than those of the glasswool construction. This is linked to the extra 2 centimetres required to reach the required thermal performance as well as slightly higher manufacturing impacts for the same volume. Looking now at all the construction materials, the highest contributions comes from the gypsum fibreboard and the insulation products. In the case of the glasswool and cellulose variants, the impacts of the gypsum fibreboard are even higher than the impacts of the insulation, which is quite surprising. That explains why the mulipor variant, which can be directly coated with light mortar, offers better results. In order to lower the total impacts of the three other construction elements, other internal coating solutions should be considered. However, an LCA re-calculation using wooden panels such as OSB instead of gypsum fibreboard does not improve the results. The possibility of using higher density for glasswool or rockwool directly coated with a thicker layer of mineral roughcast should also be evaluated[35]. Vapour barrier installation possibilities in such situations would also have to be clarified.

Finally, before going deeper in a probabilistic LCA, we can notice that the gap between the best insulation measure and the others in terms of environmental impacts depends on the indicator.

[35] These possibilities have not been assessed so far

Taking aside the multiport variant, the three other elements are very closed for the total environmental impacts indicator (rockwool is 10% higher than cellulose), the differences are higher for the GWP indicator between the best and the worst measure (e.g. 28% between cellulose and multiport). The CED_{NRE} indicator has results' differences of 37% between cellulose and rockwool.

So given that the different uncertainty sources (materials impacts, production processes, transport distances, etc.), it seems that the robustness of the results are probably easier to reach for the GWP than for the total environmental impacts (where taking into account the uncertainties could lead to a ranking inversion). For checking the reliability and robustness of this comparative LCA, the calculations should be done using a probabilistic LCA methodology.

Influence of building life cycle stages

Figure 83 shows the distribution of environmental impacts by life cycle stage for each construction element.

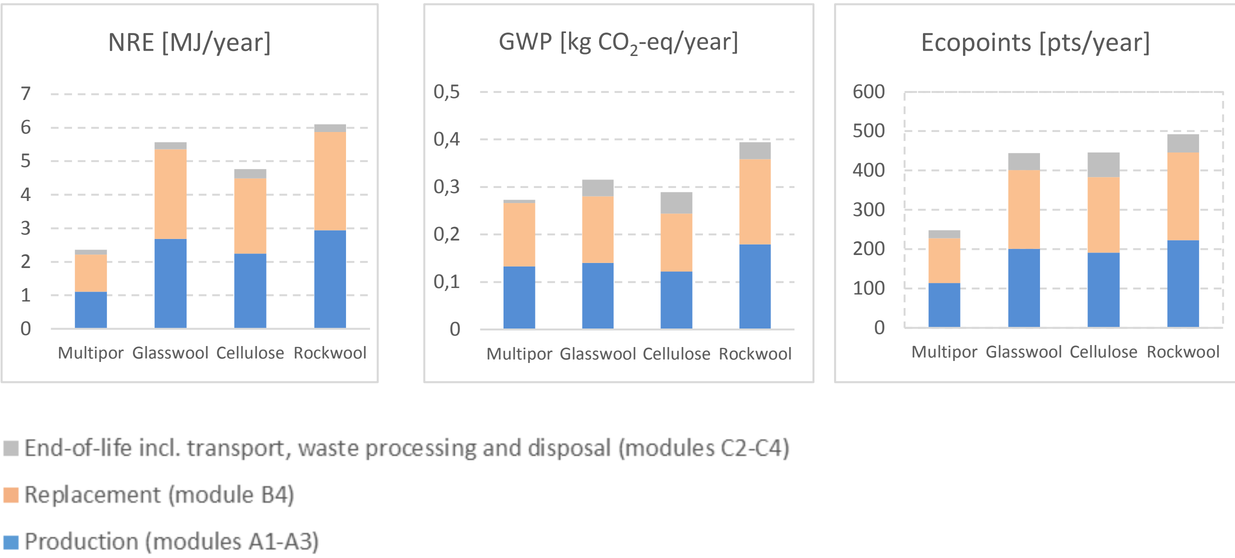


Figure 83 LCA results breakdown per life cycle stages of the four internal insulation solutions for the same functional equivalent

Results show that replacement phase impacts (module B4 in EN 15804) equal production impacts because all the materials added during the renovation process have a lifespan of 30 years. Therefore, each has to be replaced once during the building lifetime considered here (60 years study period). The impacts linked to the end-of-life phase are always lower than the production stage. Between 4 and 6% of the total non-renewable primary energy impacts come from that particular phase. These percentages usually higher for GWP (3-16%) and UBP (8-14%) as elimination processes such as incineration generate meaningful emissions.

Sensitivity analysis

No sensitivity analysis has been conducted for this comparative LCA: However, it is possible to discuss the results according to the main assumptions and parameters used for this study. First of all, results would be different if we modify the building lifetime from 60 to 30 years (and even lower). In this case, no replacement would occur and the impacts would drop. Similarly, if an insulation material like EPS or XPS would be considered in the exercise, results for the End-of-life would rise as the EoL of EPS or XPS are known to be as important as their manufacturing impacts.

Conclusion

The deterministic LCA showed that the Multipor variant generates much lower impacts than the three other solutions considered in this study. This is mainly related to the fact that it doesn't require a plasterboard or wood panel on the inside to close the system. It can be directly coated with mineral roughcast. Among the three other internal insulation systems, cellulose fibre seems to be a good compromise as it reduces CED_{NRE} by respectively 14 and 22% and GWP by 9 and 29% compared to a glasswool or rockwool solution. The glasswool construction element has lower environmental impacts that its rockwool counterpart. Rockwool is a little heavier and therefore manufacturing impacts by cubic meter are slightly disfavoured. Furthermore, a few additional centimetres are required to reach the same thermal performance.

Finally, as sometimes the differences of impacts in the ranking of insulation materials are small (e.g., for the total environmental impacts), it becomes relevant to re-do this exercise using a probabilistic approach taking into account all the relevant uncertainty sources e.g. in the production processes of materials and energy carrier to assess whether it is possible to identify a best alternative between several internal insulation measures.

Italian case study

This section presents the "deterministic" life cycle assessment (LCA) of four internal insulation solutions, among the most representative of the Italian market, on an Italian historic building. The analysis is performed at two different levels:

- **Whole building level.** The whole building interaction with the external environment is considered in the analysis. The calculation of the energy use for space heating has been performed considering the heat losses due to transmission and ventilation and the heat gains through all the building components, according to the national methodology (UNI TS 11300) based on EN ISO 13790. The energy consumption during the use phase has been calculated for the whole building before and after the wall internal insulation measure.

- **Component level**. Only the interaction between the internal insulation system and the external environment is considered in the analysis. The energy consumption of the use phase due to the insulation measure is determined only by considering the heat losses due to transmission exchange between the wall and the external environment.

The study has been performed according to the procedures and principles described in the ISO 14040 and 14044.

Case building description

The main characteristics of the insulation measures (in the following called "design options") are illustrated in the tables from Table 71 to Table 74. The options 1 and 2 are "on site composite insulating boards", i.e. insulation boards combined with an external rigid layer (plasterboard). The insulation boards are bonded on the internal wall surface with a specific metal frame. The option 3 and 4 consist on insulation boards finished by plaster (a technology similar to ETICS - External Thermal Insulation Composite Systems - commonly used for external insulation of buildings).

Table 71 Design option 1: Rockwool mat insulating material

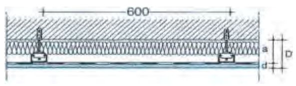
Layer	**Thickness (m)**	**Density (kg/m^3)**	**Thermal conductivity (W/mK)**		 D (mm)
Plasterboard	0,0125	760	0,20		
Vapour barrier	0,00008	416	220		
Rockwool insulating material	0,10	70	0,033		

Table 72 Design option 2: Woodwool insulating material (low density)

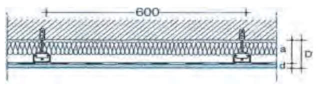
Layer	**Thickness (m)**	**Density (kg/m^3)**	**Thermal conductivity (W/mK)**		 D (mm)
Plasterboard	0,0125	760	0,20		
Vapour barrier	0,00008	416	220		
Woodwool insulating material	0,12	110	0,038		

Table 73 Design option 3: XPS insulating material

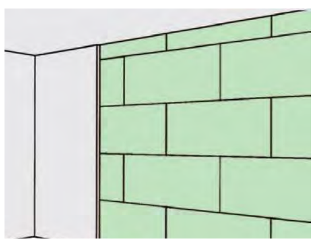
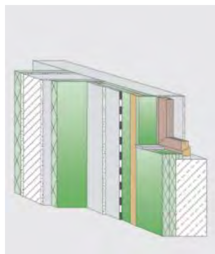
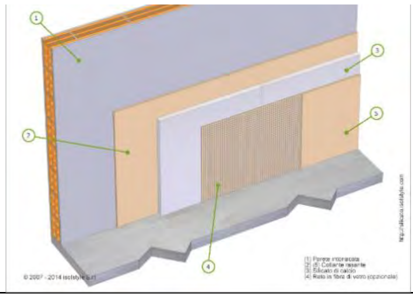
Layer	**Thickness (m)**	**Density (kg/m^3)**	**Thermal conductivity (W/mK)**		
Plasterboard	0,015	1400	0,7		
XPS insulating material	0,10	30	0,035		

Table 74 Calcium Silicate insulating material

Layer	Thickness (m)	Density (kg/m^3)	Thermal conductivity (W/mK)	
Plaster	0,010	1400	0,7	
Microporous Calcium Silicate insulating material	0,18	1000	0,035	

LCA assumptions (goal and scope, reference study period, System boundaries, functional unit, data and tools, indicators)

The goal of this preliminary "deterministic" LCA is to identify the main environmental hotspots of internal insulation measures realized in a historic Italian building. The primary function of the insulation intervention is to reduce heat dispersions through walls with the objective to optimize the building energy performance.

The **functional unit** is defined as the insulation intervention (realized with different insulating materials and technologies) needed to cover the envelope area (m^2) providing an average thermal resistance (m^2K/W) for a certain building service life (years). The substitution of damaged parts is not included in this analysis. In the four design options considered in this study, the specific functional units considered are:

- Design option 1: the insulation intervention realized with rockwool mat insulating material needed to cover an area of 197 m^2 providing an average thermal resistance of 0.30 m^2K/W for a service life of 20 years;
- Design option 2: the insulation intervention realized with Wood fibre board insulating material needed to cover an area of 197 m^2 providing an average thermal resistance of 0.30 m^2K/W for a service life of 20 years;
- Design option 3: the insulation intervention realized with extruded polystyrene panel insulating material needed to cover an area of 197 m^2 providing an average thermal resistance of 0.30 m^2K/W for a service life of 20 years;
- Design option 4: the insulation intervention realized with Calcium Silicate board insulating material needed to cover an area of 197 m^2 providing an average thermal resistance of 0.30 m^2K/W for a service life of 20 years.

197m^2 is the total surface area of the building external wall. The reference year for this study is 2016.

Figure 84 Picture of the Italian historic building Casa Graziosi

The study is carried out from cradle to use phase, including: raw materials extraction, transport to manufacturing plant, material production, building use.

Each process of each life cycle phase has been input in the LCA model in terms of input and output. It was decided to set the cut-off criteria at 5% for the inclusion of inputs and outputs in the LCA model, assuming that the inclusion of such data has a very minor effect on the results. All the building construction processes have been neglected, as well as the maintenance and replacement of the insulation solutions, the transport and End of Life phases. Different assumptions have been considered in this study, for the different phases of the life cycle. In particular:

- **Raw material and manufacturing phase**. For all the materials and for all the related manufacturing processes, the dataset contained in the EcoInvent DB v3.2 has been chosen, trying to be as similar as possible to the real materials and production processes. In following Tables (from Table 77 to Table 80) the details for all the components of the different insulation interventions used in this study will be presented.
- **Use phase**. The thermal transmittance of the insulated envelope has been established according to the Italian law D.M. 26/6/2015 on the building energy efficiency, for the climatic area of Cattolica (RN), where Casa Graziosi is located. In particular:
  - Considering the *Whole building level*: the heating energy demand before and after the internal insulation measure has been calculated through a software based on the Italian calculation standards UNI TS 11300 (based on EN ISO 13790). Natural Gas is the power source for the building heating. Considering the whole building performance, for the four design options, the heating energy demand post-intervention is 25560.8 kWh/year (168.83 kWh/m^2 year); the heating energy demand before intervention is 48149.4 kWh/year (318.03 kWh/m^2 year). The building heated floor area is 151.4 m^2.
  - Considering the *Component level*: the energy demand, due only to the heat transfer by transmission through the building walls, before and after the internal insulation measure has been calculated through the degree-day method (EN ISO 13790, EN ISO 15927). Primary Energy has been obtained considering Natural Gas as the power source for the

building heating. Considering the component level performance, for the four design options, the heating energy demand post-intervention is 3434.7 kWh/year; the heating energy demand before intervention is 20677.1 kWh/year.

Note that the difference between the energy demand before and after the intervention in the two levels is due to the fact that at the component level the solar heat gains are not considered.

Concerning the environmental impact categories, model and indicators, the following Table 75 contains a summary of the assumptions realized.

Table 75 Methods, Impact categories and category indicators applied to the study

Environmental Indicator	Unit []	LCIA Method
Climate change	kg CO2 eq	ReCiPe midpoint (H) V1.11/ (Europe H)
Ozone depletion	kg CFC-11 eq	
Terrestrial acidification	kg SO2 eq	
Freshwater eutrophication	kg P eq	
Marine eutrophication	kg N eq	
Photochemical oxidant formation	kg NMVOC	
Particulate matter formation	kg PM10 eq	
NRE – Non-Renewable Energy (fossil)	kWh	Cumulative Energy Demand (CED)
RE – Renewable Energy (biomass, wind, solar, water, etc.)	kWh	
Human health	Pt	ReCiPe endpoint (H) V1.11/ (Europe H/A)
Ecosystem	Pt	
Resources	Pt	

Life cycle inventory analysis

The Life Cycle Inventory (LCI) analysis provides a catalogue and a quantification of the energy and materials used as well as the environmental releases included in the system boundaries and associated with the product system under study. The data collection has been carried out using the following approaches:

- Data collection sheets for the insulation intervention planned;
- Literature analysis;
- EPD for the Microporous Calcium Silicate insulation material;
- Data related to material quantity, manufacturing processes needed to produce the insulation materials and energy consumption have been gathered in order to analyse the environmental impact related to the insulation interventions under study. The background system is represented by data related to extraction of raw material and their manufacturing processes, energy distribution and generation plants, and it includes secondary data, obtained from the literature available on the web and from commercial database, since it is assumed that markets related to these processes can be considered homogenous.
- The foreground system includes specific data from the product system. In particular, information about physical characteristics of the materials used in the insulation intervention analysed.

In Table 76, the type of data collected are represented.

Table 76 Foreground and background systems and data characteristics.

Life cycle stage	Data system	Type of data
Raw material extraction	*Background*	Secondary data (LCA database)
Materials and semi-finished parts manufacturing	*Background*	Secondary data (LCA database)
Use phase	*Foreground*	Primary data

All the background datasets (energy consumption, raw materials, manufacturing processes) have been retrieved from the EcoInvent v.3.2 database founded by institutes of the ETH Domain and the Swiss Federal Offices. The SimaPro v.8 software has been used to create the LCA model and calculate its environmental impact.

Components and Materials

The four design options are described in detail by presenting all the components and the materials which constitute each intervention (from Table 77 to Table 80).

Table 77 Materials for Design option 1 (1 m^2)

Name	Quantity	Material	Weight (kg)
C shape 50x15x0,6	2 m	Steel	0,754
U shape 15x30x0,6	0,7 m	Steel	0,198
Plasterboard 0,0125	1 m^2	Plasterboard	9,5
Rockwool insulating material	**1 m^2**	**Rockwool**	**7**
Vapour barriers	1 m^2	Aluminium	0,405
Adhesive tape	Neglected	Neglected	Neglected
Screw	1,5	Steel	0,12
Hook	2	Steel	0,075
Screw	14	Steel	0,138
Paper Tape	1,4 m		
Stucco	0,35 kg		0,35
First acrylic paint	0,15 kg		0,15
Paint	0,15 kg		0,15

Table 78 Materials for Design Option 2 (1 m^2)

Name	Quantity	Material	Weight (kg)
C shape 50x15x0,6	2 m	Steel	0,754
U shape 15x30x0,6	0,7 m	Steel	0,198
Plasterboard 0,0125	1 m^2	Plasterboard	9,5
Wood fibre board insulating material	**1m^2**	**Woodwool**	**13,80**
Vapour barriers	1 m^2	Aluminim	0,405
Adhesive tape	Neglected	Neglected	Neglected
Screw	1,5	Steel	0,12
Hook	2	Steel	0,075
Screw	14	Steel	0,138
Paper Tape	1,4 m		
Stucco	0,35 kg		0,35
First acrylic paint	0,15 kg		0,15
Paint	0,15 kg		0,15

Table 79 Materials for Design Option 3 (1 m^2)

Name	Quantity	Material	Weight (kg)
Adhesive	0,01 m		3,5
XPS panel insulating material	**1 m^2**	**XPS**	**3**
Plaster	0,010 m		14
Glass fibre mesh	-		-
Plaster	0,005 m		7
First acrylic paint	0,15 kg		0,15
Paint	0,15 kg		0,15

Table 80 Materials for Design Option 4 (1 m^2)

Name	Quantity	Material	Weight (kg)
Adhesive	0,01 m		3,5
Calcium Silicate board insulating material	**1 m^2**	**Calcium Silicate**	**43,2**
Plaster	0,010 m		14
Glass fibre mesh	-		-
Plaster	0,005 m		7
First acrylic paint	0,15 kg		0,15
Paint	0,15 kg		0,15

Table 81 contains the list of Components, materials, production processes and relative dataset utilized in the inventory phase and related to the four design options.

Table 81 List of Components, materials, production processes and relative dataset utilized in the inventory phase

Components	*Mass (kg)*	*N. of pieces*	*Material name in SimaPro 8*	*Production process in SimaPro 8*	*Dataset source*
C shape 50x15x0,6	***149***	***1***	***Steel, low-alloyed, hot rolled {GLO}| market for | Alloc Rec, U***	***Zinc coat, pieces {GLO}| market for | Alloc Rec, U***	***EcoInvent v3.2***
U shape 15x30x0,6	***39***	***1***	***Steel, low-alloyed, hot rolled {GLO}| market for | Alloc Rec, U***	**-**	***EcoInvent v3.2***
Plasterboard 0,0125	***1870***	***1***	***Gypsum plasterboard {GLO}| market for | Alloc Rec, U***	**-**	***EcoInvent v3.2***
Rockwool insulating material	***1380***	***1***	***Rock wool, packed {GLO}| market for | Alloc Rec, U***	**-**	***EcoInvent v3.2***
Vapour barriers	***79.8***	***1***	***Aluminium alloy, AlMg3 {GLO}| market for | Alloc Rec, U***	***Sheet rolling, aluminium {GLO}| market for | Alloc Rec, U***	***EcoInvent v3.2***
Adhesive tape	**-**	**-**	***Neglected-***	**-**	**-**
Screw	***23.6***	***1***	***Steel, low-alloyed {GLO}| market for | Alloc Rec, U***	**-**	***EcoInvent v3.2***

Hook	***14.8***	***1***	***Steel, low-alloyed {GLO}| market for | Alloc Rec, U***	***Zinc coat, pieces {GLO}| market for | Alloc Def, S***	***EcoInvent v3.2***
Screw	***27.2***	***1***	***Steel, low-alloyed {GLO}| market for | Alloc Rec, U***	-	***EcoInvent v3.2***
Tape	-	-	Neglected	-	-
Stucco	***68.9***	***1***	***Stucco {GLO}| market for | Alloc Rec, U***	-	***EcoInvent v3.2***
Base for paint	***29.5***	***1***	***Acrylic varnish, without water, in 87.5% solution state {GLO}| market for | Alloc Rec, U***	-	***EcoInvent v3.2***
Paint	***29.5***	***1***	***Alkyd paint, white, without solvent, in 60% solution state {GLO}| market for | Alloc Rec, U***	-	***EcoInvent v3.2***
Wood fibre insulating material	***197***	***1***	***Wood wool {GLO}| market for | Alloc Rec, U***	-	***EcoInvent v3.2***
Adhesive	***690***	***1***	***Adhesive mortar {GLO}| market for | Alloc Rec, U***	-	***EcoInvent v3.2***
XPS panel insulating material	***591***	***1***	***Polystyrene, extruded {GLO}| market for | Alloc Rec, U***	-	***EcoInvent v3.2***
Plaster	***4140***	***1***	***Cover plaster, mineral {GLO}| market for | Alloc Rec, U***	-	***EcoInvent v3.2***
Glass fibre mesh	-	-	Neglected	-	-
Calcium Silicate board insulating material	***1060***	***1***	***Calcium Silicate Board***	-	***EcoInvent v3.2***
Top coat plaster	***6900***	***1***	***Cover plaster, mineral {GLO}| market for | Alloc Rec, U***	-	***EcoInvent v3.2***
Plaster	***1970***	***1***	***Cover plaster, mineral {GLO}| market for | Alloc Rec, U***	-	***EcoInvent v3.2***

Use phase

As already explained, the life cycle analysis and the interpretation phase have been performed considering two different levels: the building level and the component level. The main difference concerns the use phase, i.e. the method to calculate the energy demand due to the insulation measure.

At the *whole building level*, the energy demand for heating of the whole building has been calculated before and after insulation measure, and it includes the heat losses also due to ventilation or through other building components, as windows, slabs, etc…

At the *component level*, the energy demand for heating only due to the insulation intervention has been considered (so only the heat losses due to the heat transmission through the walls have been considered).

The calculation methodologies have been specified before. Table 82 contains data related to the use phase considering the building level. In particular, for the four design options the building energy demand after intervention is 25560.8 kWh and it is assumed that this demand is covered by the use of natural gas as energy vector. Furthermore, the following assumptions have been considered:

- Yearly energy demand: 25560,8 kWh/year;
- Building life cycle: 20 years;
- Insulation intervention durability: 20 years
- Internal wall surface: 197 m2
- Number of insulation intervention: 1 (no failure)

Table 82 data related to the building use phase

Name	Process in SimaPro 8	Amount [kWh]
Life cycle building	Heat, central or small-scale, natural gas {Europe without Switzerland}| market for heat, central or small-scale, natural gas | Alloc Rec, U	25560.8

Table 83 contains data related to the use phase considering the component level. In particular, for the four design options, the building energy demand is 3434.7 kWh and it is assumed that this demand is covered by the use of natural gas as energy vector. Furthermore, the following assumptions have been considered:

- Yearly energy demand: 3434.7 kWh/year;
- Building life cycle: 20 years;
- Insulation intervention durability: 20 years
- Internal wall surface: 197 m2
- Number of insulation intervention: 1 (no failure)

Table 83 data related to the building use phase

Name	Process in SimaPro 8	Amount [kWh]
Life cycle component	Heat, central or small-scale, natural gas {Europe without Switzerland}| market for heat, central or small-scale, natural gas | Alloc Rec, U	3434.7

Transport

In this study only the transport associated to raw materials and included into the EcoInvent DB (market for datasets) is included. All the other transports have been neglected.

Life cycle impact assessment (LCIA)

Different Life Cycle Impact Assessment Methods (LCIA) have been selected in order to calculate the environmental indicators previously defined. In the following table (Table 84) the list of the environmental indicators selected for this study, as well as the related LCIA methods have been reported.

Table 84 LCIA methods used for the analysis

Environmental Indicator	Unit []	LCIA Method
Climate change	kg CO2 eq	ReCiPe midpoint (H) V1.11/ (Europe H)
Ozone depletion	kg CFC-11 eq	
Terrestrial acidification	kg SO2 eq	
Freshwater eutrophication	kg P eq	
Marine eutrophication	kg N eq	
Photochemical oxidant formation	kg NMVOC	
Particulate matter formation	kg PM10 eq	
NRE – Non-Renewable Energy (fossil)	kWh	Cumulative Energy Demand (CED)
RE – Renewable Energy (biomass, wind, solar, water, etc.)	kWh	
Human health	Pt	ReCiPe endpoint (H) V1.11/ (Europe H/A)
Ecosystem	Pt	
Resources	Pt	

Characterisation

Results from the *material phase* and the *use phase*, according to the system boundaries previously defined, are shown fromTable 85 to Table 88 and graphically from Figure 85 to Figure 86.

Table 85 Characterized LCIA results for 1st design option (Rockwool mat insulating material)

Environmental Indicator	Unit []	Material phase	Use phase (building level)	Use phase (component level)
Climate change	kg CO2 eq	4763.1	136544.5	18348.1
Ozone depletion	kg CFC-11 eq	0.00033	0.00801	0.00108
Terrestrial acidification	kg SO2 eq	34.2	414.5	55.7
Freshwater eutrophication	kg P eq	0.5	0.9	0.1
Marine eutrophication	kg N eq	1.1	3.7	0.5
Photochemical oxidant formation	kg NMVOC	20.8	173.4	23.3
Particulate matter formation	kg PM10 eq	13.8	98.7	13.3
NRE – Non-Renewable Energy	[kWh]	15586.7	608854.8	81808.1
RE – Renewable Energy	[kWh]	1952.0	3287.7	441.7
Human health	[DALY]	0.010	0.220	0.030
Ecosystem	[species*yr]	0.00005	0.00112	0.00015
Resources	[$]	302.94	7919.02	1064.11

Table 86 Characterized LCIA results for 2nd design option (Woodfibre board insulation material)

Environmental Indicator	Unit []	Material phase	Use phase (building level)	Use phase (component level)
Climate change	kg CO2 eq	2759.5	136544.5	18348.1
Ozone depletion	kg CFC-11 eq	0.00021	0.00801	0.00108
Terrestrial acidification	kg SO2 eq	18.9	414.5	55.7
Freshwater eutrophication	kg P eq	0.3	0.9	0.1
Marine eutrophication	kg N eq	0.8	3.7	0.5
Photochemical oxidant formation	kg NMVOC	11.5	173.4	23.3
Particulate matter formation	kg PM10 eq	8.7	98.7	13.3
NRE – Non-Renewable Energy	[kWh]	8651.8	608854.8	81808.1
RE – Renewable Energy	[kWh]	1699.8	3287.7	441.7
Human health	[DALY]	0.010	0.220	0.030
Ecosystem	[species*yr]	0.00003	0.00112	0.00015
Resources	[$]	202.78	7919.02	1064.11

Table 87 Characterized LCIA results for 3rd design option (XPS panel insulation material)

Environmental Indicator	Unit []	Material phase	Use phase (building level)	Use phase (component level)
Climate change	kg CO2 eq	8673.7	136544.5	18348.1
Ozone depletion	kg CFC-11 eq	0.10782	0.00801	0.00108
Terrestrial acidification	kg SO2 eq	21.0	414.5	55.7
Freshwater eutrophication	kg P eq	0.2	0.9	0.1
Marine eutrophication	kg N eq	1.0	3.7	0.5
Photochemical oxidant formation	kg NMVOC	17.4	173.4	23.3
Particulate matter formation	kg PM10 eq	9	98.7	13.3
NRE – Non-Renewable Energy	[kWh]	22868.9	608854.8	81808.1
RE – Renewable Energy	[kWh]	1011.1	3287.7	441.7
Human health	[DALY]	0.020	0.220	0.030
Ecosystem	[species*yr]	0.00008	0.00112	0.00015
Resources	[$]	314.73	7919.02	1064.11

Table 88 Characterized LCIA results for 4th design option (Calcium silicate board insulation material)

Environmental Indicator	Unit []	Material phase	Use phase (building level)	Use phase (component level)
Climate change	kg CO2 eq	4031.1	136544.5	18348.1
Ozone depletion	kg CFC-11 eq	0.00042	0.00801	0.00108
Terrestrial acidification	kg SO2 eq	18.9	414.5	55.7
Freshwater eutrophication	kg P eq	0.2	0.9	0.1
Marine eutrophication	kg N eq	1.0	3.7	0.5
Photochemical oxidant formation	kg NMVOC	13.0	173.4	23.3
Particulate matter formation	kg PM10 eq	8.2	98.7	13.3
NRE – Non-Renewable Energy	[kWh]	13798.6	608854.8	81808.1
RE – Renewable Energy	[kWh]	1766.7	3287.7	441.7
Human health	[DALY]	0.008	0.220	0.030
Ecosystem	[species*yr]	0.00004	0.00112	0.00015
Resources	[$]	194.00	7919.02	1064.11

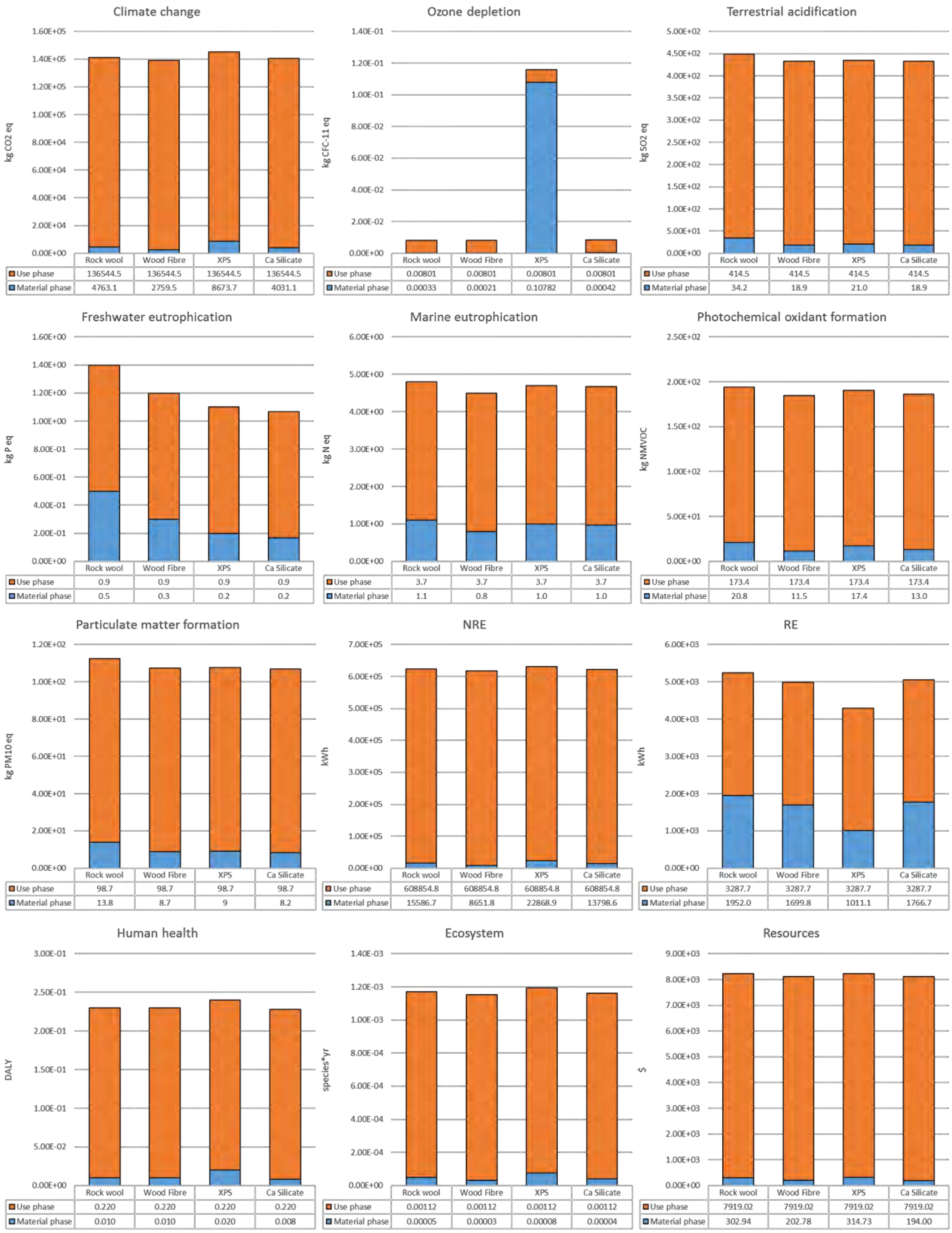


Figure 85 Life cycle analysis and comparison of the four design options for the selected environmental indicators considering the whole building level (use phase building)

Figure 86 Life cycle analysis and comparison of the four design options for the selected environmental indicators considering the components level (use phase component)

Normalization

Normalization is an optional step according to the ISO 14040 standards. However, normalization adds the benefits of placing the characterized impact indicator results in a broader context. It is expressed in a way that allows the impact indicators to be compared to each other, such that, the sum of each category indicator result is divided by a reference value according to the following equation: $N_k = S_k / R_k$, where k denotes the impact category, N is the normalized indicator, S is the category indicator from the characterization phase and R is the reference value, or the normalization factor. The normalization factors are usually chosen to represent the real or potential magnitude of the corresponding impact category for a geographic area and over a certain time span. An example for a reference value is the annual national USA contribution to climate change in terms of CO2 emission.

Results from the characterization have been normalized through the use of the specific LCIA method (ReCiPe midpoint, ReCiPe endpoint and CED). In this way, it is possible to highlight and to compare the magnitude of environmental load generated in the entire life cycle of the analysed insulation systems (design options), respect to a certain value that is meant as reference. The normalization process allows the user to make comparison among different impact categories within the study and to identify the most relevant ones.

Life cycle interpretation

In this paragraph, results from characterization are interpreted and analysed. Contributions from each life cycle stage, from each process, from each elementary flow have been investigated through a contribution analysis. Furthermore, normalization values have been analysed in order to identify which impact category is relevant for the study considering a reference value. It is expressed in a way that allows the impact indicators to be compared to each other. The normalization phase pointed out how impact categories of *Climate Change*, *Terrestrial acidification*, and *NRE* are the most relevant for this study.

Life cycle analysis based on whole building simulation

Results obtained have highlighted that the environmental load for each internal insulation design option of Casa Graziosi building is heavily affected by the use phase. This trend is the same for all environmental indicators detailed in the LCIA phase, with small differences in terms of percentage rate. As example, herein below (from Table 89 toTable 92) are reported the most relevant environmental parameters and the related share (%) considering the material phase on the whole building life cycle (tot.).

Table 89 Rockwool mat insulation material life cycle analysis (whole building level)

Design option #1 - Rockwool mat insulation					
Environmental Indicator	**Unit []**	**Material phase**	**Use phase**	**Tot.**	**Share [material / tot.]**
Climate change	kg CO2 eq	4763.1	136544.5	141307.6	3%
Terrestrial acidif.	kg SO2 eq	34.2	414.5	448.7	8%
NRE	[kWh]	15586.7	608854.8	624441.5	2%

Table 90 Woodfibre board insulation material life cycle analysis (whole building level)

Design option #2 - Woodfibre board insulation					
Environmental Indicator	**Unit []**	**Material phase**	**Use phase**	**Tot.**	**Share [material / tot.]**
Climate change	kg CO2 eq	2759.5	136544.5	139304	2%
Terrestrial acidif.	kg SO2 eq	18.9	414.5	433.4	4%
NRE	[kWh]	8651,.8	608854.8	617506.6	1%

Table 91 XPS panel insulation material life cycle analysis (whole building level)

Design option #3 - XPS panel insulation					
Environmental Indicator	**Unit []**	**Material phase**	**Use phase**	**Tot.**	**Share [material / tot.]**
Climate change	kg CO2 eq	8673.7	136544.5	145218.2	6%
Terrestrial acidif.	kg SO2 eq	21	414.5	435.5	5%
NRE	[kWh]	22868.9	608854.8	631723.7	4%

Table 92 Calcium silicate board insulation material life cycle analysis (whole building level)

Design option #4 - Calcium silicate board insulation					
Environmental Indicator	**Unit []**	**Material phase**	**Use phase**	**Tot.**	**Share [material / tot.]**
Climate change	kg CO2 eq	4031.1	136544.5	140575.6	3%
Terrestrial acidif.	kg SO2 eq	18.9	414.5	433.4	4%
NRE	[kWh]	13798.6	608854.8	622653.4	2%

For the all analysed design options this share is approx.:

- from 2% to 6% considering the Climate change indicator [kg CO2 eq].
- from 4% to 8% considering the Terrestrial acidification indicator [kg SO2 eq].
- from 1% to 4% considering the NRE – Non Renewable Energy indicator [kWh].

Life cycle analysis based on component scale

Results obtained have highlighted that the **environmental load** for each internal insulation design option of *Casa Graziosi* building **is affected by both material phase and use phase**. This trend is the same for all environmental indicators detailed in the LCIA phase, with small differences in terms of percentage rate. As example, herein below (from Table 93 to Table 96) are reported the most relevant environmental parameters and the related share (%) considering the material phase on the whole building life cycle (tot.).

Table 93 Rockwool mat insulation material life cycle analysis (component level)

Design option #1 - Rockwool mat insulation					
Environmental Indicator	**Unit []**	**Material phase**	**Use phase**	**Tot.**	**Share [material / tot.]**
Climate change	kg CO2 eq	4763.1	18348.1	23111.2	21%
Terrestrial acidif.	kg SO2 eq	34.2	55.7	89.9	38%
NRE	[kWh]	15586.7	81808.1	97394.8	16%

Table 94 Woodfibre board insulation material life cycle analysis (component level)

Design option #2 - Woodfibre board insulation					
Environmental Indicator	**Unit []**	**Material phase**	**Use phase**	**Tot.**	**Share [material / tot.]**
Climate change	kg CO2 eq	2759.5	18348.1	21107.6	13%
Terrestrial acidif.	kg SO2 eq	18.9	55.7	74.6	25%
NRE	[kWh]	8651.8	81808.1	90459.9	10%

Table 95 XPS panel insulation material life cycle analysis (component level)

Design option #3 - XPS panel insulation					
Environmental Indicator	**Unit []**	**Material phase**	**Use phase**	**Tot.**	**Share [material / tot.]**
Climate change	kg CO2 eq	8673.7	18348.1	27021.8	32%
Terrestrial acidif.	kg SO2 eq	21	55.7	76.7	27%
NRE	[kWh]	22868.9	81808.1	104677	22%

Table 96 Calcium silicate board insulation material life cycle analysis (component level)

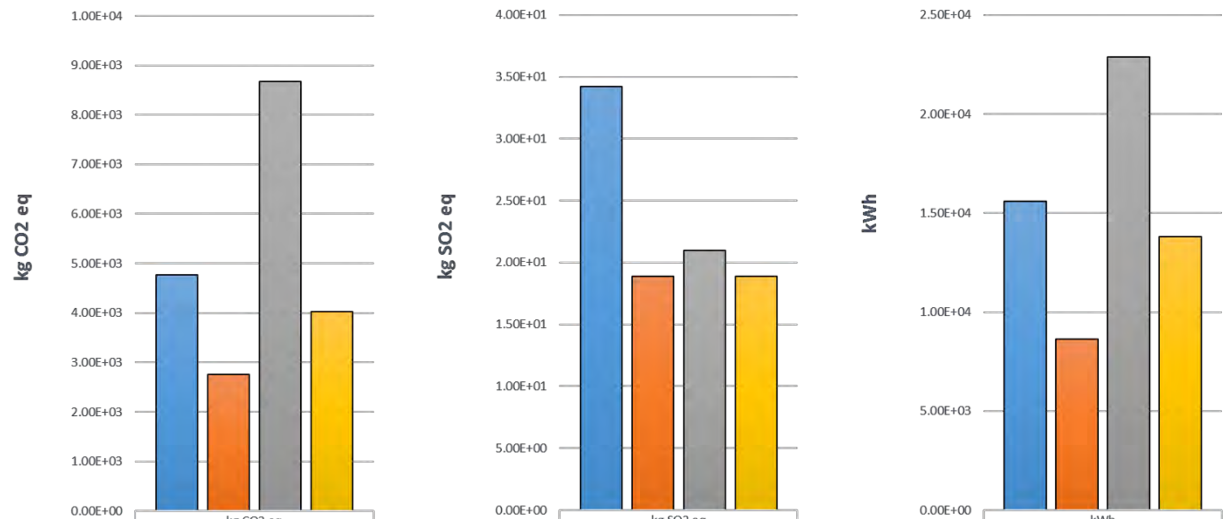
Design option #4 - Calcium silicate board insulation					
Environmental Indicator	**Unit []**	**Material phase**	**Use phase**	**Tot.**	**Share [material / tot.]**
Climate change	kg CO2 eq	4031.1	18348.1	22379.2	18%
Terrestrial acidif.	kg SO2 eq	18.9	55.7	74.6	25%
NRE	[kWh]	13798.6	81808.1	95606.7	14%

For the all analysed design options this share is approx.:

- from 13% to 32% considering the Climate change indicator [kg CO2 eq].
- from 25% to 38% considering the Terrestrial acidification indicator [kg SO2 eq].
- from 14% to 25% considering the NRE – Non Renewable Energy indicator [kWh].

Material phase analysis

It is important to highlight that the environmental contribution of the use phase is the same for each design option because the energy performance has been established as a mandatory target for the considered building (it depends on the envelope thermal transmittance limit imposed by the Italian law). Therefore, after this first analysis considering the entire life cycle, a more detailed analysis focused only on the *material phase* has been carried out to compare different design options and to identify hot-spots and criticalities.



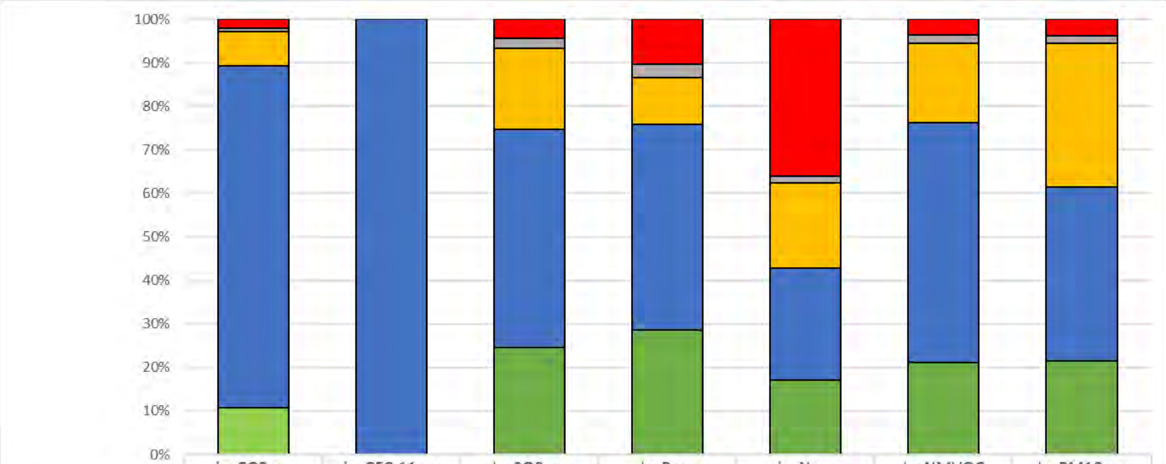
	kg CO2 eq
Rock wool mat	4763.1
Wood fibre board	2759.5
XPS panel	8673.7
Calcium Silicate board	4031.1

	kg SO2 eq
Rock wool mat	34.2
Wood fibre board	18.9
XPS panel	21
Calcium Silicate board	18.9

	kWh
Rock wool mat	15586.7
Wood fibre board	8651.8
XPS panel	22868.9
Calcium Silicate board	13798.6

Figure 87 Climate change, Terrestrial acidification and Non Renewable Energy indicators comparison for the four design options considering the only material phase

The Figure 87 clearly highlights how the XPS panel insulation is the most critical compared with the other thermal insulation design options in terms of environmental impacts considering the only *material phase*. As an example, here below is reported the specific analysis for the XPS panel insulation technology including all the materials involved. Figure below (Figure 88) summarized the contribution of each material for the selected impact categories.



	kg CO2 eq	kg CFC-11 eq	kg SO2 eq	kg P eq	kg N eq	kg NMVOC	kg PM10 eq
Paint	177.54	0.00	0.93	0.02	0.34	0.64	0.35
Base_for_paint	78.10	0.00	0.46	0.01	0.01	0.31	0.16
Cover_plaster	683.48	0.00	3.95	0.02	0.19	3.17	2.98
XPS_panels	6802.85	0.11	10.53	0.09	0.24	9.59	3.61
Adhesive_mortar	931.69	0.00	5.17	0.05	0.16	3.68	1.94

Figure 88 XPS panel insulation technology environmental impacts

In this example, *XPS_panels* have the higher contribution in terms of environmental impacts in each one of the selected environmental impact.

Conclusions

The main conclusions are reported for the *whole building level* and the *component level analysis*.

Whole building level

As already stated, considering the whole life cycle of four different internal insulation solutions applied in a typical Italian historic building, the **main environmental impact is related to the use phase considering the whole life cycle *building energy demand***. This result is characterized by massive impact in the use phase due to the long calculation period and its relative energy consumption. This trend is similar considering different environmental indicators.

This result could be considered quite "robust" for the fact that, if we consider the internal insulation measure as a "stand-alone" renovation solution, the obtained energy saving for the building will remain quite low. Furthermore, we should consider the fact that only rarely the internal insulation is applied as stand-alone measure for a building renovation. It is more often accompanied by other measures (e.g. the windows or the heating equipment replacement), considering their synergic effects.

It is important to highlight that the environmental load of the use phase for the considered building is the same for each internal insulation design option because the energy consumption is defined as a target for the considered building. Considering this, and assessed the environmental load of the building use phase, the comparison of the four internal insulation interventions could be limited to the *material phase*.

This assumption is well justified especially when the objective of designers is to compare (in environmental terms) different design options able to guarantee the same thermal performance. In this case, stated that the environmental impact of the use phase is the same for different options, the discriminating factor, which can lead the designers' choices, is the material phase impact. For this reason, even if the material phase contributes with a low impact to the total life cycle one, it can't be neglected from the LCA analysis.

The study realized demonstrates that the *Wood fibre board insulation* technology is the most sustainable in terms of environmental performances among the four design options considered, while the *XPS panel insulation* technology is the most critical one.

Component Level

In this case, where the only energy demand is due to the insulation intervention (impact on the heat losses due to transmission), the contribution to the use phase is more limited and the life cycle analysis highlights how the material phase and the use phase are comparable.

The study realized at the component level further demonstrates that the *Wood fibre board insulation* technology is the most sustainable in terms of environmental performances among the four design options considered, while the *XPS panel insulation* technology is the most critical one.

Limitations and recommendations

The performed LCA analysis limits the system boundaries till the use phase and excluded the end-of-life one, due to the lack of data regarding this phase. For the same reasons, this study has also excluded the transport phase, all the building in situ processes, the maintenance and replacement of insulation interventions. Based on these assumptions, further development will foresee the inclusion in the analysis of in situ processes, transport phase, maintenance and replacement in order to evaluate their environmental impacts.

Danish case study

This study is an illustrative example of deterministic life cycle assessment (LCA) of two internal insulation solutions realized on a Danish historic building. These two insulation solutions represent the most commonly applied products in the Danish market. To obtain an overview on the environmental hotspots from various sources, the study evaluates the impact of materials, the energy saving and activities in each life-cycle phase based on the selected insulation interventions.

Case building description

The two stories historic residential building from 1899, located in Thomas Laubs Gade in Copenhagen is selected for this case study. The building has base area of 333 m^2 and total lot size of 614 m2, which is a typical Danish multi-storey residential building from 1890-1930 (Figure 89).

Figure 89 Historic building Thomas Laubs Gade

The analysis focuses on three insulation products typically used for the internal building renovation in Denmark. The main characteristics of these insulation measures (in the following called "design options") are illustrated in Table 97 to Table 99. The options 1 and 2 are solutions with insulation board (glasswool/rockwool) bonded with a specific metal frame or an external plaster board. The option 3 consists of the IQ-therm 50 (form board) combined with plaster and adhesive mortar, which is a technology similar to the external insulation of buildings. The information of material layers in each design option were collected from the manufacturers' products catalogue or the EPDs.

Table 97 Design option 1: Isover glasswool insulation

Layer	Thickness (m)	Density (kg/m^3)	Thermal conductivity (W/mK)
Isover glass wool rolls	0,095	15	0,037
3*Isover Steel Frame Batts (U shape)	0.05	7840	0.032
2*Gyproc wallboard	0,0125	668	0,19
OSB board	0.022	650	0,13

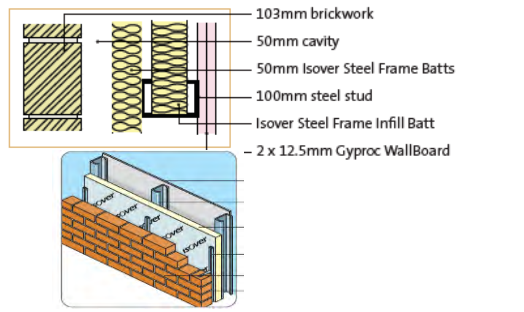


Table 98 Design option 2: Flexibatts 37 rockwool insulation

Layer	Thickness (m)	Density (kg/m^3)	Thermal conductivity (W/mK)
Rockwool Flexi-batts	0.095	30	0.037
Vapour barrier	0,0002	416	220
Egger OSB-3 board	0.022	650	0,13

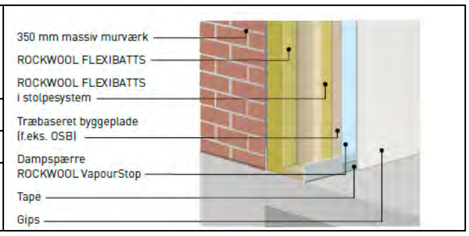
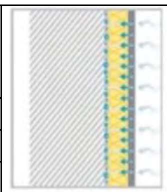


Table 99 Design option 3: IQ-therm 50

Layer	Thickness (m)	Density (kg/m^3)	Thermal conductivity (W/mK)
IQ Fix (adhesive mortar)	0.005	1500	0.497
IQ top (Plaster)	0.01	630	0.11
IQ-therm 50 (form board)	0.05	45	0.031



LCA assumptions (reference study period, System boundaries, functional unit, data and tools, indicators)

The deterministic analysis investigates the environmental impact share of various materials, life-cycle activities, the energy savings and the impact share from different life-cycle phases in each insulation intervention.

The functional unit is defined as the insulation intervention realized with each proposed insulating systems and technologies, to cover the unit area (1 m^2) providing an average thermal resistance (m^2K/W) for a certain service life period (years). The total facade area is 105.5 m^2 and the insulated area 83.1 m^2 takes account of 51.3%, considering the windows 45.24 m^2 takes account of 27.9% and the not insulated area 33.6 m^2 takes 20.7%.

In the three proposed *design options* in this study, the specific functional units are detailed below:

- Design option 1: the insulation intervention realized with glass wool roller insulating material needed to cover an area of 83.1 m^2 providing an average thermal resistance of 1.46 m^2K/W for a service life of 30 years;
- Design option 2: the insulation intervention realized with extruded polystyrene panel insulating material needed to cover an area of 83.1 m^2 providing an average thermal resistance of 1.46 m^2K/W for a service life of 30 years;

- Design option 3: the insulation intervention realized with IQ-therm board insulating material needed to cover an area of 83.1 m^2 providing an average thermal resistance of 1.46 m^2K/W for a service life of 30 years.

The case study scope covers modules A1 to A3, B4, B6 (cradle to gate) based on the definition from EN 15804/EN 15978, to assess the environmental impact of the renovation materials as well as the energy consumption due to the thermal losses before/after the intervention. The study is in line the ISO standards 14040, 14044. Several assumptions have been made through the buildings life cycle, including:

- The manufacturing process is analysed by the dataset from Ecoinvent v3.2, to model the real production process. For each design option, the material layers with negligible impacts are omitted in the analysis (e.g. screws, painting, water, low-emission MUF resin, Paraffin wax emulsion, adhesives etc.).
- Transportation: Only the transportation associated with material manufacturer are considered within the Ecoinvent database. All the other transports are neglected.
- Concerning the allocation, as this study does not involve different products assigned in different processes, therefore no allocation is involved in the analysis.
- Normalization is not applied in the analysis.

Life cycle inventory analysis

The LCI data take account of the material and energy flows as input data, and the associated waste releases as output in each material manufacture process. In this case study, the detailed material data for the three alternative design options are collected from Ecoinvent database V3.2. The material and energy consumption for the initial construction are obtained from the realistic design drawings and recorded project information. The SimaPro software is used for LCA modelling and the calculation of environmental impact categories.

The material manufacture phase

This phase takes accounts of the environmental burden due to the material manufacture, from the raw material mining until obtaining the final products at the factory. A number of raw materials would be processed in this stage and result into the air, water and solid releases. The modelling is performed via the commercial LCI database Ecoinvent v3.2, which provides the unit environmental profile for each material type, including the raw material extraction, sub-material transportation, energy consumption and waste treatment. The following tables details the specification of materials that constituents each design option, including material type, quantity and weight; while the materials with minor environmental impacts are omitted. The environmental impact of these materials due to manufacturing are modelled via SimaPro software based on the ReCiPe method.

Table 100 Materials for design option 1: Isover glasswool insulation

Name	Quantity	Material	Weight (kg)
U shape Steel Frame Batts 15x30x0,6	3	Steel	0.6
2* Gyproc wallboard 0,0125	1 m^2	Plasterboard	16.7
Glass wool insulating material	1 m^2	glasswool	1.4
1.4Egger OSB-3 board	1m^2	soft and hardwood	14.3

Table 101 Materials for design option 2: Flexibatts 37 rockwool insulation

Name	Quantity	Material	Weight (kg)
1.4Egger OSB-3 board	$1m^2$	soft and hardwood	14.3
Vapour barrier	$1\ m^2$	Aluminium	0.405
rockwool Flexi-batts	$1\ m^2$	rockwool	2.85

Table 102 Material for design option 3: IQ-therm 50

Name	Quantity	Material	Weight (kg)
0.005m IQ Fix	$1m^2$	adhesive mortar	7.5
0.01m IQ top	$1\ m^2$	plaster	6.3
0.05m IQ-therm 50	$1\ m^2$	form board	2.25

Use phase

According to EN 15978, the use phase includes B1 to B7 activities. Due to lack of data, this study only considers B4 and B7 at the building level. The analysis takes account of the building heating energy demand before and after the internal insulation measure, which is calculated through the software at Danish Building Research Institute (SBi) based on the Danish calculation standards, and in line with EN ISO 13790. Considering the whole building performance, for the three design options, the heating energy demand before intervention is 31750 kWh/year, while the heating energy demand after intervention is 26099 kWh/year. The building heated surface is 273 m^2 at the building level. The energy source of natural gas and calculation life span of 30 years is assumed in the calculation. No failure on the insulation system during the calculation period.

Table 103 Energy demand for the whole building after insulation

Name	**Process in SimaPro 8**	**Amount [kWh]**	**Amount [MJ]**
Energy demand	Heat, central or small-scale, natural gas {Europe without Switzerland}| market for heat, central or small-scale, natural gas | Alloc Rec, U	26099	93956

The following table contains the list of Components, materials, production processes and relative dataset utilized in the inventory phase.

Table 104 List of Components, materials, production processes and relative dataset utilized in the inventory phase

Components	**Quantity**	**No. of pieces**	**Material name in Ecoinvent**
U shape steel frame batts 15x30x0,6	0,6 kg	1	Steel, low-alloyed, hot rolled {GLO}| market for | Alloc Rec, U
Plasterboard 0,0125m	$1\ m^2$	2	Gypsum wallboard product, regular (12.7 mm)/m2/RNA USLCI
Glass wool board	1.4 kg	1	Glass wool mat {GLO}| market for | Alloc Def, U
Egger OSB-3 board	$0.022\ m^3$	1	Wood wool boards, cement bonded {GLO}| market for | Alloc Def, U
Rockwool	1 m	1	Insulation spiral-seam duct, rockwool, DN 400, 30 mm {GLO}| market for | Alloc Def, U
Vapour barriers	0.405 kg	1	Aluminium alloy, AlMg3 {GLO}| market for | Alloc Rec, U

IQ top/Plaster	6.3 kg	1	Cover plaster, mineral {GLO}| market for | Alloc Rec, U
IQ Fix	7.5 kg	1	Adhesive mortar {GLO}| market for | Alloc Def, U
IQ-therm 50	0.022 m^3	1	Wood wool boards, cement bonded {GLO}| market for | Alloc Def, U

Life cycle impact assessment (LCIA)

In the following table, the list of the environmental indicators selected for this study, as well as the related LCIA methods have been reported.

Table 105 Environmental impact indicators considered in the study (ReCiPe H)

Environmental Indicator	Unit	LCIA Method
Climate change	kg CO2 eq.	ReCiPe midpoint (H)
Ozone depletion	kg CFC-11 eq.	
Terrestrial acidification	kg SO_2 eq.	
Freshwater eutrophication	kg P eq.	
Marine eutrophication	kg N eq.	
Photochemical oxidant formation	kg NMVOC	
Particulate matter formation	kg PM10 eq.	
NRE – Non-Renewable Energy (fossil)	kWh	Cumulative Energy Demand (CED)
RE – Renewable Energy (biomass, wind, solar, water, etc.)	kWh	

Life cycle interpretation

The life cycle analysis and the interpretation phase are performed at the whole building level. The analysis considers the building interaction with the external environment. The energy use for space heating is modelled by considering the heat losses due to transmission and ventilation and the heat gains through the building (wall and floor), according to the Danish regulation based on the European standard EN ISO 13790. The energy consumption during the use phase has been calculated for the whole building before and after the wall internal insulation.

The following tables present the full spectrum of the environmental impact for each design option. The material manufacture phase takes account of ignorable share comparing to the energy consumption in the use phase, for instance, only 0.12% to 0.46% in terms of the climate change indicator.

Table 106 The environmental impact for design option 1: Isover glasswool system

Impact category	Unit	Material manufacture phase	Use phase	Total	Materia l %
Climate change	kg CO2 eq	13,73229	6777,16	5,16E-04	0,18%
Ozone depletion	kgCFC-11 eq	9,32E-07	0,000515	1,72E+01	0,39%
Terrestrial acidification	kg SO2 eq	0,067602	17,17335	3,33E-01	1,17%
Freshwater eutrophication	kg P eq	0,003892	0,329436	2,28E-01	1,51%
Marine eutrophication	kg N eq	0,003453	0,2248	5,55E+02	0,69%
Human toxicity	kg 1,4-DB eq	3,841239	551,3712	7,63E+00	0,61%

Photochemical oxidant formation	kg NMVOC	0,046406	7,583175	4,38E+00	0,79%
Particulate matter formation	kg PM10 eq	0,034418	4,349735	2,92E-01	0,60%
Terrestrial ecotoxicity	kg 1,4-DB eq	0,001761	0,289921	3,36E+01	0,42%
Freshwater ecotoxicity	kg 1,4-DB eq	0,142109	33,41441	1,98E+01	0,69%
Marine ecotoxicity	kg 1,4-DB eq	0,136451	19,70244	1,31E+02	0,56%
Ionising radiation	kBq U235 eq	0,731308	130,2383	3,06E+01	12,40%
Agricultural land occupation	m2a	3,790056	26,77802	5,26E+00	4,36%
Urban land occupation	m2a	0,229436	5,034307	9,63E-01	0,27%
Natural land transformation	m2	0,002561	0,960843	5,89E+00	2,88%
Water depletion	m3	0,16959	5,72091	7,98E+01	5,34%
Metal depletion	kg Fe eq	4,265439	75,57117	2,33E+03	0,15%
Fossil depletion	kg oil eq	3,519681	2323,857	1,08E+05	0,15%
Non renewable, fossil	MJ	158,4613	107964,6	2,03E+03	0,51%
Non-renewable, nuclear	MJ	10,30646	2017,078	5,40E-01	6,73%
Non-renewable, biomass	MJ	0,03636	0,504025	2,12E+02	8,54%
Renewable, biomass	MJ	18,14518	194,2899	1,57E+02	0,34%
Renewable, wind, solar, geotherm	MJ	0,532508	155,996	4,24E+02	1,14%
Renewable, water	MJ	4,83009	419,4109		

Table 107 The environmental impact for design option 2: Flexi 37 rockwool insulation

Impact category	Unit	Material manufacture phase	Use phase	Total	Material %
Climate change	kg CO2 eq	33,17493	6777,16	6810,335	0,49%
Ozone depletion	kg CFC-11 eq	1,72E-06	0,000515	0,000517	0,33%
Terrestrial acidification	kg SO2 eq	0,299038	17,17335	17,47239	1,71%
Freshwater eutrophication	kg P eq	0,013805	0,329436	0,343241	4,02%
Marine eutrophication	kg N eq	0,011135	0,2248	0,235935	4,72%
Human toxicity	kg 1,4-DB eq	18,17344	551,3712	569,5446	3,19%
Photochemical oxidant formation	kg NMVOC	0,109918	7,583175	7,693093	1,43%
Particulate matter formation	kg PM10 eq	0,115762	4,349735	4,465497	2,59%
Terrestrial ecotoxicity	kg 1,4-DB eq	0,003384	0,289921	0,293305	1,15%
Freshwater ecotoxicity	kg 1,4-DB eq	0,495071	33,41441	33,90948	1,46%
Marine ecotoxicity	kg 1,4-DB eq	0,49427	19,70244	20,19671	2,45%
Ionising radiation	kBq U235 eq	1,35275	130,2383	131,5911	1,03%
Agricultural land occupation	m2a	4,750379	26,77802	31,5284	15,07%
Urban land occupation	m2a	0,503627	5,034307	5,537934	9,09%
Natural land transformation	m2	0,006467	0,960843	0,96731	0,67%
Water depletion	m3	0,358872	5,72091	6,079782	5,90%
Metal depletion	kg Fe eq	4,949391	75,57117	80,52056	6,15%
Fossil depletion	kg oil eq	7,069222	2323,857	2330,926	0,30%
Non renewable, fossil	MJ	314,8561	107964,6	108279,5	0,29%
Non-renewable, nuclear	MJ	18,42087	2017,078	2035,499	0,90%
Non-renewable, biomass	MJ	0,065024	0,504025	0,569049	11,43%
Renewable, biomass	MJ	22,80728	194,2899	217,0972	10,51%
Renewable, wind, solar, geotherm	MJ	0,873338	155,996	156,8693	0,56%
Renewable, water	MJ	27,63332	419,4109	447,0442	6,18%

Table 108 The environmental impact for design option 3: IQ therm 50

Impact category	Unit	Material manufacture phase	Use phase	Total	Material %
Climate change	kg CO2 eq	16,21233	6777,16	6793,372	0,24%
Ozone depletion	kg CFC-11 eq	1,39E-06	0,000515	0,000516	0,27%
Terrestrial acidification	kg SO2 eq	0,077727	17,17335	17,25108	0,45%
Freshwater eutrophication	kg P eq	0,00442	0,329436	0,333856	1,32%
Marine eutrophication	kg N eq	0,002739	0,2248	0,227539	1,20%
Human toxicity	kg 1,4-DB eq	4,879466	551,3712	556,2507	0,88%
Photochemical oxidant formation	kg NMVOC	0,056896	7,583175	7,640071	0,74%
Particulate matter formation	kg PM10 eq	0,037109	4,349735	4,386844	0,85%
Terrestrial ecotoxicity	kg 1,4-DB eq	0,001765	0,289921	0,291686	0,61%
Freshwater ecotoxicity	kg 1,4-DB eq	0,198941	33,41441	33,61335	0,59%
Marine ecotoxicity	kg 1,4-DB eq	0,19039	19,70244	19,89283	0,96%
Ionising radiation	kBq U235 eq	0,978704	130,2383	131,217	0,75%
Agricultural land occupation	m2a	4,429185	26,77802	31,20721	14,19%
Urban land occupation	m2a	0,313677	5,034307	5,347984	5,87%
Natural land transformation	m2	0,003648	0,960843	0,964491	0,38%
Water depletion	m3	0,360533	5,72091	6,081443	5,93%
Metal depletion	kg Fe eq	0,707326	75,57117	76,2785	0,93%
fossil depletion	kg oil eq	4,472775	2323,857	2328,33	0,19%
Non renewable, fossil	MJ	200,3525	107964,6	108165	0,19%
Non-renewable, nuclear	MJ	14,98513	2017,078	2032,063	0,74%
Non-renewable, biomass	MJ	0,007333	0,504025	0,511358	1,43%
Renewable, biomass	MJ	20,87598	194,2899	215,1659	9,70%
Renewable, wind, solar, geotherm	MJ	0,571649	155,996	156,5676	0,37%
Renewable, water	MJ	4,612184	419,4109	424,0231	1,09%

Conclusions

This study is a simplified deterministic LCA analysis on three main insulation intervention options in Denmark. The analysis is a preliminary step for the development of the probabilistic LCA approach in the RIBuild Project. The results are reported at the building level, which highlights the impact share among materials and identifies the hotspots during different life phases. The impact from the material manufacture phase was found to be ignorable comparing to the energy consumption during the use phase. It is noted that the environmental impact is the same for all the proposed insulation options during the use phase due to the defined criteria based on the Danish energy regulation. Isover glasswool system was found to be the most favourable option.