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Abstract

This report presents the results of the work performed within WP5 Task 5.3 "Probabilistic Life Cycle Cost (LCC) analysis and Cost-Optimal (CO) levels of minimum energy performance of interior insulation solutions". The report accompanies the WP5 software tool, key part of Deliverable 5.2 that puts into practice the LCC probabilistic methodology developed and paves the way for further developments of the project, i.e. the economic assessment of internal insulation solutions for historical buildings included into the RIBuild guidelines.

Keyword list: Internal Insulation, LCC, Global Cost, Payback period, Macro-economic scenario, Probabilistic Methodology, Monte-Carlo method, Uncertainty Analysis, Sensitivity Analysis.

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Abbreviations

LCC	Life Cycle Costing
LCA	Life Cycle Assessment
LCIA	Life Cycle Impact Assessment
CO	Cost Optimal
TLC	Through-Life Costing
WLC	Whole-Life Costing
TCO	Total Cost of Ownership
NPV	Net Present Value
eLCC	environmental LCC
cLCC	conventional LCC
sLCC	societal LCC
EPD	Environmental Product Declarations
PM	Probabilistic Methodology
MC	Monte Carlo
HAM	Heat, Air and Moisture transfer
HDD	Heating Degree Day
UA	Uncertainty Analysis
SA	Sensitivity Analysis
GC	Global Cost
PB	Payback Period
PDF	Probability Density Function
CDF	Cumulative Density Function
SD	Standard Deviation
cp	Calculation Period
CI	Investment Cost
CE	Energy Cost
CM	Maintenance Cost
CR	Replacement Cost
SL	Service Life
RSL	Reference Service Life
ESL	Estimated Service Life
R	Rate
ETAh	Overall building efficiency for heating
Qh	Heat transmission losses through the wall during the heating period
EnT	Energy Tariff
Val	Final value of insulation system
U	Thermal Transmittance
GDP	Gross Domestic Product
GPSA	Quarterly growth rate of GDP seasonally adjusted
CPI	Consumer Price Indices
INT	Interest Rate

INF	Inflation Rate
RG	Regular Growth
IG	Intense Growth
SG	Stagflation
DE	Deflation
OECD	Organisation for Economic Co-operation and Development
FRED	Federal Reserve Economic Data
EIA	Energy Information Administration
VAT	Value Added Tax
ARIMA	Auto Regressive Integrated Moving Average
VAR	Vector Auto Regression

Executive Summary

This report presents the second of two deliverables related to RIBuild Work Package 5 “Development of cost/benefit and environmental impact assessment methodology based on building practice and intended use”. The main aim of WP5 is to develop a probabilistic methodology for assessing the environmental impacts and global costs of internal insulation solutions for historic buildings based on a life cycle perspective. The work of WP5 can be seen in parallel with the probabilistic methodology developed within RIBuild WP4 in the field of the hygrothermal assessment. ”*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 historical buildings usable for building designers, owners etc.

This deliverable 5.2 reports the outcome of the work performed within Task 5.3 “Probabilistic Life Cycle Cost (LCC) analysis and Cost-Optimal (CO) levels of minimum energy performance of interior insulation solutions”. Task 5.3 has been carried out in parallel with Task 5.2 “Probabilistic Life Cycle Impact Assessment of the environmental impact of internal insulation solutions”, documented in WP5 D5.1. Both tasks aimed to develop a “probabilistic” approach to Life Cycle Impact Assessment (Task 5.2) and to Life Cycle Costing (Task 5.3) to assess the environmental impacts and costs of insulation solutions. Consequently, the methodology developed in both fields has a similar structure and this is also reflected by the similar organisation of the deliverables.

The present report contains seven main sections, dealing with the approaches to Life Cycle Costing in the building context, the probabilistic LCC methodology developed, the proposal of an innovative approach for characterizing future macro-economic scenarios where performing the LCC, exemplary cases of applying the methodology, and the software tool developed to apply the probabilistic methodology during the future developments of RIBuild project.

Section 1 reports a brief overview of LCC in the field of buildings and of the already conducted works on probabilistic LCC for buildings.

Section 2 presents the specific probabilistic LCC methodology developed for application within the field of internal insulation solution of historical 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. The probabilistic LCC methodology developed is useful for providing decision support during the design phase, giving insight into design robustness and possible ranges of the global costs and payback periods during a defined calculation period 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 possible impact on the result.

The goal and main calculation assumptions of the probabilistic LCC are presented in sections 2.2 and 2.3. The methodology couples the calculation of economic indicators to Monte Carlo methods,

[1] RIBuild ANNEX 1 (Part A).

which are effective ways to build the entire output probability distribution and to assess global uncertainty and sensitivity (section 2.4), and consists in four main steps summarized below.

1. Life Cycle Costing calculation methodology: establishing the specific procedure for the LCC of internal insulation solutions, including the main input and output parameters (section 2.5);
2. Uncertainty characterization: selection and characterization of the uncertainties that are considered in the assessment (section 2.6);
3. Uncertainty propagation: performing Monte Carlo methods (section 2.7);
4. Uncertainty and sensitivity analysis: representing the output distribution and calculating the sensitivity indices to identify the most influential inputs in terms of output variance (section 2.7).

Even if specific assumptions are made for the LCC of internal insulations, the methodology developed could find other relevant applications in the building refurbishment sector. The methodology is based on a flexible approach, tailored to the user's needs. It can be coupled to three alternative methods, with increasing difficulty and accuracy level, to evaluate the heat transmission losses through the building wall before and after renovation, necessary to assess the operational energy use and determine the cost savings. These methods can be: accurate HAM (Heat, Air and Moisture transfer) procedures - even based on probabilistic approaches as that developed within RIBuild WP4 and using data inputs collected during RIBuild WPs 1, 2 and 3; monthly steady-state calculation; or a simplified annual HDD method. This last option is directly implemented in the WP5 software tool. Data on HDD at European Level are reported in *Appendix 1*.

Section 3 proposes an innovative procedure developed to identify and characterise several possible macro-economic scenarios in Europe, in order to perform the LCC in alternative economic contexts and compare the related results' robustness and variations. The proposed approach investigates how economic variables that typically affect a LCC procedure (e.g. inflation rate, interest rate, escalation rates of products and energy prices, etc.…) influence the evaluation by explicitly taking into account both their time dependence and their interdependent stochastic nature. As a consequence of the methodology described in sections 2 and 3, the evaluation of the investment is itself stochastic thus expressing both the investment's expected value and its inherent uncertainty and risk.

Exemplary national cases of the methodology application performed by Task 5.3 partners, are then reported in *Sections 4*, *5* and *6*, to illustrate its potential and its possible uses also in view of future progress of RIBuild guidelines. The exemplary cases highlight how the methodology can be applied to assess the economic performance of design options (internal insulation solutions) across various possible scenarios (original wall applications, climatic contexts, energy sources, macro-economic scenarios, reference study periods), also in relation to Life Cycle Assessment (LCA).

Finally, *Section 7* presents the *WP5 software tool*, key part of Deliverable 5.2*,* that implements the probabilistic LCC methodology developed, in view of the realisation of RIBuild guidelines in WP6. The tool includes both the LCA and LCC Monte-Carlo based methodologies developed within, respectively, WP5 tasks 5.2 and 5.3 and allows the calculation of the distributions of environmental and economic impacts of insulation systems under possible scenarios[2]. The LCC calculation assumptions behind the software architecture are reported in section 7.2, while section 7.3 includes the software user guide. The tool already includes a database of input data covering the exemplary national case studies performed within RIBuild Task 5.3 (also reported in *Appendix 2).* This

[2] The LCA section of the software is deepened in the deliverable report D5.1. This software version provided with D5.2 is the final release of the tool.

database can be edited and/or expanded according to user preferences. The software tool can be used to assess other possible renovation measures than internal insulation, to maximise its impact in the field of building renovation.

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.

The necessity of Life Cycle Costing (LCC) calculations in the building sector have been implemented in Europe at national level in compliance with the Directive 2010/31/EU, and cost assessments of design options are becoming more and more familiar to individual designers, investors, practitioners.

A considerable amount of research refers to standardized LCC methods (EN 15459, ISO 15686-5) to assess the economic impacts of energy efficiency measures for building design and renovation. In compliance with European and national legislations across Europe, LCC of building design options is usually performed based to these methods with notable simplifications related to the cost items selection and quantification and to the forecast of macro-economic variables.

Unfortunately, LCC procedures applied to energy renovation measures on historic buildings most often suffer from several intrinsic uncertainties. These uncertainties relate to the long-term perspective of the building interventions as the presence of several constraints (architectural, cultural, social, structural, etc.). These constraints often force 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 LCC is an important challenge to improve the reliability of LCC based decision making. To date in LCC, only little has been done in terms of uncertainty and sensitivity analysis and international standards are not exhaustive regarding these aspects. Building LCCs are usually performed considering deterministic data inputs for practical reasons. E.g. the lack of simulation tools supporting a probabilistic LCC 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.

D5.2 addresses these issues, by describing the probabilistic LCC methodology developed within RIBuild WP5, Task 5.3 "Probabilistic Life Cycle Cost (LCC) analysis and Cost-Optimal (CO) levels of minimum energy performance of interior insulation solutions".

The probabilistic LCC methodology can be effectively applied to offer decision support during the building renovation phase, providing possible ranges of the economic 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 analysis.

The probabilistic approach presented here considerably improves the reliability of LCC based decision making and allows for overcoming the evident limitations of traditional deterministic LCC approaches.

An important part of the methodology development is the characterisation of the LCC data inputs, particularly for what concerns the macro-economic variables. Inflation, interest and prices development rates have been investigated as time series and data-driven models have been developed to forecast their future trends in different possible European macro-economic scenarios.

The identification of these scenarios (and the related economic stochastic inputs) reflects a novelty with respect to the existing literature for several reasons. Firstly, the time dependence of the probabilistic process generating the macroeconomic variables entering the LCC is explicitly taken into account. Secondly, the multivariate nature of this stochastic process is acknowledged: not only the probabilistic distributions of these variables are time-dependent, but they are also interdependent and not independent as usually assumed. Finally, LCC simulations are based on the multivariate time-dependent distributions estimated using the respective observed time series.

The methodology developed within Task 5.3 has been illustrated through exemplary case studies and implemented in a software tool for the probabilistic Life Cycle Costing of internal insulation solutions in historic buildings.

The *WP5 software tool* is the key part of Deliverable 5.2, as it translates into practice the developed LCC 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 tools developed respectively in WP4 and WP5. The software developed within WP5 has been conceived to be applied also to other possible renovation measures than internal insulation, in order to maximise its impact within the field of research on building renovation.

[3] RIBuild ANNEX 1 (Part A).

1 Generalities on Life Cycle Costing of buildings and building renovation measures

1.1 Introduction

In the last two decades, Life Cycle Costing (LCC) has become an important decision tool, part of the whole design process of a building construction or renovation project. It is a useful decision support method to investigate benefits and risks of the investments in the building renovation sector. LCC practically allows choosing the most profitable design options, providing the total expected costs and benefits (expressed in terms of money) due to the application of alternative solutions, evaluated during an established time frame and adjusted for the time value of money.

LCC can be conducted with a multitude of purposes, and the methodological choices necessary will depend on the goal and scope of the study. This section provides a brief overview on the main reference standards for calculation especially in Europe, introduces the fundamental LCC principles followed by a description of different types of costs and LCC terminology, reports some exemplary researches on LCC in the building field, especially focusing on innovative “probabilistic” approaches to building LCC that inspired the work within RIBuild task 5.3.

1.2 Main standards, regulations and guidance notes

Global and European standards for how to conduct life cycle costing calculations within specific industrial sectors are along with a few of the industrial sectors (petroleum and gas industries) available for the construction sector.

ISO 15686-5:2017 [1] provides requirements and guidelines for performing life-cycle cost analyses of buildings and constructed assets and their parts, whether new or existing. In addition to ISO 15686, further standards are also provided in other Counties, e.g. Australia (TAM0-15 Total Asset Management of NSW Treasury), Australia/New Zealand (AS/NZS 4536:1999 Life cycle costing-An application guide - SAI Global), USA (ASTM E917 - 17 Standard Practice for Measuring Life-Cycle Costs of Buildings and Building Systems) [2].

In addition to the general approach presented by ISO 15686 focusing solely on buildings, other ISO standards focus either on specific building parts/installations or constructions in general. An example of such a building specific part standard is the upcoming ISO 12249-1 [3], which provides an LCC method specifically aimed at air cleaning devices. Such building parts specific standards usually define:

- the algebraic model used for evaluating the LCC;
- the principles to be followed when evaluating the model parameters;
- how the values for LCC can be used to optimise system design.

More broadly does the ISO/TS 21929-2:2015 (Sustainability in building construction — Sustainability indicators — Part 2: Framework for the development of indicators for civil engineering works), which focus on the implementation of LCC in civil engineering [4]. ISO 21929 part 2 describes and provides guidelines for the development of sustainability indicators related to civil engineering works and defines the aspects and impacts of civil engineering works to consider when developing systems of sustainability indicators. The 21929 LCC guidelines form a basis for the suite of ISO/TC 59/SC 17 standards intended to address specific issues and aspects of sustainability relevant to construction works.

Recently, the importance of using Life Cycle Costing in the building sector has been attested at regulatory level in Europe by Directive 2010/31/EU [5], which established that Member States shall calculate "cost-optimal levels" of minimum energy performance requirements using a comparative methodology framework according to the consequent Commission Delegated Regulation and its Guidelines [6,7] based on EN 15459:2007, now replaced by EN 15459-1:2017 "Energy performance of buildings – Economic evaluation procedure for energy systems in buildings. Part 1: Calculation procedures, Module M1-14" [8].

"Cost-optimal level" means the energy performance level which leads to the lowest cost during the estimated economic lifecycle, where the lowest cost is determined taking into account energy-related investment costs, maintenance and operating costs including energy costs and savings. Cost-optimal calculations have been subsequently implemented in Europe at national level in compliance with the Directive, are becoming more and more familiar to individual designers, investors, practitioners, and European Standard EN 15459-1:2017 [8] is considered the main reference in Europe for LCC of building energy efficiency interventions.

Standard EN 15459-1 is part of a series of standards aiming at international harmonization of the methodology for the assessment of the energy performance of buildings, called "set of EPB standards". It provides a method for the economic assessment of the building envelope and other building systems that are involved in the energy demand of the building, with the aims of considering the economic feasibility of energy efficiency options or compare the performance of different options.

The standard provides the required evaluation inputs and outputs, the calculation formulas and defines the type of energy systems concerned with the energy performance of the building. The calculation method is named "Global Cost" and is used for aggregation of the past, present and future costs over a period of calculation. Future costs are taken into account by the use of discount rates that allow figuring the performance of the money placed on the market during time. The outputs of the method included in the standard are: global cost and payback period.

The total global cost is determined by summing up the global costs of all cost categories and subtracting global cost of the final (residual) value. Further details on the calculation performed with this approach are given in section 2.5.2.

The different types of costs (initial investment costs, replacement costs, annual costs and energy costs) as well as the final (residual) value of the building/component are converted to global cost (i.e. referred to the starting year 0) by applying the appropriate discount rates. The discount rates may be different for different types of costs, due to different rates of price development for energy, human operation, components, etc. Dynamic calculations may be introduced annually if variation of the inflation rate and of the rate of development of price for energy, price for human operation, price for products are required (this approach is followed in the probabilistic methodology developed and described in section 2.5.2).

The payback period illustrates the potential of different options compared to a reference situation by the time when the initial investment is expected to be recovered. The payback is considered when the global cost of the option is lower than the global cost of the reference for an identical period of calculation. For existing buildings, the reference could be the actual state (doing nothing). The (discounted) payback period is the time when the difference between the initial investment cost for the optional and the reference case are balanced with the cumulative discounted annual costs difference in each individual year. Further details on the calculation performed with this approach are given in section 2.5.2.

The approach of the calculation method is made according to a global point of view (overall costs). However, it may be applied, according to the investor's objectives, considering only selected specific cost items. For example, calculations concerning alternative solutions for internal insulation of buildings may be performed considering only costs for their purchase/installation and related to building energy needs for heating.

1.3 Basic principles of the calculation methodologies

1.3.1 Goals and targets

As the name reveals, LCC is a methodology that can be applied to assess costs over the entire life cycle of a product or a system. In the literature a multitude of terms exist synonymous with LCC. These terms are applied to describe costs across the life cycle of a product, a system or a project, including Through-Life Costing (TLC), Whole-Life Costing (WLC) and Total Cost of Ownership (TCO). It should be noted that, in the absence of any internationally recognised terminology standard to describe these terms in detail, differences between them remain quite subjective and are based upon experience, field of study and economic standpoint.

Conducting an LCC may serve quite different purposes. LCC may be used for planning purposes, as optimisation tool, as tool for (cost) hotspot identification, as part of a life cycle sustainability assessment of a specific product or system, or simply to evaluate the potential of investment decisions. A primary consideration relates to the timing of the analysis, where two main types of LCC can be distinguished. *Ex ante* LCC is a prospective approach based on estimates, and is conducted at the early stages of decision-making. *Ex post* LCC on the other hand is a more retrospective approach based on actual results, usually conducted towards the end of a building/construction project or for a specific time period of a project. An additional highly relevant consideration is the target/receiving group of an LCC. The target group might be a single actor in a value chain such as a building component producer or a user or it might take the whole value chain into perspective. The choice of the target group during the goal and scope definition phase of an LCC will hence have implications on the appropriate level of detail [9].

In an LCC, costs are quantified over the entire life cycle of a product. Costs are normally considered being equal to price i.e. the monetary value that someone has to pay for something. LCC can include revenues which are considered negative costs. Some authors argue that there are no problems associated with adding the revenues in an analysis, as long as it is clear how the addition is being conducted, although for practical reasons revenues are most often left out [10]. For certain LCC application contexts, inclusion of revenues can be required in order to effectively support economic decision making. When an LCC addresses multiple target groups—e.g. manufacturer and users—adding revenues might lead to confusion for certain parts of the target group, as the cost for one actor is often the revenue for another. In such cases, it is important to clearly distinguish between what are perceived costs and revenues for the individual target groups. In environmental LCCs, where multiple perspectives are typically applied, only the value added for each life cycle stage is accumulated in the LCC, thus avoiding double counting.

1.3.2 LCC archetypes

An LCC may have a multitude of goals, depending on the needs and perspectives of the study commissioners. Based on that, three general types of LCC have been proposed: societal, environmental and conventional LCC [9]. Figure 1 depicts the major differences between these 3 archetypes of LCC.

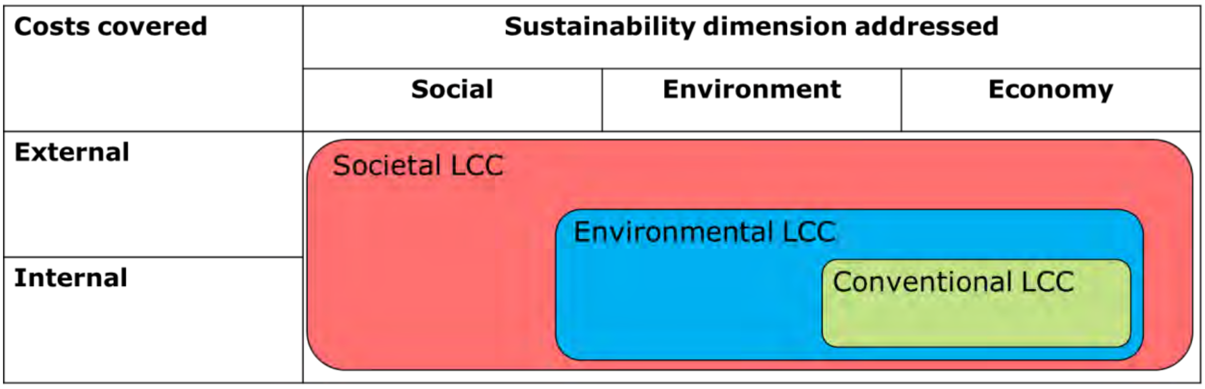


Figure 1Illustration of the sustainability dimensions and costs covered by the 3 archetypes of LCC. Based on [9]

Conventional LCC (sometimes referred to as financial LCC or cLCC) was originally proposed and applied for procurement purposes in the U.S. Department of Defense [11,12]. cLCCs are mainly applied as a decision-making tool, to support acquisition of capital equipment and long-lasting products with high investment costs [10]. cLCCs are typically conducted from the perspective of a single actor, often the user of a solution. cLCCs can also be conducted from the manufacturer's point of view, breaking down the life cycle costs with specific focus on the production stages, and—if also borne by the manufacturer—end-of-life costs. In conventional LCC, only internal costs are considered, and discounting of the results is recommended.

Unlike the single actor perspective of the conventional LCC, environmental LCC (often referred to as eLCC) is closely aligned with the ISO LCA standard 14040 and 14044 [13,14] by applying so-called functional units and taking into account the whole life cycle, as well as all actors in the value chain or life cycle. Unlike the cLCC, which is most often industry driven, eLCC was developed to support LCA in the sense that it covers the economic dimension of the sustainability matrix, and helps in combination with LCA the identification of hot-spots in terms of both cost and environmental impacts. In addition to the internal costs borne by the actors in the life cycle, eLCC can include external costs expected to be internalized in the near future. Including such external costs induced by environmental impacts that are already addressed in the Life Cycle Impact Assessment (LCIA) will inevitably yield double counting, since the impacts are accounted for in both analyses and hence both sustainability dimensions. Double counting is not necessarily a problem as long as it is presented in a transparent manner upon presentation of results and is conducted consistently for all alternatives being compared. Just as is the case for LCA, is eLCC a steady-state model, and hence no discounting of the results is usually applied.

Societal LCC (sometimes referred to as sLCC) is intended to support decision-making on a societal level including governments and public authorities. This type of LCC includes quantification of the environmental effects in monetary terms. sLCC includes selected external costs by assigning a monetary value to them. This process is called monetarization of costs (or impacts). In practice, monetarization is performed by translating the LCA impact results into monetary units, e.g. assessing damage costs. Hence, the sLCC incorporates the LCA results, and the LCA results should therefore be reported as a subset of the LCC results in order to avoid double counting. An LCC that monetarizes all environmental impacts from the LCA is in some cases called “full” eLCC. A sLCC goes one step further by adding monetarization of social impacts such as: affected social well-being, job quality, etc. A sLCC offers the possibility to present the results in one single monetary unit, essentially comprising all three sustainability pillars in a combined Life Cycle Sustainability Assessment aimed at supporting e.g. policy decisions. The common unit of LCC facilitates aggregation of the results into one single indication, however aggregating all results into one single value is often criticized, mainly due to the uncertainties relating to coverage of all relevant external costs and the fact that the external costs are highly uncertain. The eLCC is recommended as supplement for LCA with economic measures, due to the consistency in the scope of the two analyses.

1.3.3 Temporal perspectives

As costs are accumulated in LCCs, over the lifespan of a product, the assessor needs to keep in mind that the monetary flows can occur at quite different times.

In general, prices will change due to the market dynamics. In the long run there is a general increase in the overall prices of goods, which at the same time may affect the purchasing power of currency—known as “inflation”. In LCC the aim is to compare costs based on a chosen reference year and thus all costs accounted for needs are to be adjusted to this reference year when doing the comparison. This adjustment is conducted by using the so-called “inflation rates”. Eq. 1 shows how to calculate the price P of a product at time t (in years) with an inflation rate r, where $P(0)$ is the price at the reference year ($t = 0$).

$$P(t) = (1 + r)^t \times P(0)$$

Eq. 1

Costs that occur at different points in time are not directly comparable. A solution facilitating the comparison among future and present costs in LCC is “discounting”. Discounting essentially weighs impacts by assigning a lower weight to costs in the future than present costs. A weight $w(t)$ for payments occurring at time t is hence called the “discount factor”. This discount factor will thus depend on the discount rate r, which is the rate by which the discount factor $w(t)$ decreases over time assuming first order discounting rate. The discount factor is calculated as follows:

$$w(t) = \frac{1}{(1 + r)^t}$$

Eq. 2

If the discounted costs and revenues are summed this yields the Net Present Value (NPV) and is equal to:

$$NPV = \sum \frac{P(t)}{(1 + r)^t} = \frac{P(0)}{(1 + r)^0} + \frac{P(1)}{(1 + r)^1} + \frac{P(2)}{(1 + r)^2} + \cdots \frac{P(t_{max})}{(1 + r)^{t_{max}}}$$

Eq. 3

where $P(t)$ correspond to the cash flows at the time t i.e. the time of the cash flow. The appropriate discount rate will depend upon the type of cost that is being discounted. For internal costs this rate is closely related to the cost of borrowing. In the public sector, national ministries of finance generally specify the discount rates to be used in the economic analysis of publicly funded projects. These discount rates typically fall in the range of 3–5% [10,15].

1.3.4 Cost types

Costs borne by the different actors directly associated with the life cycle of the product being assessed are termed "internal costs" (sometimes may also be referred to as "private costs"). However, a product or system life cycle may involve other types of costs, borne by other actors more indirectly influenced by the product life cycle such as a result of pollution affecting the health of people/ecosystem functions or other more social impacts. These types of costs are called external costs. External costs (sometimes referred to as externalities) are value changes caused by a specific business transaction, which are not covered by the product price, or value changes caused as side effects of the economic activity. In societal LCC, externalities can be monetarised and included in the assessment. If the external costs are already expressed in some monetary unit, they can quite easily be included in an environmental LCC. In conventional LCC, external costs are usually not included [9].

Table 1 provides an overview of the most common terms used in LCC and their definitions.

Table 1 Overview the most relevant LCC terms

Term	Definition
Discounting	A method used to convert future costs or benefits to present values using a discount rate [15]
Exchange rate	Currency conversion between different currencies
External costs	External costs (also termed externalities) are value changes caused by a business transaction, which are not included in its price, or which occur as side effects of economic activity [10]
Inflation rate	A measure of the overall change in prices for goods and services over time
Internal cost	Costs borne by actors directly involved in the life cycle of the system under study
Life cycle costs	The sum of value added over the life cycle of a product or a system [16]
Net Present Value (NPV)	NPV is the sum of all the discounted future cash flows that takes into account the time value of money over the entire life time [17]
Price	The amount of money that will purchase a finite quantity, weight, or other measure of a good or service [18]
Revenue	The income generated from sale of goods or services, or any other use of capital or assets, associated with the main operations of an organisation before any costs or expenses are deducted
Value added	Value added is the difference between the sales of products and the purchases of products or materials by a firm, covering its labour costs and capital costs as well as its profits [10]

1.4 Researches and "probabilistic" approaches to buildings and building elements LCC

A huge amount of scientific papers has been published on the application/improvement of LCC on the built environment over the years. The earliest of these publications date back to 1980's and LCC is hence a building engineering discipline in (or rather close to completing) it's 4th decade of application.

LCC has hence just like LCA achieved a multipurpose role in building engineering and is being applied in a multitude of contexts within the building industry all with the aim of optimising the economic performance of buildings, built environments and constructions either already in the design phase prospectively or retrospectively.

A considerable amount of research uses LCC methods to assess the economic impacts of alternative options for building design and renovation (exemplary cases are reported in [19–27]). The more recent publications on LCC and how it is being applied within the built environment are only to a very limited extent focusing on application of LCC in its classical sense, to determine whole life costs of buildings and building components. They are often applying LCC in new contexts (e.g. circular economy), illustrating how LCC can be applied within various certification schemes, application of LCC in decision support etc.

By way of example, Table 2 reports several recent publications on LCC in the building field, addressing different aims.

Table 2 Contemporary examples of application of LCC within the built environment

Example	LCC topic area	Publication
1	LCC application survey	[28]
2	Circular economy and LCC	[29]
3	Life cycle (costing) management	[30]
4	Certification of building materials	[31]
5	Building software integration of LCC	[32]
6	Infrastructure accounting	[33]
7	Coupled environmental and cost performance	[34]

As shown, several national and EU regulations explicitly acknowledge LCC as a proper assessment tool and a vast amount of research addresses building LCC referring to standardized LCC methods (EN 15459, ISO 15686-5). However, standard LCC does not fully capture the logic and the determinants of investors' decision implied by the uncertainty and, thus, the risk associated to the investment. Furthermore, in many studies, in respect of a significant effort in the identification and parameterization of energy efficiency measures and in the evaluation of the related energy performance, the LCC calculation is often achieved with notable simplifications related to the cost items and macro-economic scenarios identification and quantification. For instance, constant market interest rates are used in practice, ignoring the possibility of variations over the life cycle of the building resulting from changes in national and international monetary and fiscal policies.

In reality, the practical application of LCC methodologies is not straightforward. Accurate cost analysis rely on quality of data and long-term forecasts, and data uncertainty is a well-recognized matter associated with LCC methods [35–43]. Poor availability and reliability of input data increase the result uncertainty and could limit the LCC application. Ignoring these uncertainties may led to improper decisions, based on faulty assumptions [38].

According to Sesana and Salvalai, the main problems in buildings LCC are: the lack of reliable information; the difficulty in forecasting time factors over a long period (life cycles, future operating, maintenance and demolition costs and discount rates); the variability of construction costs of the same component or materials (depending on the company, the quantity and the availability in the specific context, etc.) [43].

Gluch and Baumann extensively discuss the theoretical assumptions and the practical usefulness of the LCC approach in making environmentally responsible investment decisions [36]. They underline that LCC's practical usefulness is constrained by its oversimplification to a monetary unit, the lack of data, the complexity of the building process and the conceptual confusions.

Moore and Morrissey [44] underlined that LCC analysis is informed by considerable assumptions on key parameters, such as discount rates, investment costs, future prices of energy, building lifespans, that can be heavily contested by researchers and stakeholders. Furthermore, there is limited exploration of their implications within wider policy developments.

Recently, Ilg et al. provided a comprehensive overview of uncertainties in LCC [45], trying to systematize the sources and types of uncertainty. They have, however, concluded that the variety of uncertainties makes it difficult to provide a meaningful and simple categorization.

Several other works demonstrated that poor availability and reliability of input data can increase the result uncertainty and limit the credibility of the LCC results [35–37,39–43,46]. LCC methods may still be useful in practice if the decision maker is aware of their inherent limitations and can assess and communicate the problem of uncertainties properly [36].

“Probabilistic” approaches to LCC in the building sector then provide a more realistic decision support about investments for energy efficient projects during the design phase, giving insight into possible ranges of the economic indicator of a specific design option. However, in the past, only few authors addressed this issue.

Burhenne et al. [46] performed a combined building energy simulation and LCC analysis, focusing on the prediction of the future trends for economic variables based on time series data through ARIMA (auto regressive integrated moving average) models typically used in econometrics. They then subjected the predictions on energy prices and inflation rates to uncertainties to account for different scenarios. The authors also established specific probability distributions for the interest rate and the component investment costs. They found that the future gas price and the expected interest rate are the most influential parameters on the results, also compared to the other economic parameters and the investment cost.

Morrissey et al. [47] investigated the impact of the discount rate on cost-benefit assessment of investment options for residential building efficiency, considering it as the primary driver of difference in estimates about costs and benefits. Copiello et al. [48] confirm the prominence of the discount rate in influencing the LCC results uncertainty during the assessment of energy retrofit interventions in a building case study, therefore they argue that its estimation is critical to the soundness of economic evaluations.

Some researches propose methods to address LCC uncertainty. Almeida et al. [49] suggest an integrated methodology that quantify and include building energy performance assessment uncertainty in LCC estimation. The methodology relies on Monte Carlo simulation to calculate statistical distributions of energy demand. The associated costs distributions are then introduced in an LCC analysis, while the other LCC parameters are considered as deterministic, in certain respects similarly to [40,50].

Di Giuseppe et al. [51,52] proposed a LCC probabilistic methodology based on uncertainty and sensitivity analysis via Monte Carlo (MC) approach (whose potential and effectiveness in several engineering applications is already widely documented, e.g. in [53]). The methodology allows comparing alternative design options based on their primary energy demand and Global Costs and is illustrated through building case studies under different energy renovation scenarios. To our knowledge few other studies applied in practice methods to address uncertainty in buildings LCC analysis [54,55], and they were often limited to few types of data inputs uncertainties.

1.5 Conclusions

This section presents a brief illustration of Life Cycle Costing applied in the building context, in order to introduce the field of application of RIBuild task 5.3.

Several LCC methodologies are included in international standards and especially European Standard EN 15459-1:2017 [8] sets the stage for a robust LCC methodology of buildings energy renovation. Nevertheless, traditional "deterministic" approaches to LCC based on these standards do not fully capture the logic and the determinants of investors' decision implied by the uncertainty and, thus, the risk associated to the investment. Furthermore, in many LCC studies, the calculation is achieved with notable simplifications related to the cost items and macro-economic scenarios identification and quantification.

"Probabilistic" approaches to LCC in the building sector then provide a more realistic decision support about investments for energy efficient projects. However few authors investigated this topic in the past.

The proposed "probabilistic" approach to building LCC, described in next sections 2 and 3, partially based on previous works [52,56], aims to contribute to the recent literature on the probabilistic LCC analysis. Major novelties in the LCC approach are introduced to take into account the time dependence of the probabilistic process generating the macroeconomic variables entering the LCC, making the proposed approach a "stochastic" rather than a "probabilistic" one. Moreover, the multivariate nature of this stochastic process is recognized as the distributions of these variables are interdependent. Consequently, LCC simulations are not based on some distributional assumption for any macroeconomic variable involved, but on the multivariate time-dependent distributions estimated within a Vector AutoRegressive (VAR) model using the respective observed time series.

2 Development of a probabilistic methodology for the Life Cycle Costing of interior insulation solutions in historic buildings

2.1 Introduction

In this section, the specific probabilistic LCC methodology (PM) developed within RIBuild Task 5.3 for the assessment of internal insulation solutions of historic buildings is described.

The PM allows assessing the economic impact of insulation solutions for a wall case-study, assuming a given energy and macro-economic scenario and a calculation period.

The PM is useful to:

- provide decision support during the design phase, giving insight into design robustness and possible ranges of performance indicators (global costs and payback periods) 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 cost 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 LCC 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 LCC 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 sections 4, 5, 6 to illustrate its potential and possible uses also in view of future developments of RIBuild guidelines in WP6. The methodology has been implemented in the WP5 software tool, described later in section 7.

2.2 Goal and scope for the LCC

As highlighted in section 1, Life Cycle Costing is an important decision support, to investigate benefits and risks of the investments in the building renovation sector. It practically assesses the cost effectiveness of a design option, providing the total expected costs and eventually benefits, expressed in terms of money, evaluated during an established time frame and adjusted for the time value of money.

The probabilistic LCC is performed at "component level" (component-level LCC analysis [1]) and is based on the procedures of EN 15459:2017 [8] and ISO 15686-5:2017 [1], in order to calculate two possible economic indicators:

- The Global Cost (GC);
- The Payback Period (PB).

In particular, the Global Costs can be used to:

- assess economic performance of an internal insulation solution applied to a historical wall;
- compare economic performance of different internal insulations and the corresponding reference scenario (uninsulated wall) in order to find the *cost-optimal* insulation solutions according to the European framework reported in EPBD Recast 2010/31/EU [5] and following documentation[4].
- compare the economic performance of different internal insulations and the corresponding reference scenario (uninsulated wall) in order to find the *cost-effective*[5] insulation solutions according to IEA Annex 56 [57].

The Payback Period can be used to:

- assess the time period during which the investment is at risk;
- compare design options, assessing the lowest payback period provided.

The functional unit (FU)[6] of the LCC is defined as *"the insulation intervention using a possible interior insulation system needed to cover 1 m² of façade for a calculation period[7] expressed in years*". The functional unit for the LCC 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 assessment 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 risk of moisture related damage; or an insulation thickness compliant to a given U-value (based on renovation standards) if there is no moisture risk.

The Global Cost is directly linked to the duration of the LCC calculation period (cp). The Methodology developed and implemented allows the calculation in different study periods to compare the results on different time horizons, also taking into account the following references: the European Commission Delegated Regulation and its Guidelines [6,7] suggest a calculation period of 30 years for residential and public buildings and of 20 years for commercial buildings; IEA Annex 56 [57] suggests to use a reference study period of 60 years; EN 15459:2017 [8] suggests calculation periods of 50 years for residential buildings, 20 years for commercial buildings and 30 years for other typologies.

[4] Commission Delegated Regulation 012/244/EU and Guidelines (comparative methodology framework for calculating cost-optimal levels of minimum energy performance) [6,7].

[5] The EPBD recast assumes that the improvement of energy related building performance should go up to an efficiency level which is "cost optimal" (the highest efficiency at the low possible cost). In the case of building renovation, cost optimal energy related renovation measures will usually not allow to achieve a nearly Zero Energy Building level. Therefore, the range of economically viable renovation measures, has to be extended to comprise the evaluation of all renovation measures, being still "cost effective".

[6] Even if in LCC the definition of a Functional Unit is not a mandatory requirement, it is defined here for consistency with the probabilistic LCA methodology developed within RIBuild task 5.2.

[7] In the probabilistic LCA "reference study period".

The scope of the methodology comprises the assessment of the economic impacts and the transmission heat losses of the insulation solution (assuming a given energy and economic scenario, and a calculation period). The LCC of the new interior insulation systems after renovation covers next to the investment costs, the use phase costs related to the possible needs for maintenance and replacement of material layers or whole insulation system and costs related to the energy consumptions. Further detail on the LCC calculation model are provided in section 2.5.2.

In the probabilistic LCC 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 life. Instead, *replacement* involves the whole insulation system, according to its estimated service life.

2.3 Initial requirements for the probabilistic methodology

2.3.1 Multi-layer sampling scheme as a framework

Within the PM, it is proposed to sort out the LCC simulation parameters, related to several design options under several possible simulation scenarios, according to a *multi-layered sampling scheme* as proposed by Van Gelder et al. [50]. 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 2).

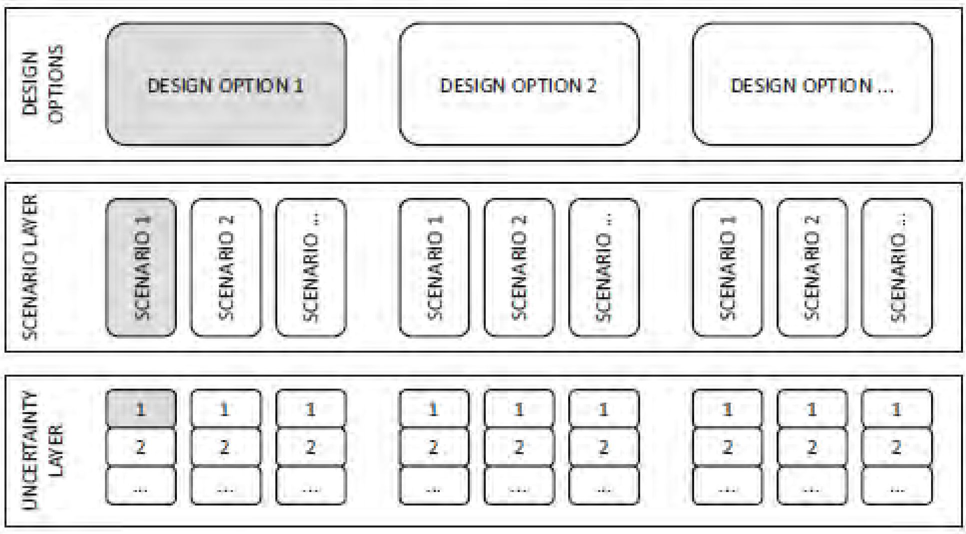


Figure 2 Multi-layered sampling scheme according to [50]

Applied specifically to the context of the LCC of internal insulation renovation of historic buildings, a schematic illustration is provided in Figure 3 to illustrate this approach for four possible design options (insulation solutions), installed in a specific wall configuration, and under four different heating system scenarios and four different macro-economic scenarios. With the approach presented in Figure 3, 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 and macro-economic variables are assumed to belong to the scenario layer, while, in reality, further scenarios are included in the assessment, i.e. the calculation period and the specific wall installation configuration under a certain climate (wall case-study).

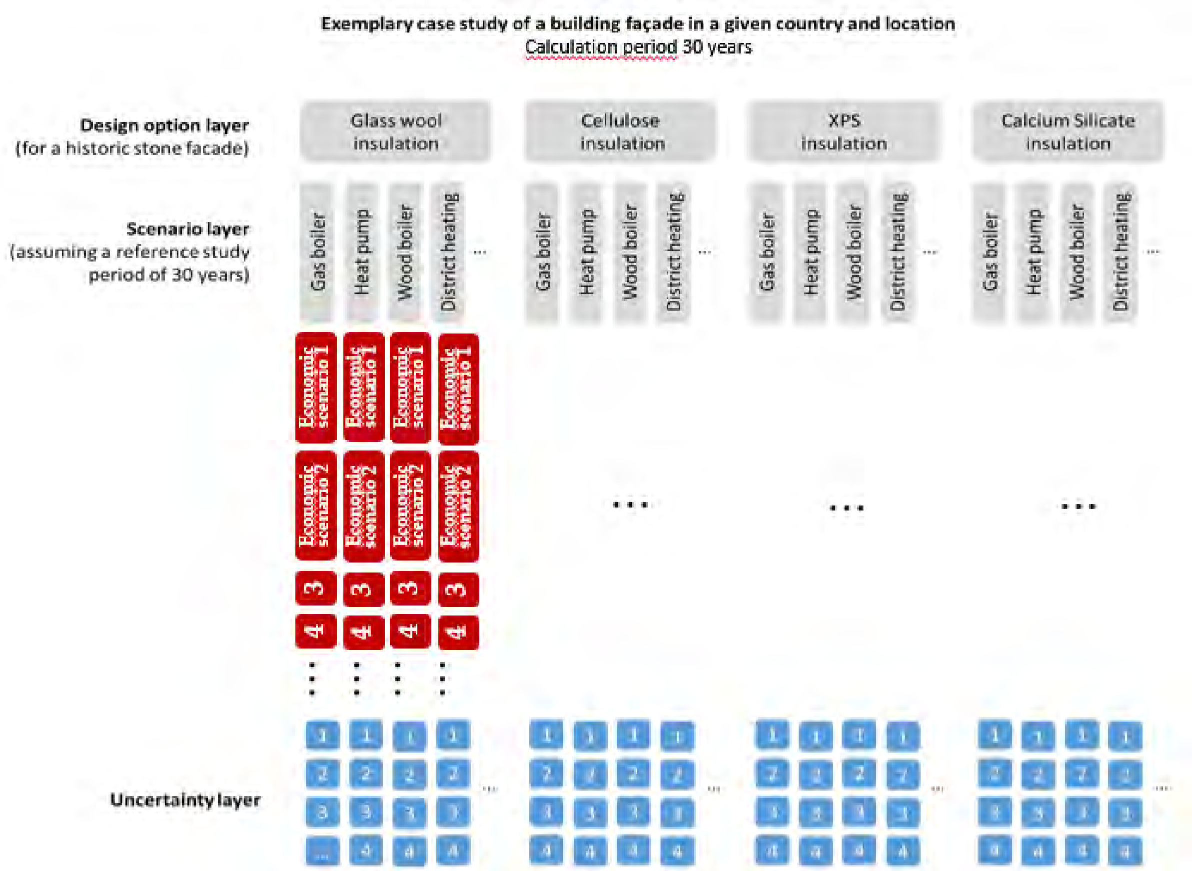


Figure 3 Multi-layered sampling scheme adapted from [50] **in the specific case of LCC of design options; in this figure the scenario layer only considers the different heating systems and the macro-economic scenarios for a fixed calculation period and wall case-study**

According to this approach, three simulation layers are distinguished:

1. The **design options layer** contains the internal insulation solutions, with their 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 calculation periods, application configurations (original walls), energy scenarios (possible energy sources and consequently energy tariffs), macro-economic scenarios. 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.

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 purchase and installation costs data of insulation material: if the user has a specific manufacturer data with a high confidence in the cost value).

As it will be demonstrated in more detail below, the possible uncertain parameters in the PM for LCC of internal insulation systems are:

- insulation system investment (and replacement) cost, insulation system maintenance cost, insulation system service life. These are the stochastic variables related to a specific *design option* choice;
- heat transmission losses. It is the stochastic variable related to a specific *historic wall installation configuration scenario* choice;
- interest rate, inflation rate, price development rates. These are the stochastic variables related to a specific *macro-economic scenario* choice;
- building overall efficiency for heating and the tariff of the energy vector. These are related to a specific *energy scenario choice*.

2.3.2 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.

Of course, the level of uncertainty (range of possible output) decreases with the amount of information the user can provide (e.g., costs and service life of materials). For a given parameter, if the user has no information, then the probabilistic LCC methodology will use generic background Probability Density Functions (PDF), implemented into a database of cases included into the software tool[8]. 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 databases, etc.).

[8] As shown in section 7.3.2 and Appendix 2, the software tool now includes a database with several national cases from Italy, Switzerland and Denmark, implemented to illustrate the probabilistic methodology developed. The LCC 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.

The proposed approach is applicable to LCC but also to other probabilistic assessments in RIBuild i.e., hygrothermal assessment (as reported in deliverable D4.1 and D4.2), or LCA (as reported in deliverable D5.1).

2.3.3 Heat transmission losses calculation methods

As the LCC is performed at "component level" (the original or the insulated wall), the operational energy use is related to the heat transmission loss through the wall. So, the LCC assessment requires input data on transmission heat losses through the building wall before and after the insulation measure, in order to account for the heating costs and determine the cost savings.

The LCC 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, as they are used in the exemplary cases reported later or in connection with the work performed in RIBuild WP4:

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

Option 1 allows having an accurate and consistent assessment on the hygrothermal benefits and risks prior to the LCC. It requires 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 5.3 nor presented in this report. Nevertheless, the software tool for probabilistic LCC of internal insulations developed within Task 5.3 (WP5 software Tool) allows using PDFs or deterministic data of the heat losses coming from HAM tools results for the LCC 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[9].

Annual Heating Degree Days Method (Option 3 implemented in WP5 software tool)

This calculation method has been implemented into the WP5 software tool, in order to obtain (in an easy but simplified manner) the annual calculations of heat losses through the facade (during the heating season) when these data are not obtainable through other methods/tools. It requires input parameters such as the Annual Heating Degree Days for a certain town/region and the wall thermal transmittance. The calculation is based on Eq. 4:

[9] *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. This approach is documented in deliverable report 5.1.

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

Eq. 4

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 following Eq. 5:

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

Eq. 5

Where:
R_{si} and R_{se} are the internal and external surface resistances [58]: 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).

2.4 Overview of the probabilistic methodology

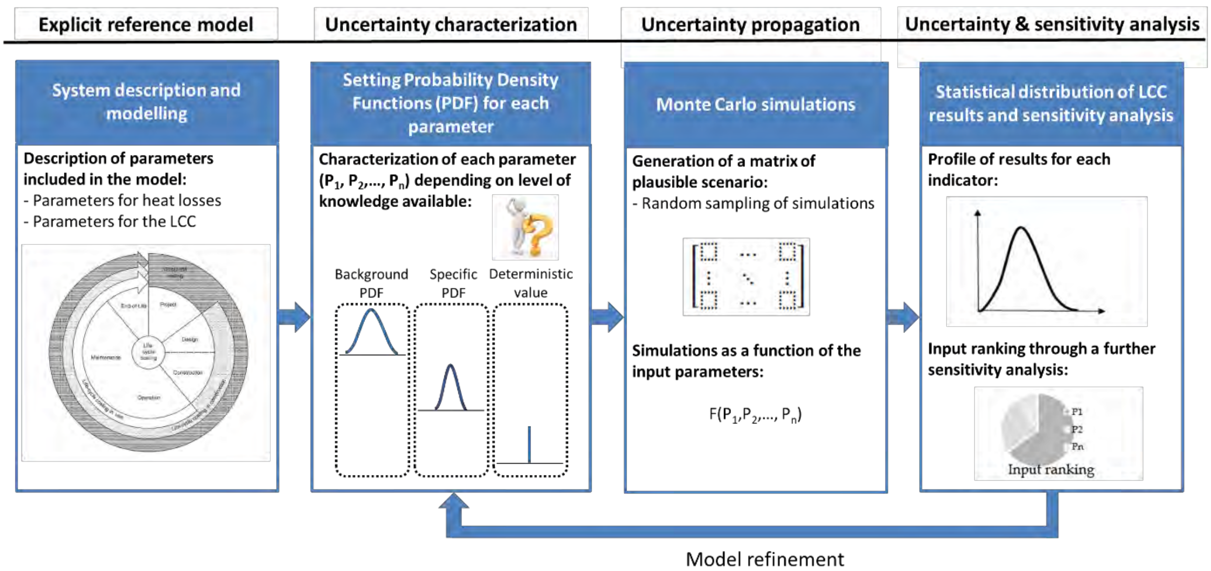


Figure 4 LCC probabilistic methodology overview with the different steps

The probabilistic LCC methodology is based on an uncertainty and sensitivity analysis applying the Monte Carlo (MC) method. It couples the calculation of economic indicators (as Global Cost and Payback Period) to MC methods, in order to build the entire output probability distribution and to assess global uncertainty and sensitivity [59]. The PM developed consists in four main steps described in detail in the next paragraphs and summarized below.

1. *LCC calculation model*. This step establishes the specific procedure to be applied for the LCC of internal insulation solutions. The main input parameters are identified; the output parameters and a suitable model to simulate them are selected (section 2.5).
2. *Uncertainty characterization*. In this step the selection and characterization of the uncertainties that are considered in the assessment is conducted. The most uncertain LCC data inputs are identified and procedures for characterization of their PDFs are proposed (section 2.6).
3. *Uncertainty propagation*. This step applies the MC methods in combination with a specific sampling procedure (section 2.7).
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 2.7).

Figure 4 presents a graphical illustration of the probabilistic methodology developed.

2.5 LCC calculation

This section describes the LCC calculation model as well as the parameters used in the calculations of the heat losses necessary to assess the energy costs.

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, macro-economic scenarios or calculation periods.

Table 3 presents the possible design options and scenarios.

Table 3 Design options and scenarios identified in the probabilistic LCC 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[10]	**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) of the wall.	Country-specific information.
Scenarios for the LCC	**Comments**
Energy sources and features of the heating system.	Country-specific information. Different heating systems and sources available.

[10] 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 LCC be consistent (HAM and LCA should address the same "case study"). Nevertheless, specific information on climatic conditions or original wall structures is not necessary for the LCC.

Calculation period.	Different deterministic values possible (e.g. 30, 45, 60 years).
Macro-economic scenarios.	Different possible scenarios characterized (see chapter 3).

2.5.1 Heat transmission losses model and parameters

As already introduced in section 2.3.3, within the PM, different options have been proposed to determine the wall heat losses.

As shown later in section 7, 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. 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 approach cannot address the hygrothermal properties of the walls in an hourly time step for instance. However, option 3 can be used under specific conditions (within its validity domain) to determine the U-value and the heat losses prior to any LCC. In this section, the heat losses reference model of option 3 (annual calculation), implemented in the WP5 software, is presented.

Annual Heating Degree Days Method

Regarding the design option layer, the following parameters are considered (and required by WP5 software tool, as documented in section 7):

- 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 countries involved in RIBuild project were extracted from Eurostat database, as calculated by the Joint Research Centre (Institute for Environment and Sustainability - IES/MARS Unit) [60], and included in WP5 software tool. They are reported in Appendix 1.

Data are detailed at national and regional level, and this allows performing the LCC considering "general" case studies (subjected to the climatic variability of the whole Country) 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.

2.5.2 LCC equation and parameters

2.5.2.1 Cost Categories

The LCC is performed at component level based on the procedures of European Standards EN 15459:2017 [8] and ISO 15686-5:2008 [61] and covers, next to the investment costs, the use phase costs related to the possible needs for maintenance and replacement of the insulation system and related to the energy consumptions and consequently costs. The cost categories included in the calculation are the following (highlighted in Figure 5 and described in the next sections)[11]: Initial investment cost; Energy cost; Maintenance cost; Replacement cost.

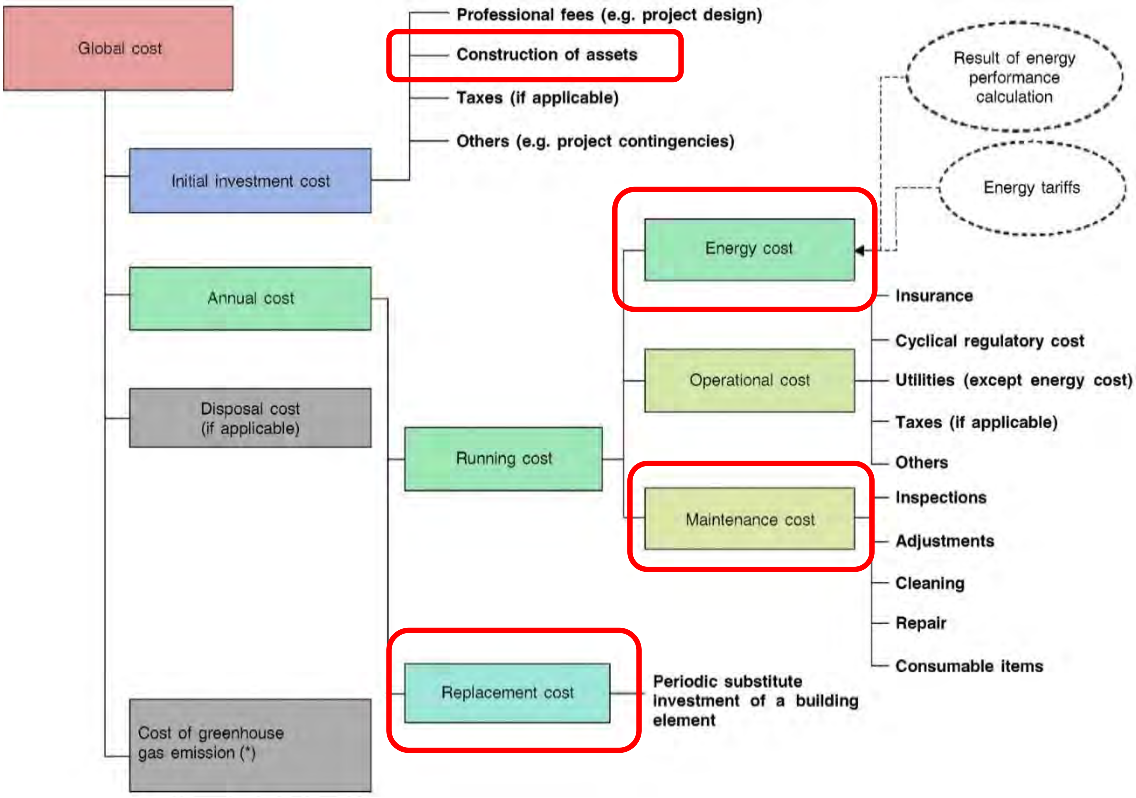


Figure 5 Cost categorization included in the methodology framework reported in Commission Delegated Regulation 012/244/EU and Guidelines [6,7].

[11] The cost of greenhouse gas emissions is neglected because LCC is performed in the perspective of a building designer or owner.

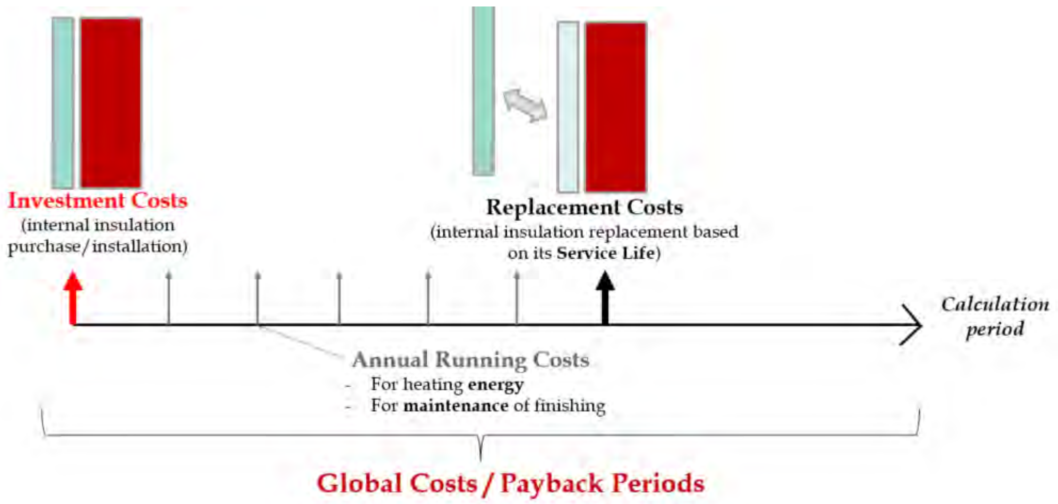


Figure 6 Schematic illustration of the cost categories included in the assessment

Initial investment cost

The initial investment cost (CI) represents the cost for the purchase and construction/installation of the design option (insulation system) considered. In general, the investment cost is composed by the cost of each material belonging to the design option and the labour cost of its installation, depending on the installation procedure and the necessary installation time.

Energy cost

The energy cost (CE) is an annual cost for the energy use for heating according to EN 13790 [62], including national taxes. It is obtained multiplying the annual energy use by the tariff for the energy carrier considered (EnT). Since RIBuild focuses on the heating savings due to insulation options, the energy use concerned is that for *heating* (PE_H) that depends on energy needed for heating expressed by the heat transmission loss through the wall (Q_H) and the building overall efficiency for heating (ETA_H), as reported in the following Eq. 6.

$$PE_H = \left(\frac{Q_H}{ETA_H} \right)$$

Eq. 6

The building global efficiency for heating (ETA_H) and the energy tariff depend on the level knowledge of the building heating equipment and energy source typology. These parameters are related to specific national contexts.

Maintenance cost

The maintenance cost (CM) represents the cost for measures for preserving and restoring the desired quality of the building element (internal insulation) [8]. At the aim of the probabilistic LCC of interior insulations on historic buildings developed in RIBuild, the maintenance is considered as the need of periodic replacement of the internal finishing material, i.e. the rendering or the painting on the internal surface, which depends on these specific materials' estimated service life (or life span). Consistently with standard EN 15459, maintenance costs are then "yearly distributed" in order to obtain annual maintenance costs.

Replacement cost

The replacement cost (CR) represents the substitute investment for the design option, according to the estimated economic lifecycle during the calculation period. It is a recurrent cost, with a frequency that depends on the Service Life (SL) of the insulation system concerned. The replacement cost is here considered equal to the investment cost necessary to replace the whole design option, discounted at the beginning of the calculation.

2.5.2.2 Economic Indicators

The LCC PM developed and implemented in the software tool allows calculating two possible economic indicators, with the calculation procedures described in the next sections: Global Cost and Payback Period. The time step of the output is yearly based.

Global Cost

The Global Cost (GC) is used for aggregation of the past, present and future costs over a period of calculation. The Global Cost is then the sum of the present value of the initial investment costs, the annual costs (for energy and maintenance) and the replacement costs. The Global Cost (GC_{cp}) at the end of the calculation period (cp) referred to the starting year is calculated based on the method described in standard EN 15459 [8] through the following Eq. 7:

$$GC_{cp} = \sum_{j=1}^{N} \left\{ CI_j + \sum_{t=1}^{CP} \left[\left(CM_{j,t} * R_t^{disc} * R_t^L \right) + \left(CE_{j,t} * R_t^{disc} * R_t^E \right) \right] + CR_{j,t_j} - Val_{j,cp} \right\}$$

Eq. 7

where:

t is the number of the year;
j is the insulation system;
cp is the calculation period;
CI_j is the initial investment cost of the insulation system j;
$CM_{j,t}$ is the annual maintenance cost of the insulation system j;
$CE_{j,t}$ is the annual energy cost due to the insulation system j ;
R_t^{disc} is the discount rate;
R_t^L is the price development rate for human operation (labour cost);
R_t^E is the price development rate for energy;
CR_{j,t_j} is the replacement cost;
$Val_{j,cp}$ is the residual value of the insulation system at the end of the calculation period.

The frequency of the replacement cost CR_{j,t_j} depends on the service life SL_j of the insulation system concerned, as shown in Eq. 8:

$$\left\{ CR_{j,t_j} = CI_j * R_{t_j}^{disc} * R_{t_j}^L \ , \ t_j = SL_j + 1, 2SL_j + 1, ..; SL_j < cp \right\}$$

Eq. 8

The residual value of the insulation system $Val_{j,cp}$ corresponds to the value of the system at the end of the calculation period. It is calculated based on a straight-line depreciation of the initial investment or replacement cost of the component until the end of the calculation, discounted at the beginning of the evaluation period, as shown in Eq. 9:

$$Val_{j,cp} = CI_j \left(\frac{r_j}{SL_j} \right) R_{cp}^{disc} \; R_{cp}^{L}$$

Eq. 9

where:

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

Eq. 10

represents the remaining life span at the end of the calculation period of the last replacement of the system j, depending on the service life SL_j of the system concerned.

The annual energy costs are calculated multiplying the annual energy use (Eq. 6) by the tariff for the energy carrier considered (EnT).

In the PM developed, the calculation of GC is “dynamic”, i.e. annual variations of the discount rate as well as annual variations of the price development rates of the annual costs (i.e. energy costs, periodic or replacement costs, maintenance costs) are considered.

The discount rate R_t^{disc} is a definite value for comparison of the value of money at different times expressed in real terms. It depends on the discount factor, d_t, which is a multiplicative number used to convert a cash flow occurring at a given point in time (year *t*) to its equivalent value at the starting point [8]. The discount rate R_T^{disc} at any generic time period T is calculated as in Eq. 11:

$$R_T^{disc} = \prod_{t=1}^{T} \frac{1}{1+d_t} = \frac{1}{1+d_1} \; \frac{1}{1+d_2} \cdots \; \frac{1}{1+d_T}$$

Eq. 11

The real discount factor, d_t, is a function of the inflation rate, π_t, and the nominal interest rate, i_t^N, according to Eq. 12.

$$d_t = \frac{i_t^N - \pi_t}{1+\pi_t}$$

Eq. 12

Furthermore, the methodology includes the possibility of development over time of prices for energy and labour that can be different from the inflation rate.

Accordingly, R_T^L and R_T^E are the price development rates that are applied to all cost components of the LCC equation (i.e. energy costs, periodic or replacement costs, maintenance costs), defined according to Eq. 13:

$$R_T^L = \prod_{t=1}^{T}(1 + e_t^L) = (1 + e_1^L)\ (1 + e_2^L)\ \dots\ (1 + e_T^L)$$

$$R_T^E = \prod_{t=1}^{T}(1 + e_t^E) = (1 + e_1^E)\ (1 + e_2^E)\ \dots\ (1 + e_T^E)$$

Eq. 13

where:

e_t^L is the escalation factor of the prices for human operation i.e. the growth rate of GDP (Gross Domestic Product) and it is computed in real terms as:

$$e_t^L = \frac{g_t^N - \pi_t}{1 + \pi_t}$$

Eq. 14

with g_t^N the nominal growth rate of GDP;

and e_t^E is the escalation factor of the prices for energy, i.e., the growth rate of crude oil price and it is computed in real terms as:

$$e_t^E = \frac{oilpg_t^N - \pi_t}{1 + \pi_t}$$

Eq. 15

where $oilpg_t^N$ is the nominal growth rate of crude oil price.
R_T^L expresses the price development rate of labour (L) (i.e, the wage development rate) and, as clear in Eq. 7, applies to maintenance and replacement costs. R_T^E expresses the price development rate of energy (E) and applies to energy costs.

Payback period

The payback period (PB) can be used to illustrate the potential of different design options (internal insulations) compared to a reference situation (uninsulated wall) by the time when initial investment is expected to be recovered. The payback period is reached when the global cost of the option is lower than the global cost of the reference for an identical period of calculation.

Since an investment with future expenditure is considered, a discounted payback period is used to reflect the time value of money. The discounted payback period is the time when the difference between the initial investment cost for the optional and reference case are balanced with the cumulative discounted annual costs difference in each individual year. The payback period can then be calculated as the number of years, S, required to the cumulative energy savings (Eq. 16) to equalize the initial investment costs and its subsequent operating costs (maintenance and replacement costs) (Eq. 17). The present value of operating-related savings and the present value of all other costs are considered, according to the following equations:

$$Savings = \sum_{t=1}^{S} \left\{ \left[\left(\frac{Qh^{pre} - Qh^{post}}{ETA_H} \right) \right] EnT \right\} R_t^{disc} \; R_t^E$$

Eq. 16

$$Costs = \sum_{j=1}^{N} \left\{ CI_j + \sum_{t=1}^{S} \left[\left(CM_{j,t} + CR_{j,t_j} \right) R_t^{disc} \, R_t^L \right] \right\}$$

Eq. 17

where:

Qh^{pre} is the pre-renovation energy need, namely the heat transmission losses through the not-insulated wall;

Qh^{post} is the post-renovation energy need, namely the heat transmission losses through the insulated wall;

Cost categories and economic parameters are calculated in the same way as in the Global Costs calculation. Furthermore payback, in general, ignores all costs and savings that occur after payback has been reached.

So, in summary, regarding the LCC model for calculating the global cost and payback period, the following parameters are considered in the probabilistic assessment:

- Design option layer
    - Investment cost of the insulation system
    - Annual maintenance cost of the insulation system
    - Service life of the insulation system[12]

- Scenario Layer
    - Calculation period
    - Inflation rate, interest rate, rate pf development of prices of the human operation and energy (depending on the macro-economic scenario)
    - Energy tariff, overall efficiency for heating (depending on the energy scenario).

2.6 Uncertainty characterisation

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

[12] influencing the number of replacements

- identify the uncertainty sources to be considered in the LCC 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 with a proposed "background PDF", that can be modified by the software 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.

2.6.1 Uncertainty characterisation for heat transmission losses

Heat losses uncertainty characterization is presented below for the annual calculation included in the WP5 software tool (option 3, see section 2.5.1)[13].Table 4 presents the parameters considered in the calculation.

Table 4 Uncertainty characterisation of heat losses parameters for the annual heat losses calculation

	Parameter description	**Distribution type in background PDF**
Local context (historic building façade)	Thermal Resistance of the existing wall	Normal distributions are implemented in WP5 software tool, based on an uncertainty range defined by the user.
Local context (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 1.
Design option (interior insulation system)	Thermal Resistance of the insulation system	Deterministic value.

[13] This is a simplified approach. As stated before, heat loss distributions can be obtained through "probabilistic" HAM methodologies, including a vast amount of uncertain input parameters (as done in RIBuild WP4).

2.6.2 Uncertainty characterisation for LCC data inputs

According to the multi-layer sampling scheme presented in section 2.3.1, the uncertain parameters in the PM for LCC of interior insulation systems are:

- insulation system investment (and replacement) cost, insulation system maintenance cost, insulation system service life. These are the stochastic variables related to a specific *design option* choice;
- heat transmission losses. It is the stochastic variable related to a specific *historic wall installation configuration scenario* choice;
- interest rate, inflation rate, rate of development of prices. These are the stochastic variables related to a specific *macro-economic scenario* choice;
- building overall efficiency for heating and the tariff of the energy vector. These are related to a specific *energy scenario choice*.

Except for the duration of the calculation period fixed as a deterministic value, all the other LCC parameters are considered stochastic. Table 5 reports all LCC input parameters considered in the assessment and the proposed distributions and characterisation method. All these parameters are included in the WP5 tool described in section 7.

Table 5 Uncertainty characterisation of LCC input parameters

LCC Input parameters		**LCC Cost Category details**	**LCC Parameter description**	**Proposed distribution type in background PDF**
Financial data	**Duration of the calculation**		Duration of the calculation [years]	Deterministic
	Financial rates	Necessary for the calculation of the discount rate	Inflation rate [%]	PDF established based on the macro-economic scenario (see section 3)
			Market interest rate [%]	PDF established based on the macro-economic scenario (see section 3)
	Prices development rates	May be different from inflation rate	Prices development rates [%]	PDF and trends established based on the macro-economic scenario (see section 3)
System characteristics	**Component Investment cost**	Insulation systems purchase and installation costs	Insulation system Investment cost [€]	No mandatory PDFs. PDFs can be established based on data-fitting on available costs data (see exemplary cases in sections 4, 5 and 6)
	Periodic costs for replacements	Depending on systems Service Life and replacement costs (also necessary to calculate the Final Value)	Insulation system Service Life [years]	No mandatory PDFs. PDFs can be established based on the probabilistic factorial method (see exemplary cases in sections 4, 5 and 6 and Deliverable Report 5.1)
			Insulation system Replacement costs [€]	As investment costs
	Running Costs	Component annual preventive maintenance and repair	Insulation system annual Maintenance cost [€]	No mandatory PDFs. PDFs can be established based on data-fitting on available costs data (see exemplary cases in sections 4, 5 and 6)

Energy Costs	**Energy consumption**	Calculated by heat transmission losses through the wall and based on equipment efficiency and energy source typology	Heat transmission losses through the wall [kWh/y]	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 Costs	Energy consumption is coupled with tariff for the energy considered	Energy source national tariff [€/kWh/y]	No mandatory PDFs. PDFs can be established based on data-fitting on available costs data (see exemplary cases in sections 4, 5 and 6)

The uncertainty characterisation for the service life data is presented in more details in section 2.6.3.

Furthermore, Section 3 proposes a specific approach for the characterisation of the macro-economic variables (financial rates and rates of development of prices) included in the LCC PM.

The characterisation of some input parameters (as the systems investment and maintenance costs, the energy equipment efficiency and the energy tariffs) is strongly dependant on the typology of design options selected and the national context. Characterisation methodologies for these inputs are proposed as examples in sections 4, 5 and 6.

2.6.3 Uncertainty characterisation for materials/systems 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*, while the estimated SL of the whole insulation system affects the need of periodic *replacement*. 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 service life of materials and insulation systems is kept flexible in the PM. So, proper PDFs or values can be chosen considering the available data and literature on this topic.

Nevertheless, among the characterisation methods, the PM suggests using the “probabilistic factorial method”, included in ISO 15686 standards, to go from reference service life (RSL) to estimated service life (ESL). Due to the specific environmental exposure, maintenance policies and other factors, the actual estimated service life differs from reference service life.

In the factorial method, the 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. 18. 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 [63] and also explained in [64],

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

Eq. 18

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 [64], 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 [65–68];
- 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 [69,70].

In practice, in the "probabilistic" factorial method, each factor can be defined by a probability distribution and the PDF of the ESL is obtained through a Monte-Carlo process that combines the factors PDFs.

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 [66,71], scientific research, regulations and building standards (with conventional or recommended service lives data to use), technical information from producers, laboratory tests and statistical analysis [71–73] and materials Environmental Products Declarations (EPDs). In addition, investment banks, professional building owners or tenants also provide service life data.

Appendix 1 of RIBuild deliverable D5.1 gives examples of reference values for service life of building materials, especially insulations, coming from different sources and different bodies, including the EPDs.

2.7 Uncertainty propagation and sensitivity analysis

This section presents the last two steps of the LCC PM (uncertainty propagation, uncertainty and sensitivity analysis).

For uncertainty propagation, Monte Carlo methods are chosen to propagate the heat losses and LCC parameter uncertainties into a distribution of the output variable. The output sample can then be visually represented by Probability Density Functions, 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 4.

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 (SA) through variance based decomposition (Sobol' method) techniques, part of the Global Sensitivity Analysis (GSA) [74,75]. Indeed, the SA based on Sobol's variance decomposition approach imperatively needs the input sample generated by the Sobol sequences [76]. The number of model evaluations (sample size) depends on the number of variables [77]. 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 [77]. 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 [78].

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 [74]. The higher the value of the sensitivity indices, the more 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 LCC model can be simplified by considering for the not-influential inputs their "deterministic" values.

As specified later in section 3.6, the PM developed and the related software tool allow to perform the Sensitivity Analysis in two different ways.

In this case, the Sobol sampling is performed only on the other LCC parameters, in order to assess the eventual variation of the sensitivity indices once fixed the economic inputs.

2.8 Conclusions

In section 2, the probabilistic LCC methodology is presented, developed within RIBuild Task 5.3 in the field of internal insulation solution of historic buildings. The probabilistic methodology (PM) can be seen in parallel with that of Task 5.2 "Probabilistic Life Cycle Impact Assessment of the environmental impact of internal insulation solutions", reported in WP5 Deliverable 5.1. Both tasks 5.2 and 5.3 aimed to develop a "probabilistic" approach, respectively to Life Cycle Impact Assessment and to Life Cycle Costing to assess the possible environmental impacts and costs of internal insulation measures. Consequently, the methodology developed in both fields has a similar structure.

The PM presented is based on an LCC assessment performed at "component level", according to international standards EN 15459:2017 [8] and ISO 15686-5:2017 [1]. The LCC calculation is coupled with a Monte-Carlo based method for the propagation of the inputs' probability distributions into the output distributions, in terms of the two economic indicators: global cost and Payback period.

The LCC PM can be applied to assess the economic feasibility of several design options (internal insulation solutions) in several possible scenarios (original wall applications, climatic contexts, energy sources, macro-economic scenarios, calculation periods). At this aim, the LCC simulation parameters can be sorted out according to a *multi-layered sampling scheme* [50]. 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 approach can be used to assess the economic impact of several insulation solutions, in several existing walls configurations and in different climates, in order to realize the WP6 guidelines on internal insulation.

The PM is based on a flexible approach, tailored to the user needs. In particular, it proposes 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 economic 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, can be made during WP6 to realize the RIBuild guidelines.

In order to contribute to the recent literature on LCC under uncertainty, the methodology proposed can be used to provide realistic decision support during the design phase, giving insight into design robustness and possible ranges of economic returns of a specific design option. Secondly, it compares the economic performance of different design options both in terms of expected returns and of its variance, thus possibly identifying the dominant/dominated alternatives (i.e. those with a higher/lower expected return and a lower/higher variance thus risk). Thirdly, it provides evidence about the magnitude of LCC input parameters' and variables' uncertainty and about their impact on the result (through a sensitivity analysis).

Sections 4, 5 and 6 present exemplary case studies applying the methodology in different contexts. The different aspects of the methodology (comparison of design options in several scenarios, sensitivity analyses for identifying influential parameters) are illustrated.

Finally, the software tool, with the methodology implemented, is presented in section 7.

3 Identification and characterisation of alternative macro-economic scenarios for the LCC

3.1 Introduction

In this section, an innovative specific procedure developed to identify and characterise several possible macro-economic scenarios in Europe is described. These alternative scenarios allow to perform the calculation of the economic indicators (Global Costs and Payback Period) of a given insulation solution considering different economic contexts and compare the related results' robustness and variations.

These scenarios are discrete and deterministically identified. However, within each scenario, the variables entering the LCC calculation behave as stochastic variables and projections are generated as draws from appropriate probability distributions.

Scenarios refer to alternative general macro-economic conditions and perspectives and are defined on the basis of actual historical experiences that expressed an interdependence among macro-economic variables. The event of an economy falling in one of these conditions is largely unpredictable. The choice among scenarios, therefore, should be driven by other orders of arguments: political relevance, ethical concerns, attitude towards risk, etc.

The identification of the macro-economic scenarios reflects the main feature of the proposed methodology and is perhaps one of the major novelty with respect to the existing literature [37,38]: macro-economic variables are time-dependent and interdependent and scenarios express possible combinations of these variables that can be encountered under different economic conditions and medium and long-term growth patterns.

In the developed approach, in practice, the first element of novelty is that the time dependence of economic variables is taken into account. Thus, economic variables behave like random variables whose distribution at a given time is conditional on their realization at previous times. The second major novelty is that their multivariate nature of the variables is also accounted for. As a result, LCC macroeconomic variables are not only time dependent, but also interdependent. This means that any variable's distribution is conditional on the distribution of the other variables and, therefore, due to time dependency, on the lagged distributions of the other economic variables. To this nature of the variables is given a strong economic justification: indeed, macroeconomic theory and empirics have largely emphasized and investigated the relationships occurring among these variables [79].

Furthermore, as economic theory and empirical evidence highlight, this interdependence also is a function (in terms of intensity and direction) of the macroeconomic climate or scenario in which it occurs. "High growth-low inflation" and "low grow-high inflation" are two quite diverse macroeconomic conditions whose difference is in fact reflected into a different interdependence between the macroeconomic variables involved. Scenarios are then defined on the basis of actual historical experiences that expressed a different linkage and interdependence among macroeconomic variables.

Consequently, no distributional assumption is made (actually, normality is maintained for simplicity) as the estimated distributions of the macroeconomic variables are based on observed time series. Therefore, one of the main issues in probabilistic LCC calculations that concerning the reliability of the distributional assumption, is here substantially downscaled: not only these distributions are estimated from real data, but also alternative distributions can be obtained by looking at different time series as expressions of different medium-long term macroeconomic conditions.

The quantitative expression of the qualitative scenarios is pursued by looking at historical data of those (macro)economic variables affecting the life-cycle costs (either implicitly or explicitly). These variables are:

- Inflation rate = % variation of the Relative consumer price indices (CPI)

- Interest rate = Long-term interest rates, Per cent per annum (INT) (nominal)
- GDP = Quarterly growth rate of GDP (Gross Domestic Product), seasonally adjusted (GPSA). This GDP has been used as escalation factor of the prices for human operation (labour cost), e_t^L, in the formula of Global Costs calculation (Eq. 7).
- Oil price = Crude oil, Brendt, nominal (available since 1978). This has been used as the escalation factor of the prices for energy, e_t^E, in the formula of Global Costs calculation (Eq. 7).

The inflation rate and the (real) interest rate together define the discount rate; while the oil price and GDP affect the annual costs associated to individual components.

Table 6 summarizes the macro-economic scenarios to be considered.

Table 6 Alternative macro-economic scenarios, where "Regular growth" can be considered the baseline scenario and the respective long-term expected values (and variances) are indicated with "=" as they serve as reference for the alternative scenarios; ↑ means higher than the baseline; ↓ means lower than the baseline

Variable: ***Scenario:***	**Inflation rate**	**Interest rate**	**GDP**	**Oil price**
Regular growth ***(Baseline)***	=	=	=	=
Intense growth	↑	↑	↑	↑
Stagflation	↑	=	↓	↑
Deflation	↓	↓	↓	↓

Table 7 reports the reference country and historical data and sources of (macro) economic variables used for the quantitative expression of the scenarios.

As mentioned, these scenarios are defined using actual historical experiences that expressed a linkage and interdependence among macro-economic variables. In particular, the values associated to the "Baseline" scenario are obtained by looking at the EU performances for the variable analysed over the period 1980-2005. The "Intense growth" values are taken from the 1990-2007 performance of the US economy. Values of the "Stagflation" scenario are taken from the US performances over the period from 1968 to 1974. The "Deflation" values are taken from the 1990-2005 Japan data (Table 7).

Table 7 Reference country and data used. Notes for baseline scenario: *Germany when EU not available (i.e. for GDP growth rate 1980-1995)

Variable: ***(data source)*** ***Scenario:*** ***(ref. country)***	**CPI**	**Interest rate**	**GDP**	**Oil price**
Regular growth ***(Baseline)***	=	=	=	=
EU **1980-2005***	Quarterly **OECD** financial statistics	Quarterly **OECD** financial statistics	Quarterly **OECD** national accounts	Monthly/Annual **World Bank**

Intense growth	↑	↑	↑	↑
US **1990-2007**	Quarterly (**FRED** Economic data)	Quarterly **OECD** financial statistics	Quarterly **OECD** national accounts	Monthly/Annual **World Bank**
Stagflation	↑	=	↓	↑
US **1968-1974**	Quarterly (**FRED** economic data)	Quarterly **OECD** financial statistics	Quarterly **OECD** national accounts	Monthly/Annual **World Bank**
Deflation	↓	↓	↓	↓
Japan **1990-2005**	Quarterly **Japan - Statistics Bureau**	Quarterly **OECD** financial statistics	Quarterly **OECD** national accounts	Quarterly **Bank of Japan**

Once the macro-economic scenarios are characterized, it is possible to enter the stochastic part of the analysis, that is, the generation of N-years projections of all relevant macro-economic variables.

The aim is to estimate, from historical data, multivariate statistical distributions that characterize the evolution of the main macro-economic variables influencing economic activities, namely interest rate, inflation rate and growth rate of GDP, under the different scenarios' assumptions.

It is assumed that the crude oil price acts as exogenous driver and influences the evolution of the variables.

A specific joint distribution is estimated for each hypothesized economic scenario. The distributions contain all the statistical properties regarding the interdependence between the macro-economic variables and their variability that can be used to predict the evolution of the economy under each scenario.

The VAR (Vector Autoregression) is used to model the relationships between variables and obtain the joint distributions. This modelling method has been found to be the most appropriate one, given the stochastic characteristics of the data[14]. Time series variables enter the VAR model as follows: each variable has an equation explaining its evolution based on its own lagged values, the lagged values of the other model variables and an error term. The best model that fits the data (i.e. how many lags to include), is identified using an iterative procedure based on information criteria. This VAR model will be used also for predictions.

Given the probabilistic nature of the model, for each scenario, predictions (i.e. simulations) are generated. These simulations are the outcome of a Monte Carlo procedure in which the estimated

[14] The variables series must be stationary (i.e., I(0)), to enter the equation in the level in order to estimate the unknown parameters. If some of the series are non-stationary (i.e., I(1)), they have to enter the equation as first difference to have consistent estimation and projections of the relationship occurring among variables. If all series are I(1), the Vector Error Correction (VEC) variant of the model must be specified and estimated in order to generate projections of the long-term relationship among variables captured by the respective cointegration vector. Augmented Dickey-Fuller stationarity tests have been carried out for each variable [107].

dynamical system characterizing the mean of the distribution is perturbed by random draws from a normal distribution that account for the interdependence and for the variability of the economic variables. Simulations are useful because they represent alternative possible trajectories that the macro-economic variables could show, while retaining the statistical properties characterizing each scenario. Thus, the correlation structure among variables and the variance-covariance structure of the estimated models are used to generate the predictions.

Data of future oil prices used as driver of the models are taken from the EIA (Energy Information Administration)[15] and are up to 2050.

3.2 Characterization of the Regular Growth scenario

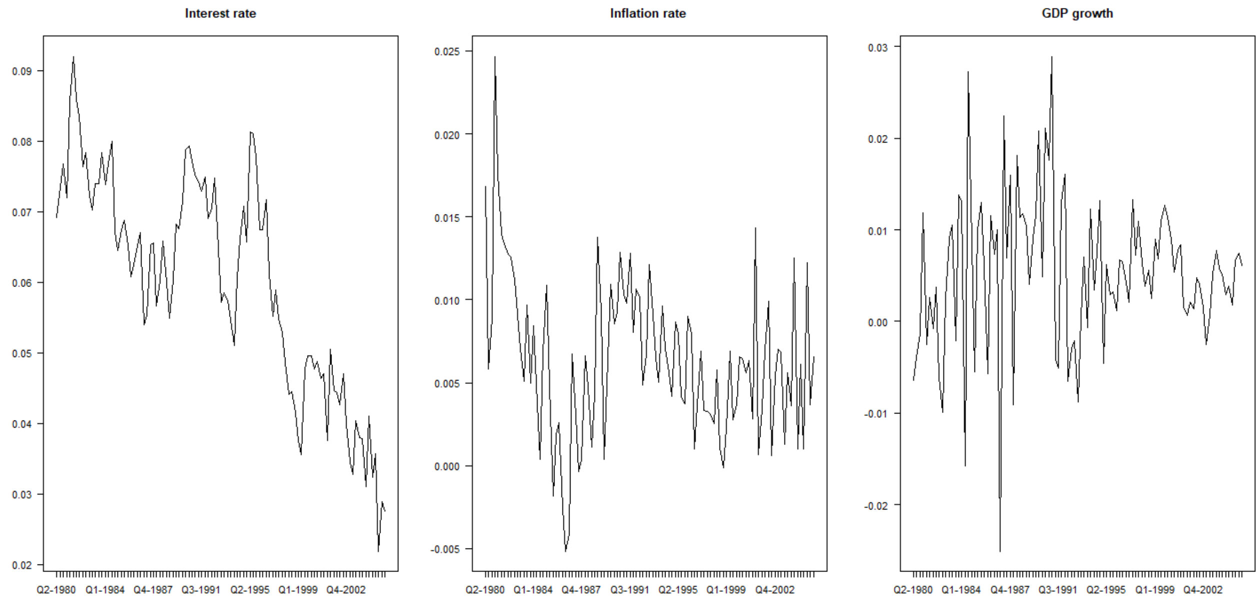


Figure 7 Quarterly observations 1980-2005 of the three endogenous variables: real interest rate; inflation rate; real GDP growth rate

The regular growth (RG) scenario aims to express a sort of regular (or baseline) case, characterised by a balanced growth path of the economy with an inflation rate around 2%, mild GDP growth rate and long-term real interest rate. Such scenario is represented in Figure 7. Data are quarterly observations and span the period from the second quarter of 1980 to the last quarter of 2005.

In the present scenario, unit root tests clearly indicate that all variables in the model behave like I(0) series while the oil price is I(1)[16]. Therefore, this latter variable enters the equation as first difference (i.e., the change of oil price from t-1 to t).

Assuming the oil prices could influence the inflation rate with up to a 6 quarters lags, information criteria identify two possible VAR models to best fit the data. Two criteria suggest a more parsimonious model with one lag for autoregressive term and one plus the contemporaneous effect

[15] https://www.eia.gov/
[16] While inflation and GDP growth are stationary around a constant, interest rate is found to be trend-stationary.

for the oil prices (i.e. a VAR(1,1)), while the other two criteria identify a VAR(4,1) as the appropriate one.

The VAR(4,1) proved to better fit the data after the analysis of the results for both models. Thus, the final model is a dynamical system with four lags for the endogenous variables and one lag for the exogenous ones. The model can be written as follows (Eq. 19)[17]:

$$\begin{bmatrix} di_t \\ \pi_t \\ g_t \end{bmatrix} = A \begin{bmatrix} di_{t-1} \\ \pi_{t-1} \\ g_{t-1} \end{bmatrix} + B \begin{bmatrix} di_{t-2} \\ \pi_{t-2} \\ g_{t-2} \end{bmatrix} + C \begin{bmatrix} di_{t-2} \\ \pi_{t-2} \\ g_{t-2} \end{bmatrix} + D \begin{bmatrix} di_{t-2} \\ \pi_{t-2} \\ g_{t-2} \end{bmatrix} + EX + \varepsilon_t \qquad \varepsilon_t \sim N(\mathbf{0}, \boldsymbol{V})$$

Eq. 19

Where: di_t is the detrended interest rate, π_t is the inflation rate and g_t the growth rate of GDP in real terms, A, B, C and D are the matrixes of coefficients associated with the lags of the endogenous variables, X is the matrix containing the information on the oil price up to two quarters lag and E is the corresponding coefficient matrix. Residuals ε_t are assumed to be drawn from a normal distribution with mean zero and the $\boldsymbol{V}$ as variance covariance matrix.

The estimated model is evaluated with a set of diagnostic tests on the residuals of the model (Figure 8, Figure 9, Figure 10).

Diagnostic test indicate that the residuals are not serially correlated and do not exhibit volatility clustering at 95% confidence level[18]. However, the Normality assumption might not hold.

Values of the EIA annual projected oil prices, together with their estimated quarterly growth rates, are presented in Figure 11.

Using the correlation structure and the variance covariance matrix estimated from the VAR, and using the projection for the oil price provided by the EIA, predictions of the average level and confidence intervals for the macro-economic variables are generated up to 2050[19] (Figure 12).

With the statistical information contained in the VAR estimates, it is possible to simulate different trajectories for the three variables, assuming the exogenous path of the oil price and that the dynamical system is perturbed in every quarter by a random draw from the joint normal distribution with mean zero and variance-covariance matrix equal to the matrix **V** estimated.

The results of twenty simulations for the three variables is presented in the graphs in Figure 13.

It is possible to see that the simulations move mostly within the estimated confidence intervals, and that prediction rarely cross those boundaries. As the confidence interval was designed for a confidence level of 95%, the simulated paths are expected to cross the confidence interval boundaries 5% of the times.

[17] The variance-covariance structure is obtained from the residuals of this model.

[18] JB-Test (multivariate): *Chi-squared = 32.105, df = 6, p-value = 1.558e-05,* Portmanteau Test (asymptotic): *Chi-squared = 90.353, df = 108, p-value = 0.890,* ARCH (multivariate): *Chi-squared = 170.79, df = 180, p-value = 0.6768.*

[19] VAR predicitons are produced up to 2050 as the Energy Information Administration estimates of future oil prices are available until 2050. However, LCC analysis can be performed over longer time horizons. In the case the horizon exceeds year 2050, predicitons of economic variables are calculated as the average of the previous predictions.

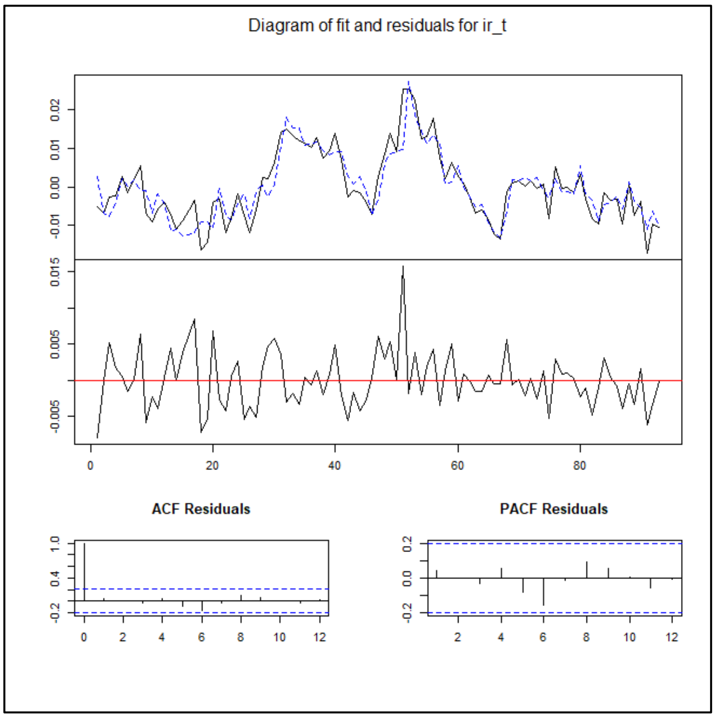


Figure 8 Fitted values, residuals and autocorrelation of residuals for the detrended real interest rate data

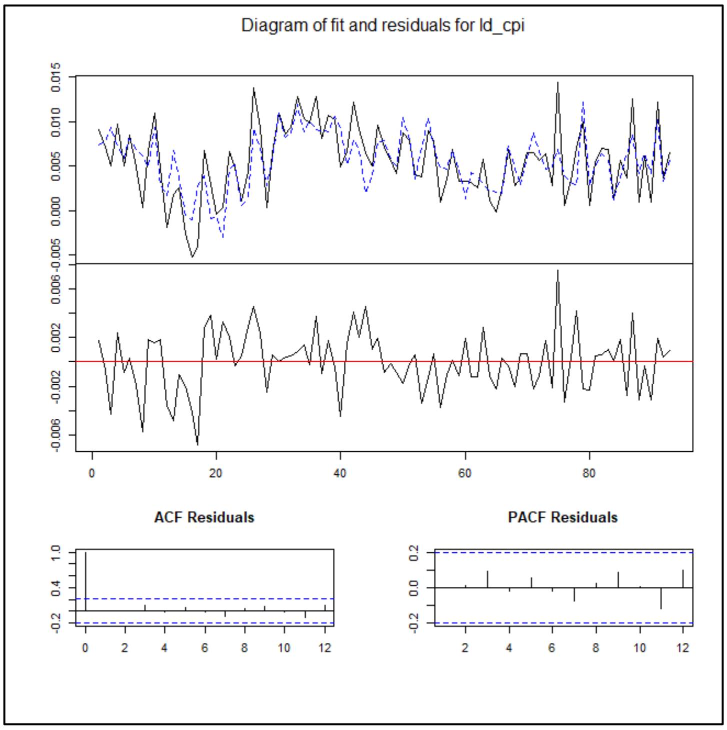


Figure 9 Fitted values, residuals and autocorrelation of residuals for the inflation data

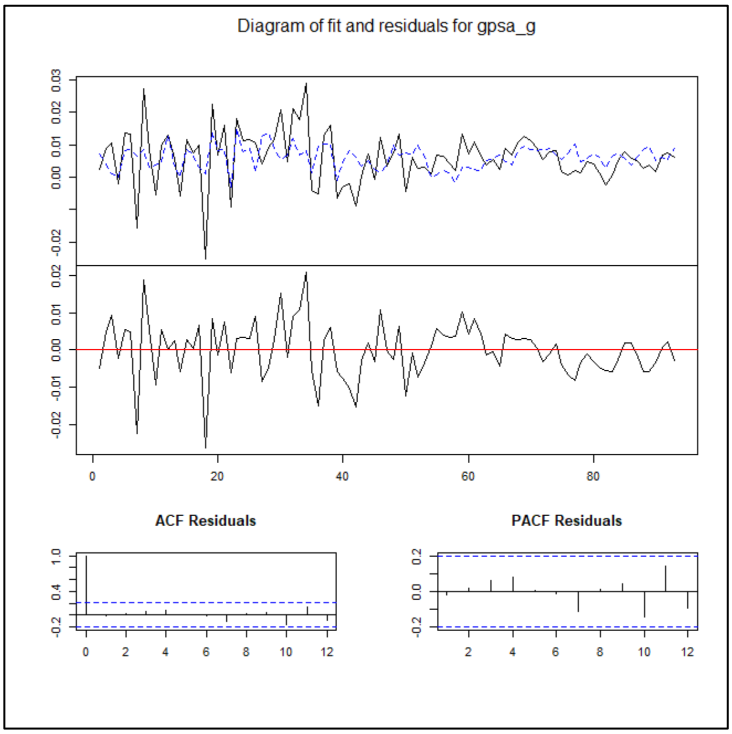


Figure 10 Fitted values, residuals and autocorrelation of residuals for the real GDP growth data

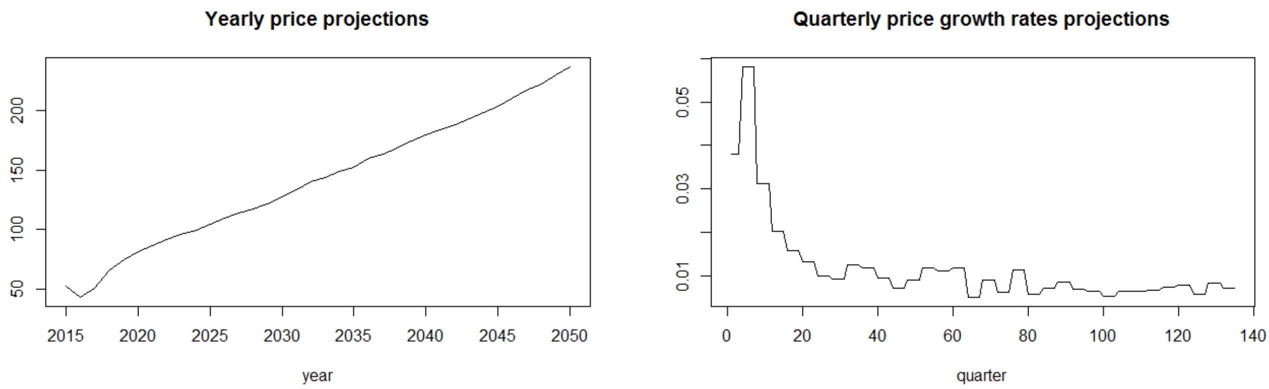


Figure 11 Values of the annual projected price and the estimated quarterly growth rates of the crude oil

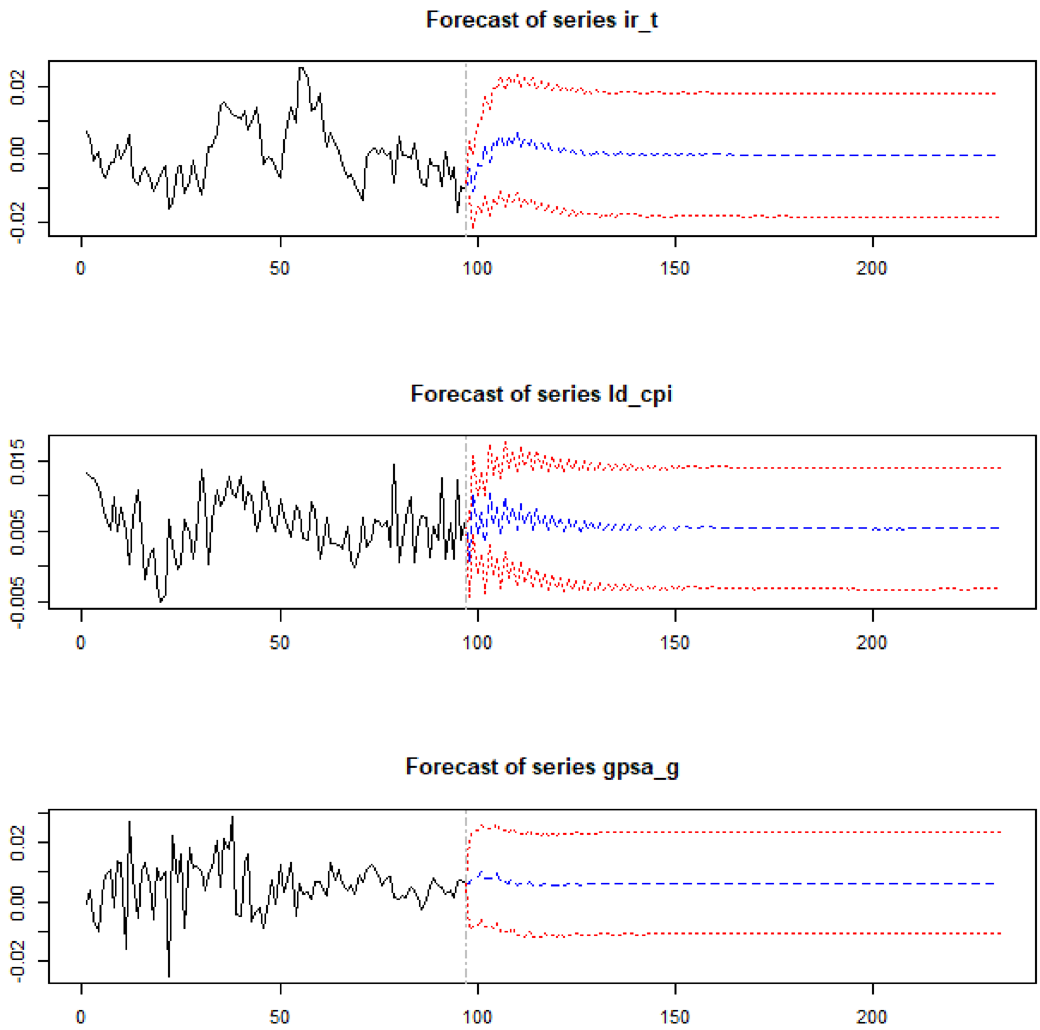


Figure 12 Predictions of the average level and confidence intervals for the macro-economic variables up to 2050: real interest rate, inflation, real GDP growth

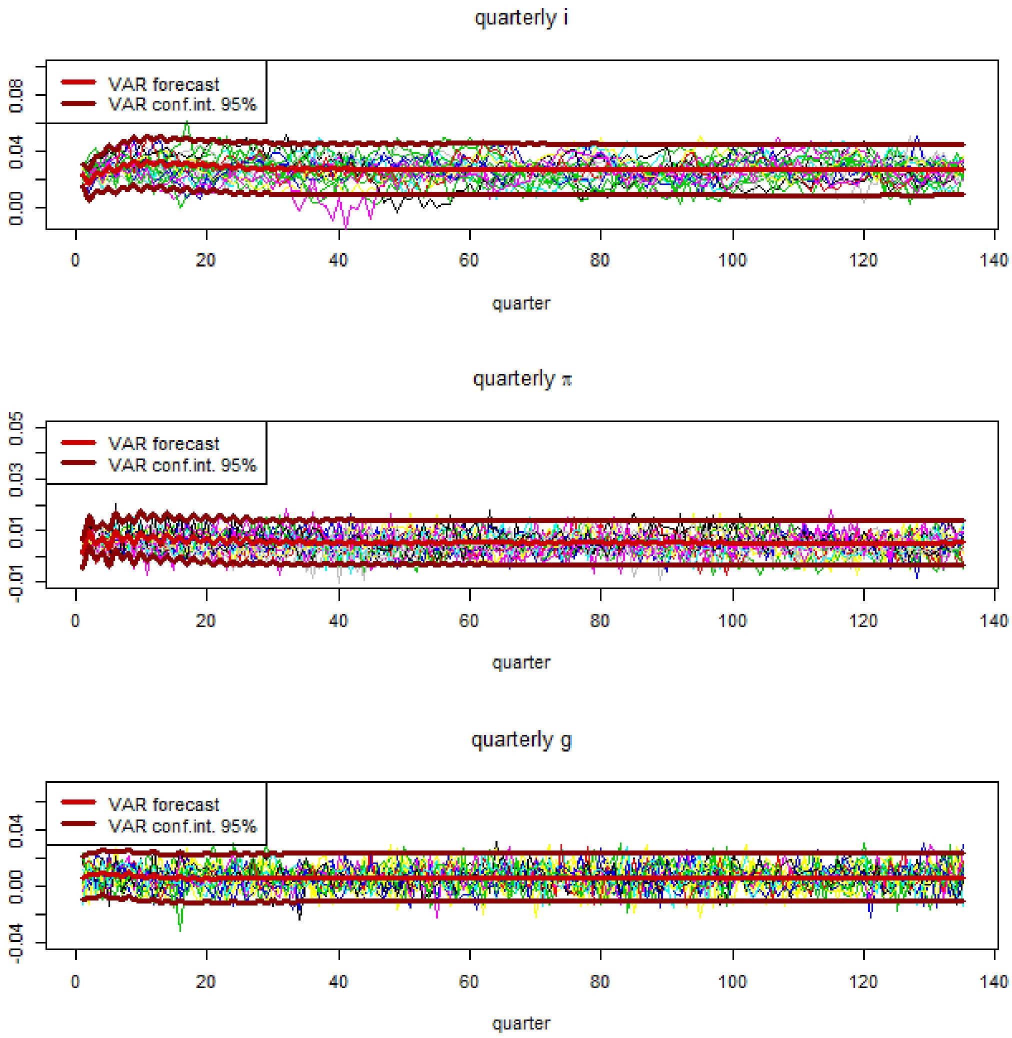


Figure 13 Twenty simulations and confidence intervals for the three variables real interest rate; inflation rate; real GDP growth rate (quarterly frequency)

The predictions generated are the results of the VAR estimates using quarterly data. To formulate the predictions of the growth rate of GDP and of the inflation rate with annual frequency, which was useful for the purposes of the LCC assessment, an aggregation of the quarterly data to annual data was required. To annualize the quarterly series of the interest rate, their average value is taken in every year[20]. For every year, the annual growth rate is obtained as follows (Eq. 20):

$$annual\ growth\ rate = \prod_{i=1}^{4}(1 + quarterly\ growth\ rate_i) - 1$$

Eq. 20

Annualized predictions are presented in Figure 14. Summary statistics of the yearly predictions are presented in Table 8.

[20] The quarterly growth rate related to the previous quarter.

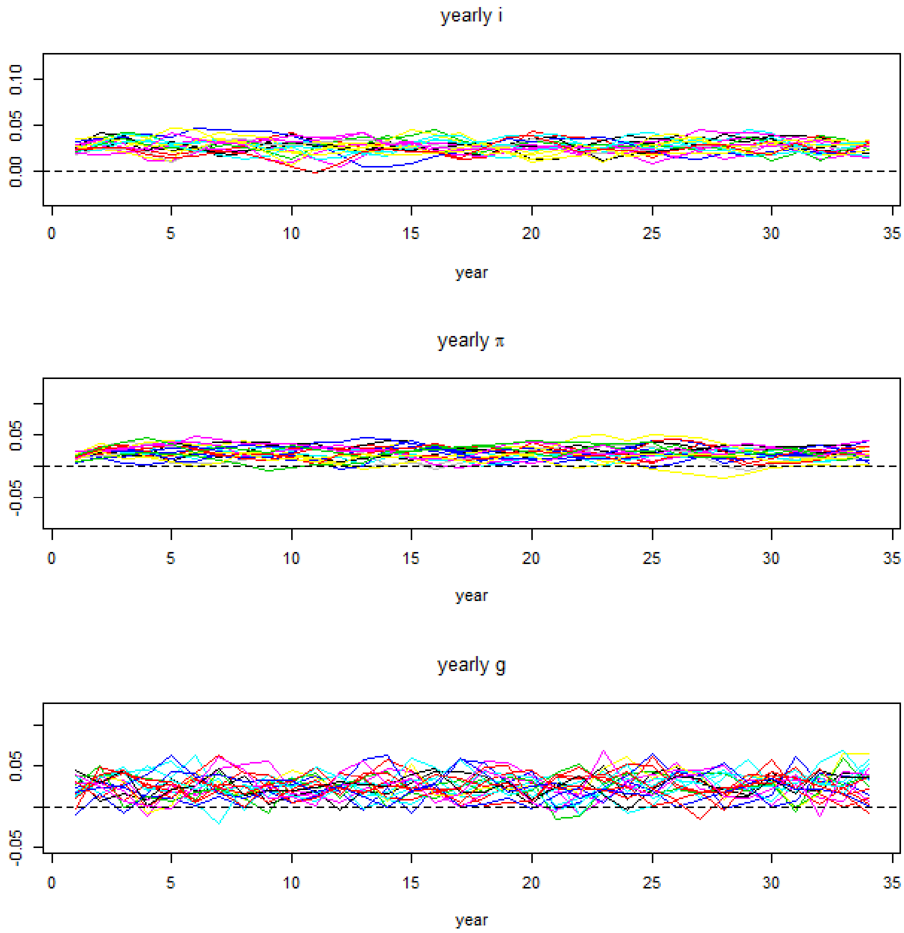


Figure 14 Twenty simulations for the three variables real interest rate; inflation rate; real GDP growth rate (annual frequency)

Table 8 Summary statistics of annual predictions: inflation rate (π_t); real GDP growth (g_t); real interest rate (i_t).

VARIABLE	MEAN	SD
π_t	2.25%	0.97%
g_t	2.54%	1.64%
i_t	2.77%	0.78%

3.3 Characterization of the Intense Growth scenario

The Intense Growth (IG) scenario is characterized by a robust growth of the real GDP and an inflation rate and interest rate higher than in the baseline case. Such conditions are met during the period 1990- 2007 in the USA. Therefore, data at quarterly frequency describing the evolution of this historical setting are used to estimate a VAR model and generate predictions. Data are presented in Figure 15.

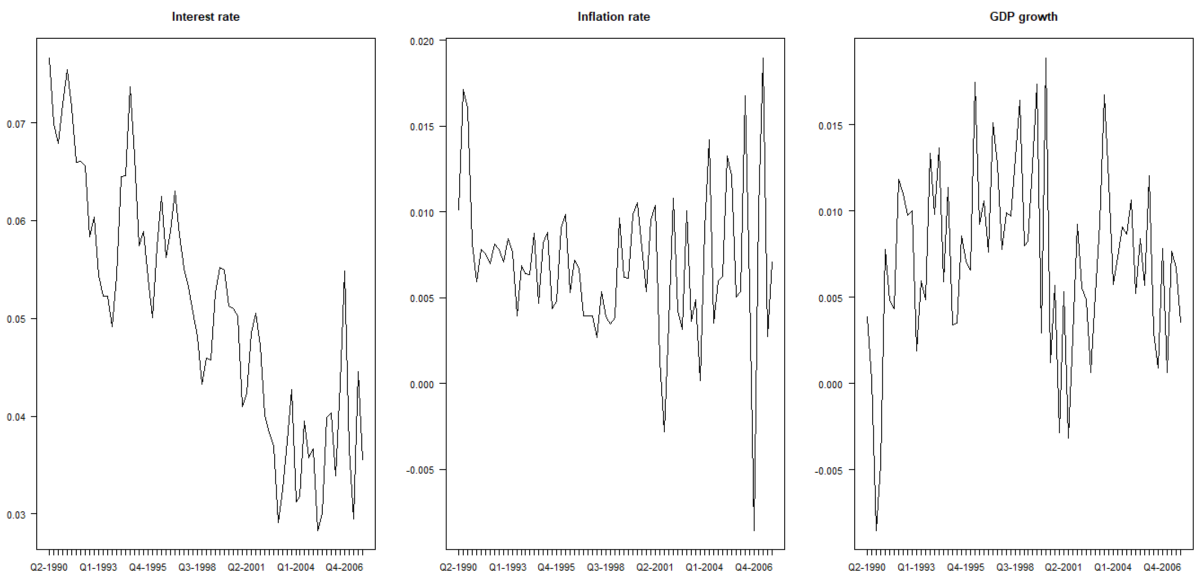


Figure 15 Quarterly observations 1990-2007 of the three endogenous variables: real interest rate; inflation rate; real GDP growth

Even in the intense growth scenario, augmented Dickey–Fuller test unit root tests point to the stationarity of all endogenous variables[21]. The information criteria-based, iterative procedure to find the best fitting model for the data of the IG scenario selects again a VAR(4,1) as the best one. Model fit and residuals autocorrelations are found in Figure 16, Figure 17, Figure 18.

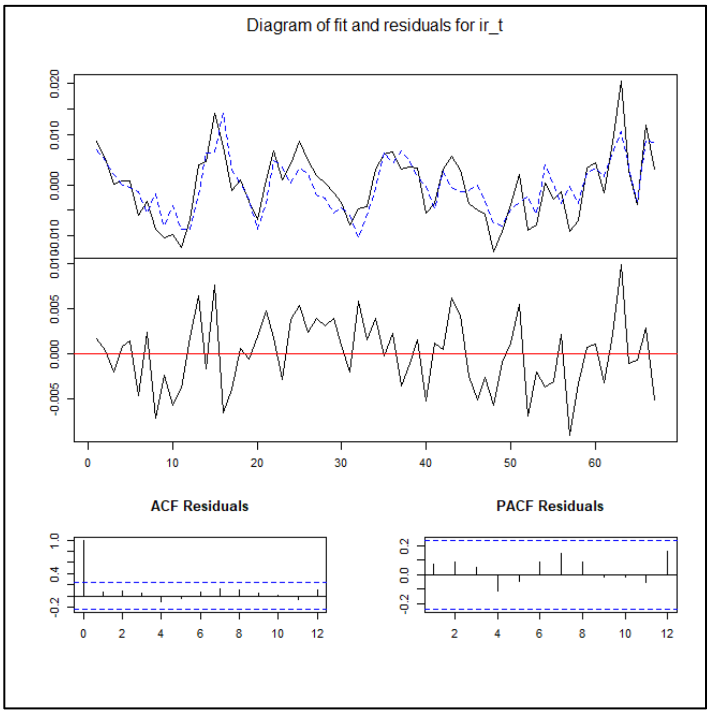


Figure 16 Fitted values, residuals and autocorrelation of residuals for the detrended real interest rate data

[21]Inflation and GDP growth data are stationary around a constant while the interest rate data is stationary around a trend.

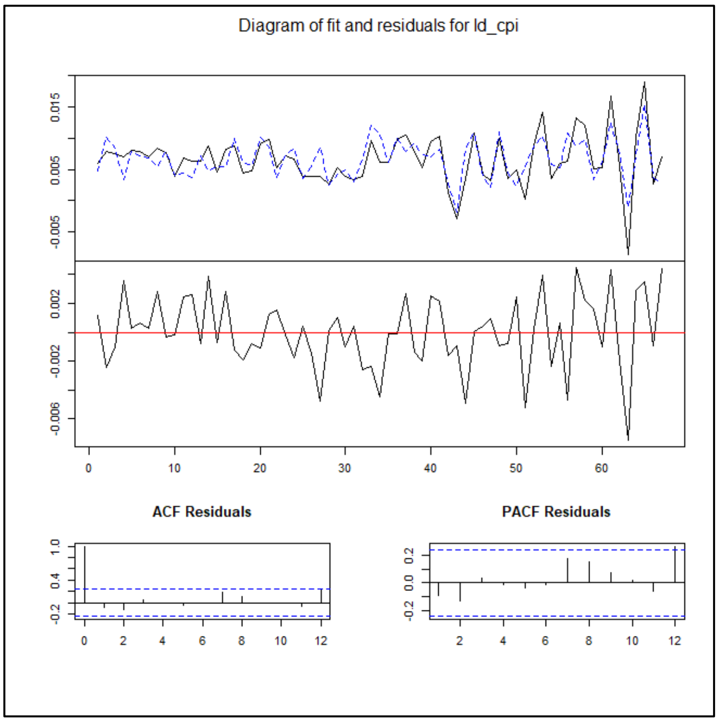


Figure 17 Fitted values, residuals and autocorrelation of residuals for the inflation data

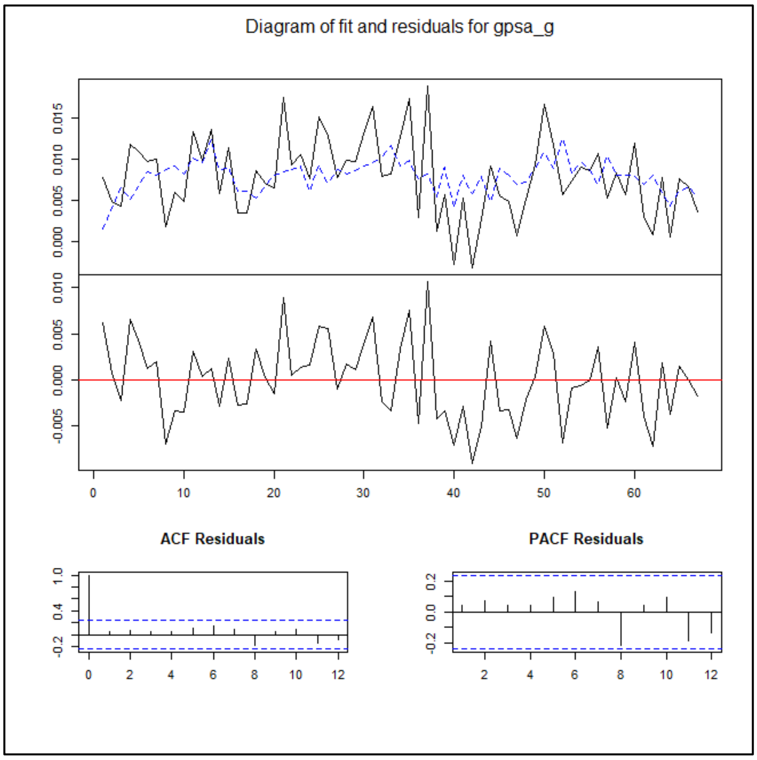


Figure 18 Fitted values, residuals and autocorrelation of residuals for the real GDP growth data

Diagnostic tests find neither serial correlation nor volatility clustering in the residuals. In addition, the Jarque-Bera test fails to reject the null hypothesis of normality[22].

A sample of quarterly predictions together with their 95% confidence intervals are presented in Figure 19. A sample of annual predictions is presented in Figure 20. Summary statistics of predictions are found in Table 8.

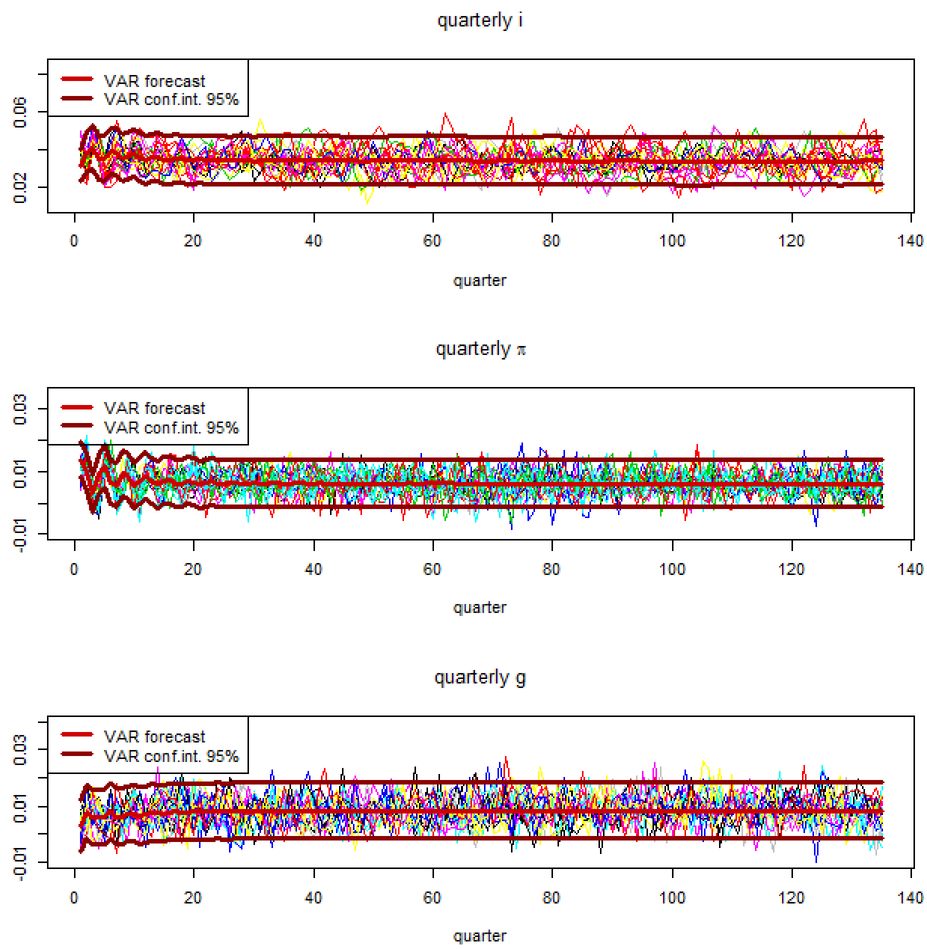


Figure 19 Sample of simulations and confidence intervals for the three variables real interest rate; inflation rate; real GDP growth rate (quarterly frequency)

[22] JB-Test (multivariate): *Chi-squared = 3.2349, df = 3, p-value = 0.3568,* Portmanteau Test (asymptotic): *Chi-squared = 98.291, df = 108, p-value = 0.7376,* ARCH (multivariate): *Chi-squared = 189.71, df = 180, p-value = 0.2953.*

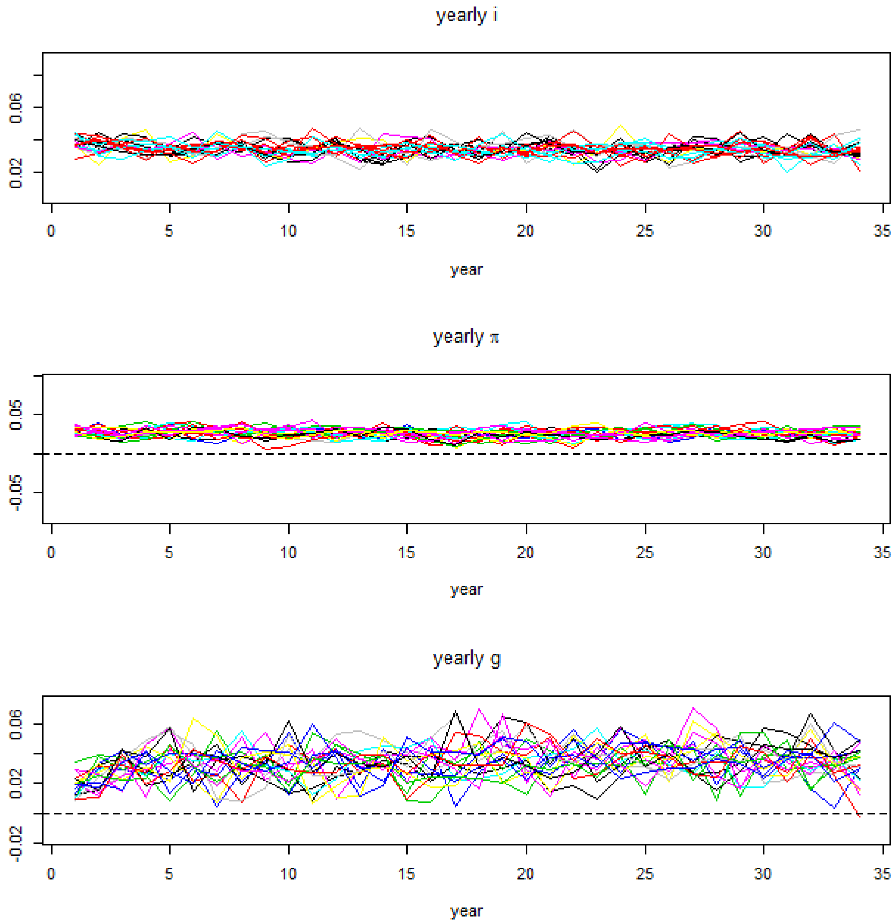


Figure 20 Samples of simulations for the three variables real interest rate; inflation rate; real GDP growth rate (annual frequency)

Table 9 Summary statistics of annual predictions: inflation rate (π_t); real GDP growth (g_t); real interest rate (i_t)

VARIABLE	MEAN	SD
π_t	2.55%	0.63%
g_t	3.31%	1.19%
i_t	3.45%	0.73%

3.4 Characterization of the Stagflation scenario

Stagflation (SF) is a situation in which the economy is characterized by low growth of GDP and high inflation. At the same time, a high interest rate might not be enough to rein in inflation and to drive the economy to a more balance growth path. A situation in which high inflation and stagnation coexisted is represented by the period 1968-1974 in the USA. Data at quarterly frequency are presented in Figure 21. Given the smaller number of observations, augmented

Dickey–Fuller tests point to stationarity with less confidence[23]. However, overall the series have been considered stationary.

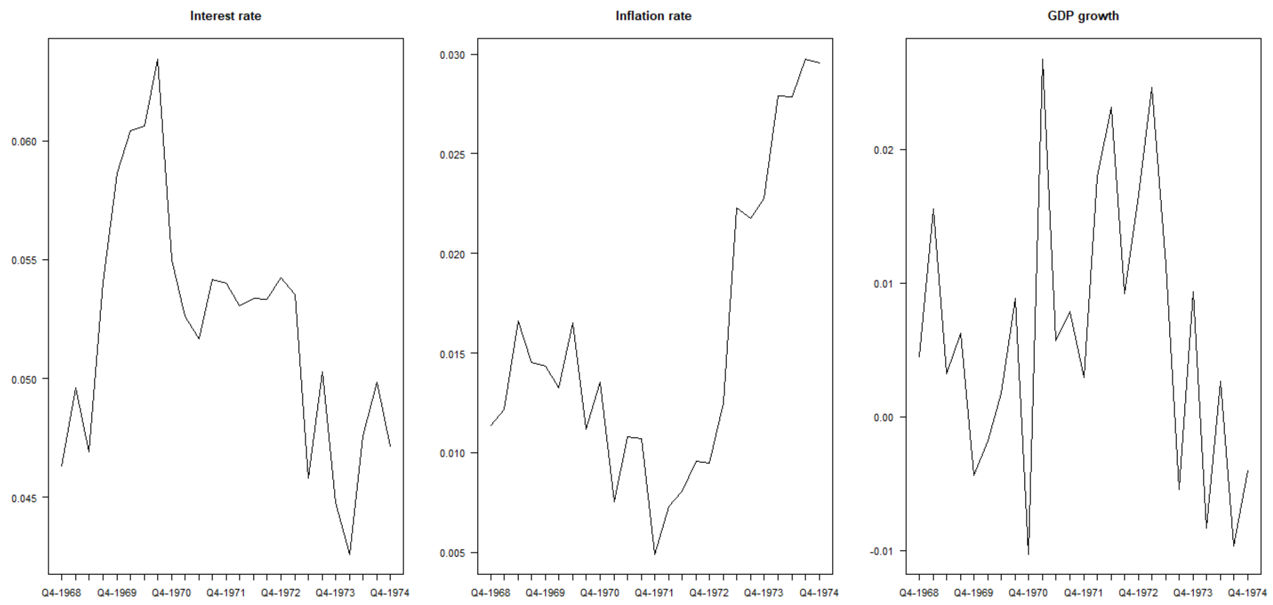


Figure 21 Quarterly observations 1968-1974 of the three endogenous variables: real interest rate; inflation rate; real GDP growth rate

The best VAR model to fit these data is given by a VAR(1,1). Therefore, the best model assumes that in such an historical period, the three main macro-economic variables can be predicted by their own first time lag plus the contemporaneous effect of the oil price as well as its first lagged effect.

Model fit and residuals are presented in Figure 22, Figure 23, Figure 24.

[23] Interest rate data are stationary around a trend at 95% confidence, inflation is stationary at 90% confidence while GDP growth is close to stationarity at 90% confidence.

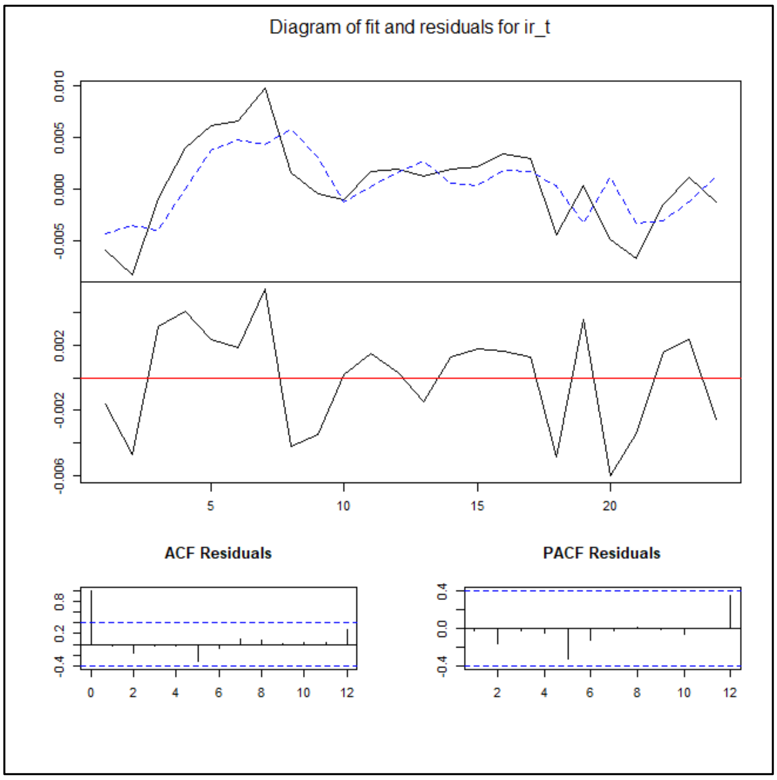


Figure 22 Fitted values, residuals and autocorrelation of residuals for the detrended real interest rate data

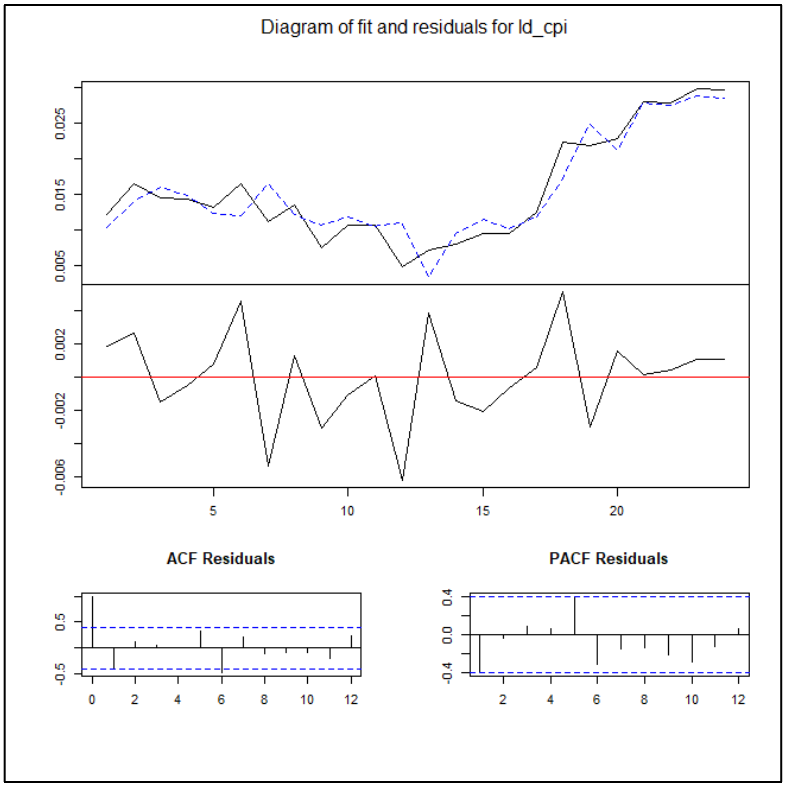


Figure 23 Fitted values, residuals and autocorrelation of residuals for the inflation data

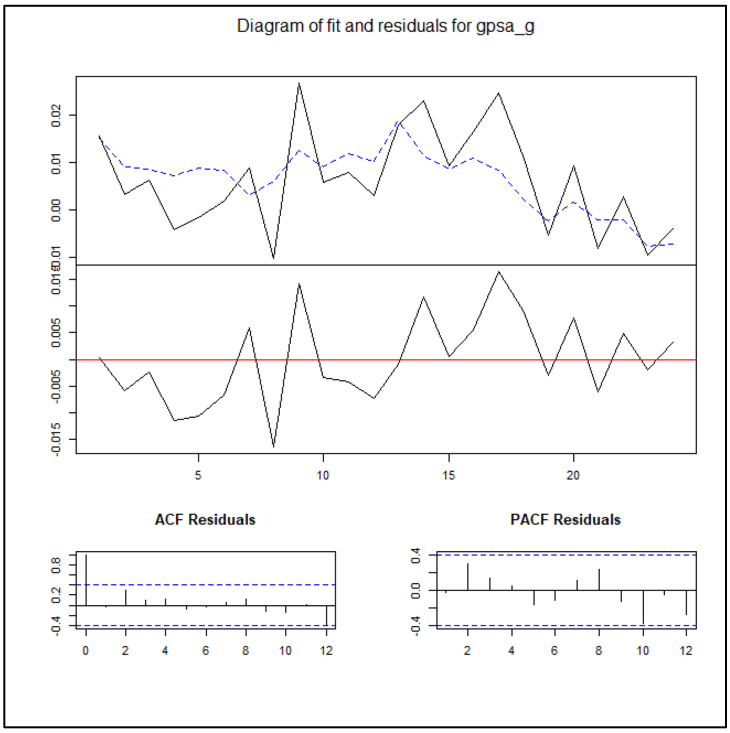


Figure 24 Fitted values, residuals and autocorrelation of residuals for the real GDP growth data

Diagnostic test indicate that the residuals are normally distributed, not autocorrelated and present no volatility clustering[24].

Given the test results, this model is used to generate predictions to be fed to the LCC equation. Examples of such Monte-Carlo generated predictions are presented in Figure 25. A sample of annual predictions is presented in Figure 26. Summary statistics of annual predictions are presented in Table 10.

[24] JB-Test (multivariate): *Chi-squared = 2.6532, df = 6, p-value = 0.8509,* Portmanteau Test (asymptotic): *Chi-squared = 90.957, df = 135, p-value = 0.9987,* ARCH (multivariate): *Chi-squared = 114, df = 180, p-value = 1.*

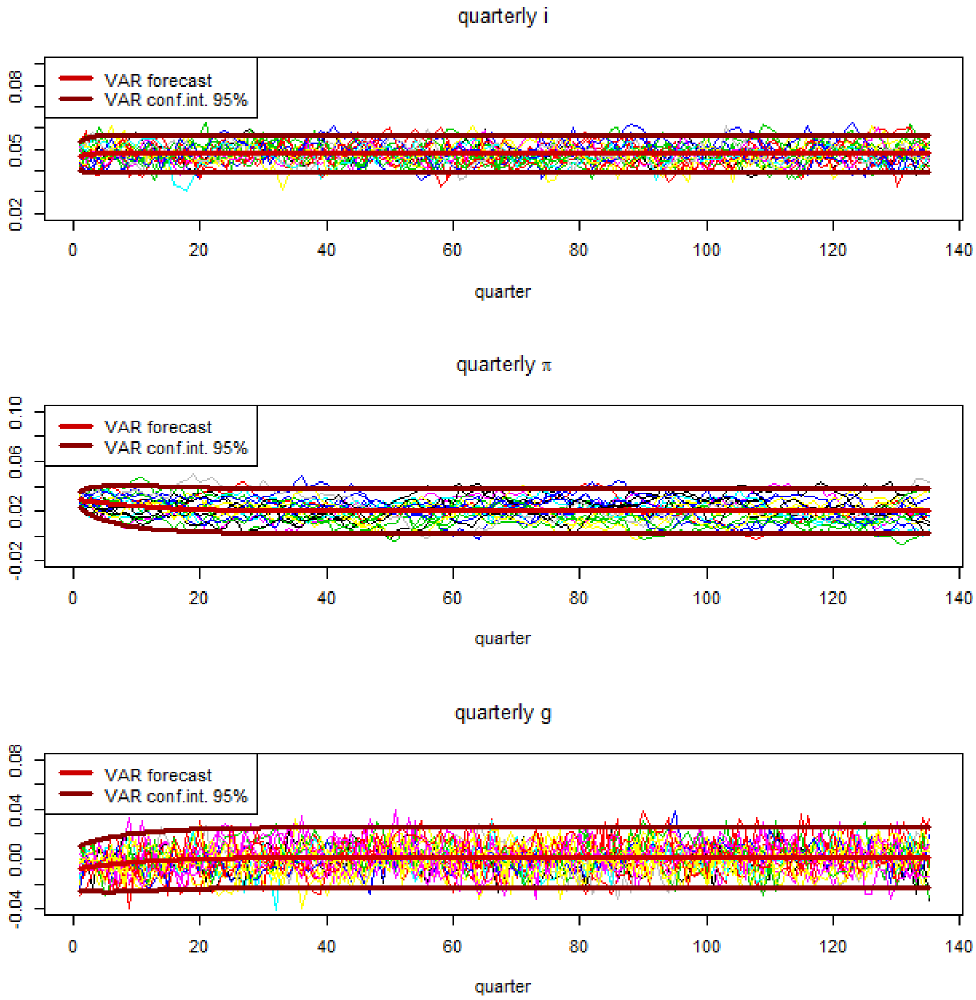


Figure 25 Sample of simulations and confidence intervals for the three variables real interest rate; inflation rate; real GDP growth rate (quarterly frequency)

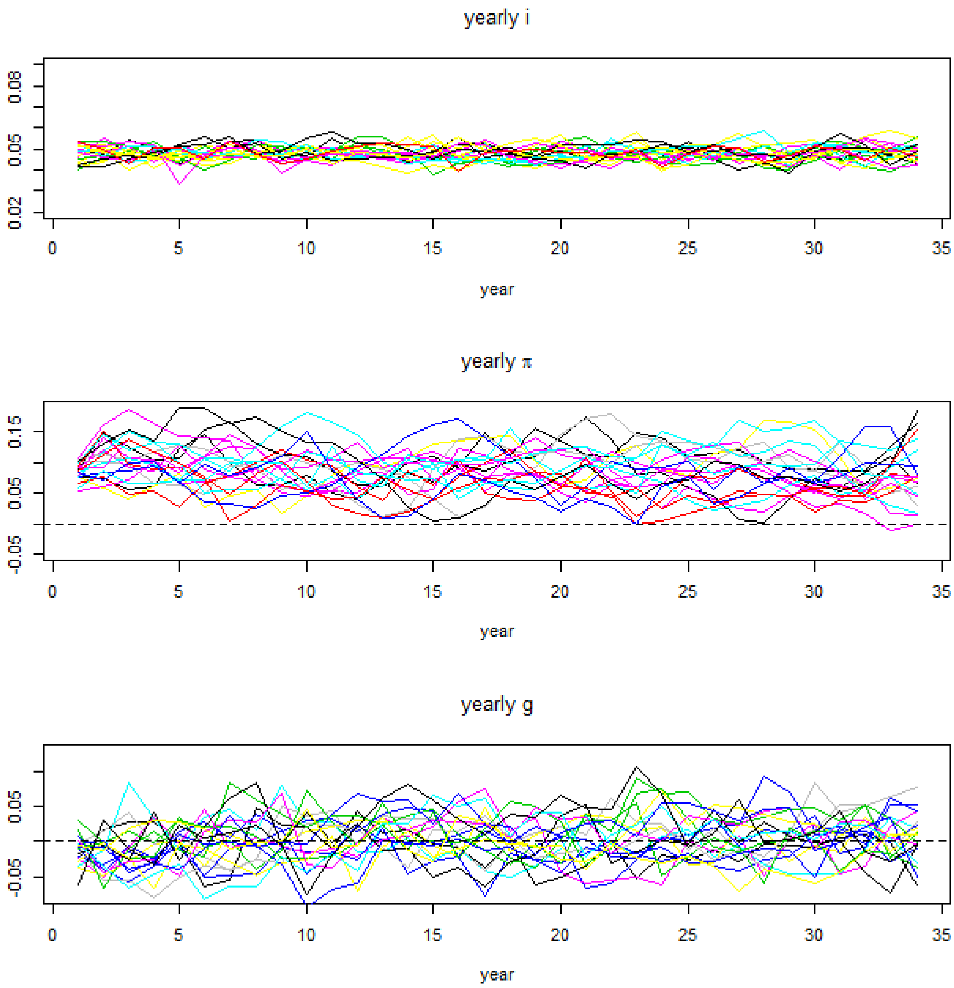


Figure 26 Sample of simulations and confidence intervals for the three variables real interest rate; inflation rate; real GDP growth rate (annual frequency)

Table 10 Summary statistics of annual predictions: inflation rate (π_t); real GDP growth (g_t); interest rate (i_t)

VARIABLE	MEAN	SD
π_t	8.41%	3.35%
g_t	0.34%	3.21%
i_t	4.81%	0.34%

3.5 Characterization of the Deflation scenario

The main feature of a scenario under deflation (DE) are low growth in GDP and low inflation. As a case study to study inflation, macro-economic typically uses the economy of Japan between 1991 and 2010. Of this period, we selected the sub period 1990-2005 to run the statistical analysis and generate the multivariate model. Data for this period are represented in Figure 27. Stationarity tests point to stationarity at 95% confidence level for all data series.

The best-fitting VAR model for the DE scenario is found to be a VAR(1,1) where the current value of the macro-economic variables can be predicted using their own immediate past and the current value and the first lag of the oil prices.

Model fit and residuals are presented in Figure 28, Figure 29, Figure 30.

The model fit reasonably well the interest rate and inflation series. However, apparently it does not perform well for the GDP growth rate. Despite this, the diagnostic tests presented below show uncorrelated, normally distributed residuals with no evidence of volatility clustering[25]. Therefore, we decided to use this model to generate predictions. Examples of such Monte-Carlo generated predictions are presented in Figure 31. A sample of annual predictions is presented in Figure 32.

Summary statistics of the predictions are found in Table 11.

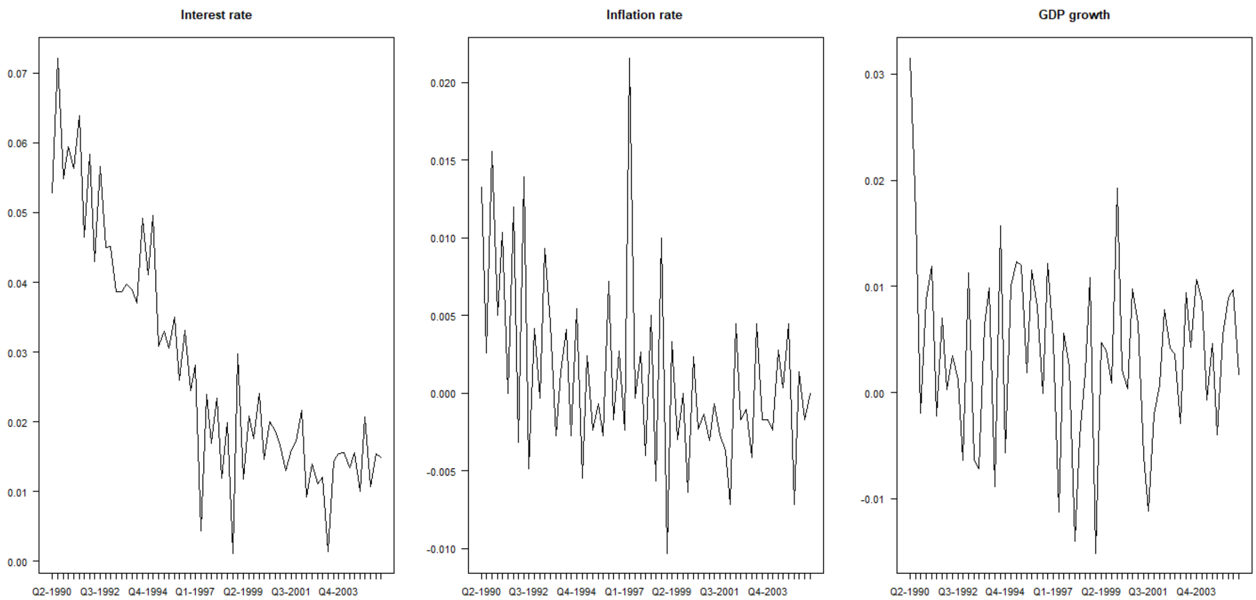


Figure 27 Quarterly observations 1990-2005 of the three endogenous variables: real interest rate; inflation rate; real GDP growth rate

[25] JB-Test (multivariate): *Chi-squared = 2.6532, df = 6, p-value = 0.8509,* Portmanteau Test (asymptotic): *Chi-squared = 90.957, df = 135, p-value = 0.9987,* ARCH (multivariate): *Chi-squared = 114, df = 180, p-value = 1.*

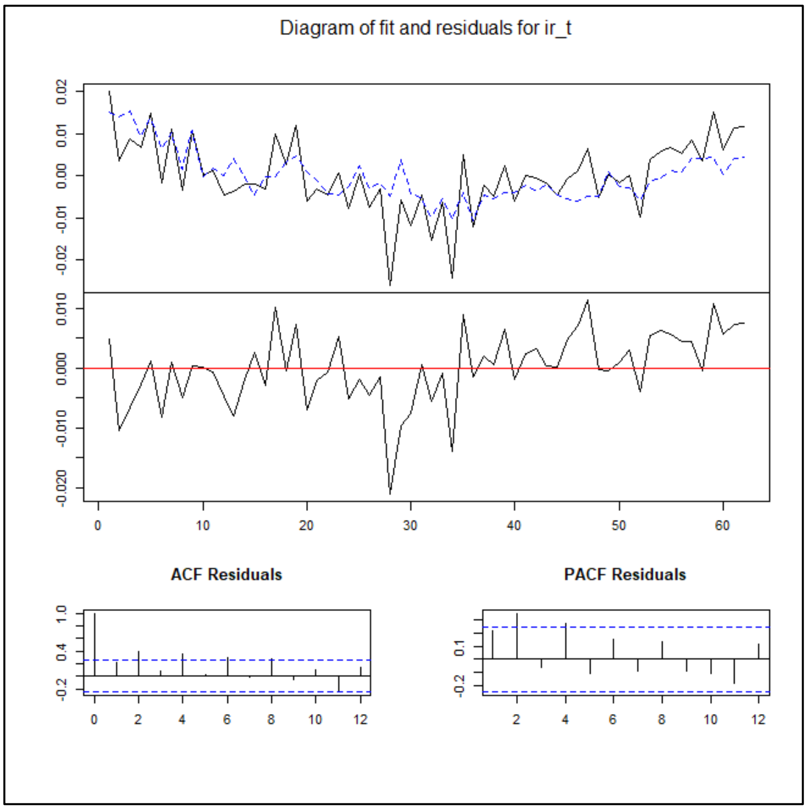


Figure 28 Fitted values, residuals and autocorrelation of residuals for the detrended real interest rate data

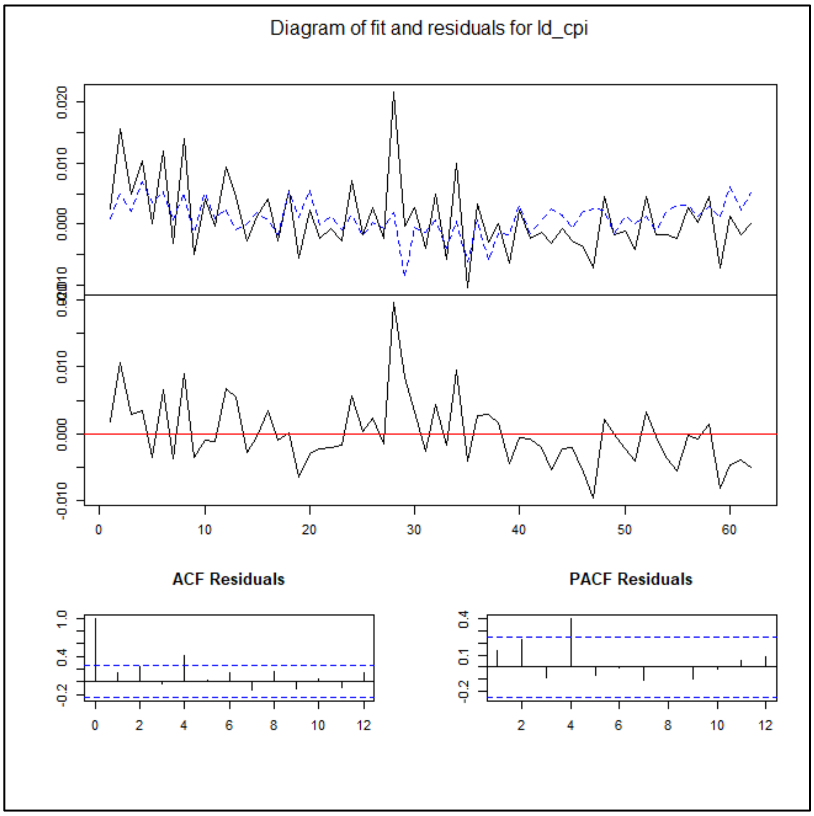


Figure 29 Fitted values, residuals and autocorrelation of residuals for the inflation data

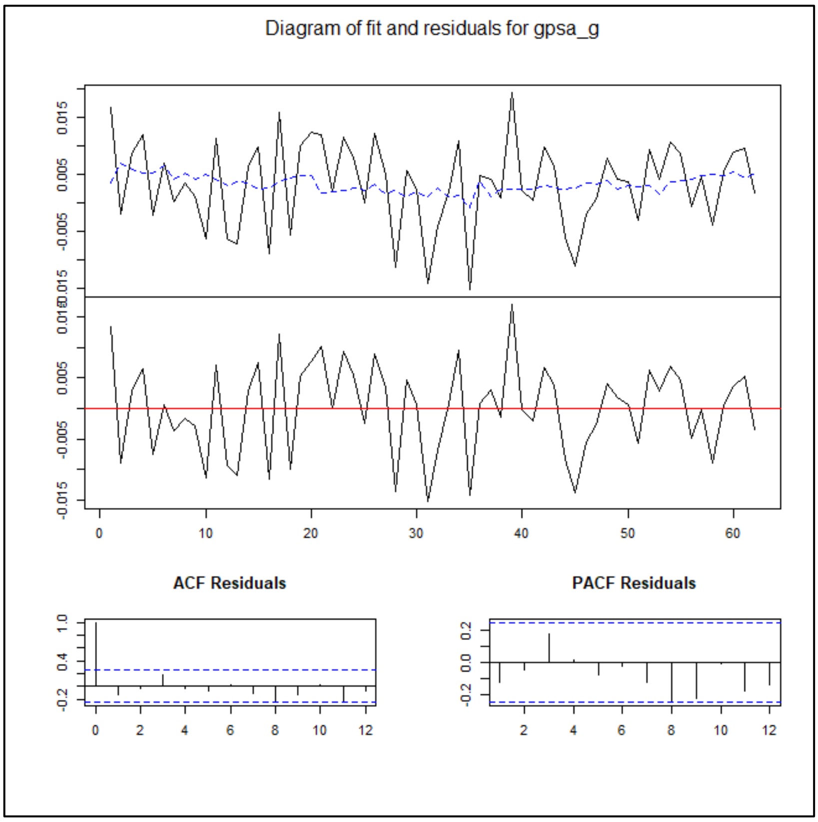


Figure 30 Fitted values, residuals and autocorrelation of residuals for the real GDP growth data

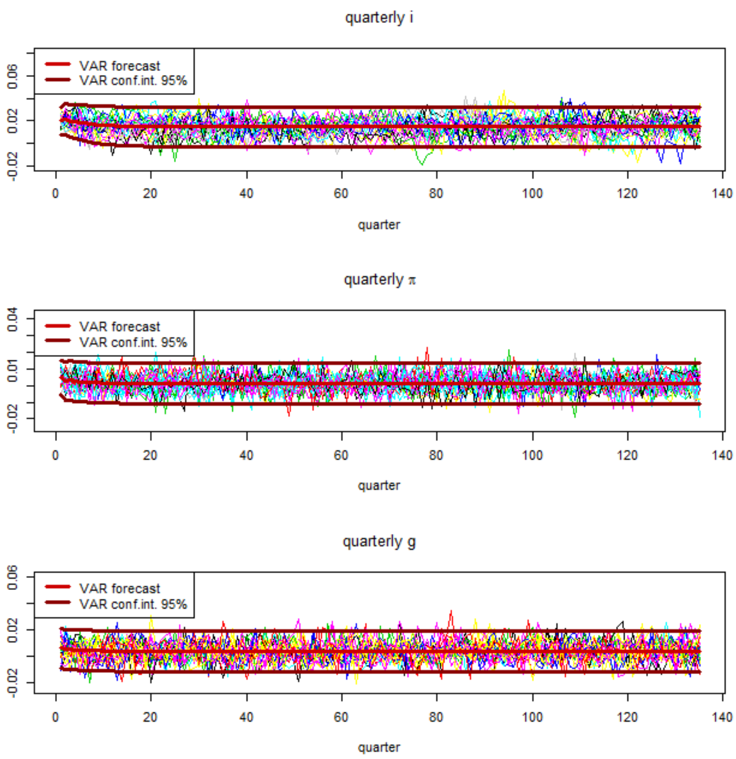


Figure 31 Sample of simulations and confidence intervals for the three variables real interest rate; inflation rate; real GDP growth rate (quarterly frequency)

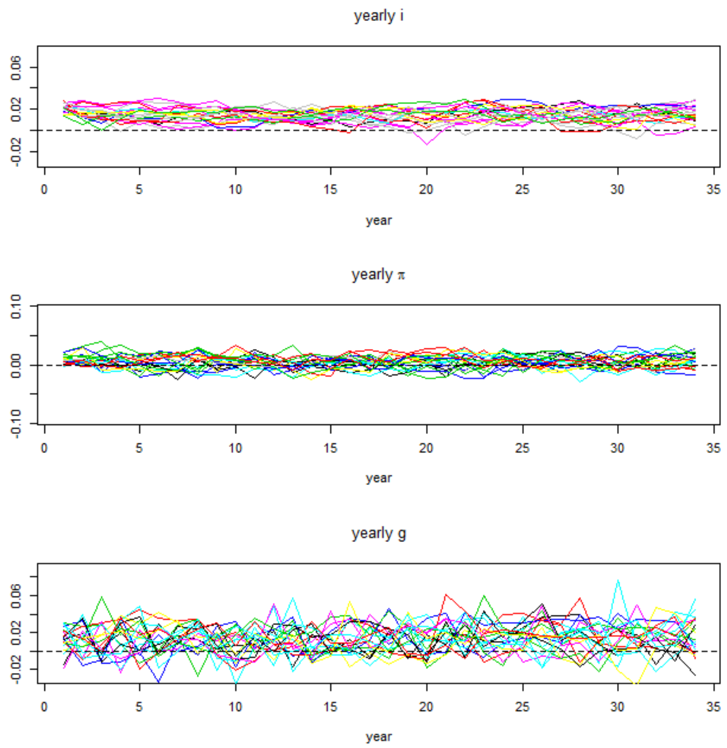


Figure 32 Sample of simulations and confidence intervals for the three variables real interest rate; inflation rate; real GDP growth rate (annual frequency)

Table 11 Summary statistics of annual predictions: inflation rate (π_t); real GDP growth (g_t); interest rate (i_t)

VARIABLE	MEAN	SD
π_t	0.46%	1.11%
g_t	1.34%	1.62%
i_t	1.50%	0.63%

3.6 Implication of the scenario assessment for the sensitivity analysis

As mentioned in section 2.7, the PM developed and the related software tool, allow to perform the Sensitivity Analysis in two different ways.

In the first way, the macro-economic variables are included in the sensitivity assessment in order to evaluate the influence of their uncertainty on the final result. With this method, it is possible to compare the importance of economic inputs across different macro-economic scenarios.

Considering, for all macro-economic scenarios characterised, the predictions on the average level and confidence intervals for the macro-economic variables obtained using the correlation structure and the variance covariance matrix estimated from the VAR, it is clear that already after few quarterly simulations, the obtained means and variances converge to constant values. Consequently, in this SA method the macro-economic variables are considered as normal distributions, whose means are the predicted average levels obtained from the VAR estimates while their standard deviations are the square roots of the diagonal elements of the variance-covariance matrix estimated using the model residuals.

In this case, the macro-economic variables, as the other LCC parameters, are all included in the Sobol samples. Consequently, the analysis of their variance is included into the sensitivity analysis (their influence on the Sobol sensitivity indices is taken into account).

In the second way, the SA is performed in order to focus on the influence of the LCC inputs uncertainties, except for macro-economic variables. This approach is useful if the user is interested to compare the performance of several design options which are subjected to the same macro-economic scenario uncertainties, by assessing the influence on the output variance given by other factors as investment costs, service lives, energy tariffs, etc.…

In this case, alternative trajectories of the three macro-economic variables are simulated and for each simulation the Sobol sampling is performed only on the other LCC parameters, in order to assess the eventual variation of the sensitivity indices of these parameters following different trajectories for the three macro-economic variables.

3.7 Conclusions

In this section, the scenario-based creation of the macro-economic variables necessary to run the LCC analysis was presented. The four macro-economic variables entering the LCC equation are the interest rate, the inflation rate, the growth of oil prices and the growth of GDP.

Predicting the future of such variables have historically proven to be very challenging especially in the longer run. Business cycle theory predicts, and empirical evidence shows, that periods of economic expansion alternate with periods of recession. However, the movement from one setting to the next one is largely unpredictable.

The four scenarios characterised are a baseline scenario of regular growth, an intense growth scenario, a stagflation scenario and a deflation scenario. For each of them, historical data are presented, and the various steps in the creation of the VAR models explained. The best fitting models are selected using a data-driven procedure based on information criteria. The modelling is carried out using data recorded at quarterly frequency. Consistently, predictions are generated at quarterly frequency but are then annualized before entering the LCC equation. Summary statistics of the annualized predictions are presented at the end of each section. They largely reflect the initial expectations on the differences between alternative scenarios.

The present study aims to bypass the challenge of predicting the economic scenario by leaving the scenario choice to the user that can perform the LCC analysis under any of the presented ones. Consistent with the probabilistic LCC, for each scenario a multivariate statistical model is created from historical data and a series of Monte Carlo predictions are generated. The modelling exercises are carried out using historical time-series data on countries that experienced the expected scenario conditions.

This methodology is designed to account for both the dynamic properties of time series data and their interdependence. The multivariate time-series approach to the generation of economic variables for the LCC constitutes a main novelty of this work and adds to the LCC methodological literature.

4 Exemplary application of the "probabilistic" LCC: uncertainty and sensitivity analysis of different interior insulation systems under several assessment scenarios (*UNIVPM*)

4.1 Introduction

The aim of the exemplary case study reported in this section is to show the potential application of the probabilistic LCC 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 this section different applications are presented:
- Comparison of the economic performance of several design options under a specific scenario (one economic scenario, one energy source, one calculation period);
- Comparison of the economic performance of several design options under different scenarios (for energy sources, calculation periods and macro-economic variables);
- Identification of influential parameters on the outcome uncertainty.

4.1 Comparison of the economic performance of several design options under a specific scenario

This exemplary application of the LCC probabilistic methodology shows how the method can be effectively used to compare the economic performance of several different design options, given a specific assessment scenario.

4.1.1 Definition of design options and simulation scenario

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 mineral wool coupled with plasterboard, with vapour barrier, fixed to the wall through a metallic frame.

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;
- Calculation period of 30 years;
- Regular growth macro-economic scenario;
- Natural gas as heating source.

Table 12 Insulation system A

Layer	Standard thickness [m]	Density [kg/m^3]	Thermal conductivity (W/mK)
Adhesive Mortar	0.006	1 400	0.540
EPS	0.100	18	0.035
Adhesive Mortar	0.006	1 400	0.540
Plasterboard	0.013	680	0.200
Skimcoat	0.004	1 200	-
Primer + paint	0.0002	1 670	-

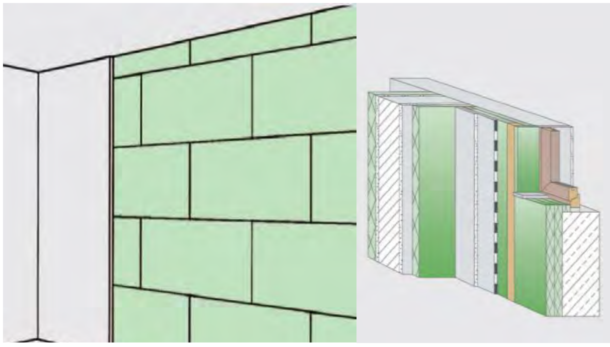
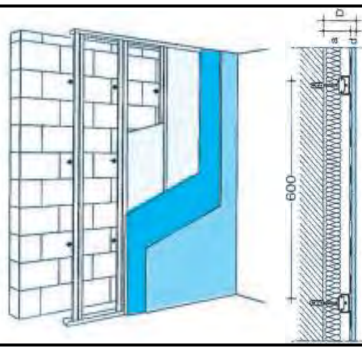


Table 13 Insulation system B

Layer	Standard thickness [m]	Density [kg/m^3]	Thermal conductivity (W/mK)
Adhesive Mortar	0.007	950	0.310
Cork	0.120	120	0.040
Surface rendering	0.007	950	0.310
Primer + paint	0.0002	1 670	-

Table 14 Insulation system C

Layer	Standard thickness [m]	Density [kg/m^3]	Thermal conductivity (W/mK)
Mineral Wool	0.1	70	0.035
Vapor barrier	0.0002	2 700	-
Plasterboard	0.013	680	0.200
Skimcoat	0.004	1 200	-
Primer + paint	0.0002	1 670	-



The "functional unit" for the economic assessment 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 calculation period of 30 years. The internal insulations thicknesses 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.

4.1.2 Uncertainty characterisation and propagation

In the following Table 15 the PDFs of the parameters included in the LCC assessment are summarized.

Table 15 PDFs of the parameters included in the LCC

LCC Input parameters		LCC Cost Category details	LCC Parameter description	PDF
Financial data	**Duration of the calculation**		Duration of the calculation [years]	Deterministic
	Financial rates	Necessary for the calculation of the discount rate	Inflation rate [%]	Normal distribution (based on the macro-economic scenario characterisation, see section 3)
			Market interest rate [%]	Normal distribution (based on the macro-economic scenario characterisation, see section 3)
	Prices development rates	May be different from inflation rate	Price development rate for human operation (labour cost) [%]	Normal distribution (based on the baseline macro-economic scenario characterisation, see section 3)
			Price development rate for energy [%]	Deterministic, from the EIA (Energy Information Administration)[26]
System characteristics	**Component Investment cost**	Insulation systems purchase and installation costs	Insulation systems Investment cost [€]	Normal distribution (based on data-fitting on available costs data)
	Periodic costs for replacements	Depending on systems Service Life and replacement costs (also necessary to calculate the Final Value)	Insulation systems Service Life [years]	Normal distribution (Probabilistic Factorial method)
			Insulation systems replacement costs [€]	As investment costs
	Running Costs	Component annual preventive maintenance and repair	Insulation systems annual Maintenance cost [€]	Normal distribution (based on data-fitting on available costs data)
Energy Costs	**Energy consumption**	Calculated by heat transmission losses through the wall and based on equipment efficiency and energy source typology	Heat transmission losses through the wall [kWh/y]	Normal distribution (probabilistic annual HDD method)
			Building overall efficiency for heating, depending on the heating generator, distribution and regulation efficiency [-]	Uniform distribution (experts' judgment based on national situation on heating equipment)
	Energy Costs	Energy consumption is coupled with tariff for the energy considered	Energy source national tariff [€/kWh/y]	Uniform distribution (based on data-fitting on available costs data)

[26] https://www.eia.gov/

The specific characterization procedures for the Service Life and for the Investment and Maintenance costs are described in the following paragraphs.

Details on all the inputs PDFs are presented in the data frames reported in Appendix 2 where the insulation solutions here presented as A, B, C are respectively number 1, 6, 7 of the data frame *insulation_system*[27].

The uncertainty analysis is performed through the WP5 software tool (presented in section 7).

Sobol's sequences technique is used to generate samples from the input PDFs and propagate the uncertainties according to the methodology developed (section 2.7). 5632 simulation runs were performed, based on preliminary investigations on the accuracy of this sample size, and finally the probability distributions of the resulting global costs and payback periods were obtained.

Materials and Insulation Systems Service Life

For each material included in insulation systems, the Reference Service Life (RSL) is considered as a deterministic value. When the Environmental Product Declarations (EPD) for a specific product is available, the RSL is taken from the EPD, otherwise it is taken from literature or databases.

Since internal insulation solutions are composed of several materials with different service life, 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 2.6.3. 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.

Insulation Systems investment cost

The insulation systems investment costs are composed of the following cost items, commonly used for the "price analysis" in tendering procedures in the building sector in Italy:

1. price of materials being part of the insulation system;
2. labour cost for the insulation system installation;
3. overhead (including safety costs);
4. enterprise profits;

[27] The data frame includes other insulation solutions for Italy not selected for this exemplary case-study.

5. total discount
6. VAT

1. Material costs are obtained from price lists available at retailers.
2. Labour costs depend on the installation and the enterprise organization facing the specific work. Insulation systems A and B are directly fixed to the wall making use of a specific mortar; insulation system C is fixed to the wall by a metallic frame. The standard values for the labour costs have been extracted from a regional pricelist according to the installation procedures. The cost variability is introduced by analysing national data on labour costs published by Italian Labour Ministry [80] and depends on the workers' qualification and the geographical locations.
   Data-fitting and goodness-of-fit plots for labour cost data have been performed, in order to find the theoretical distribution that better represents the data trend. The PDFs obtained are lognormal distributions.
3. Overheads are estimated to 15% of the sum of material and labour costs and include general safety costs.
4. Enterprise profits are estimated to 10% of the sum of all previous cost items.
5. In order to take into account the possibility for enterprises to apply a discount to the amount obtained by summing the items from 1 to 4, we analysed discounting data provided by Italian regional administrations. Data-fitting and goodness-of-fit plots for discounting data have been performed, in order to find the theoretical distribution that better represents the data trend. The PDFs obtained are Weibull distributions. This amount is subtracted from the sum of all previous cost items
6. Finally, VAT can be applied. For this building work typology, it depends on the applicability of the national Italian incentive for building renovation for the private user or the public owner. In this assessment, we considered a VAT of 10% (as for private user).

Considering cost items 1 to 5, the final investment costs PDFs for the three insulation systems obtained with data-fitting processes, are normal distributions, as shown in Figure 33 to Figure 35. The VAT is then added to the mean value of the normal distribution.

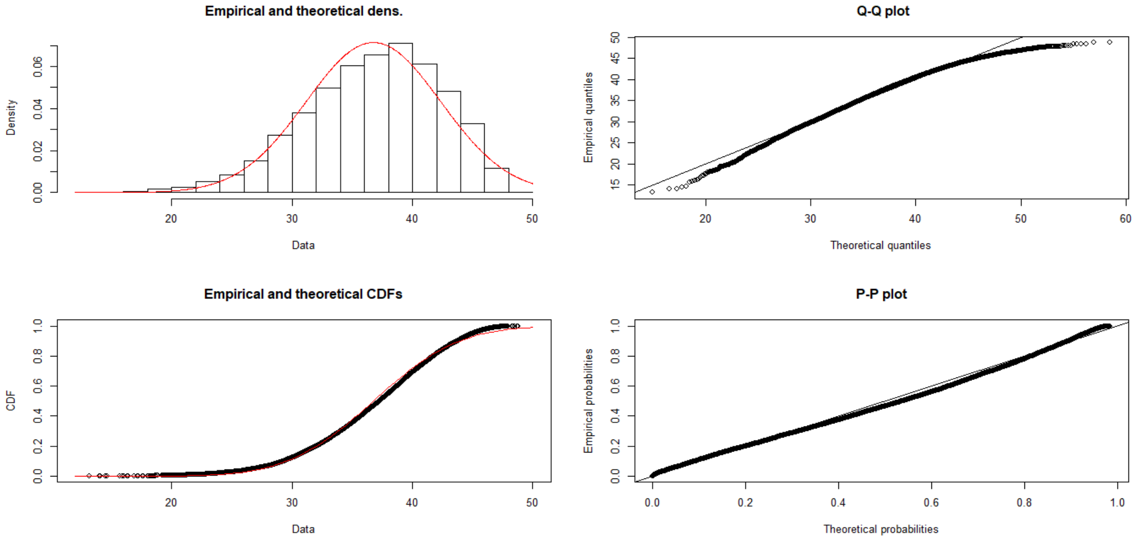


Figure 33 Goodness-of-fit plots (density, CDF, Q-Q plot and P-P plot) for the investment cost of the insulation system A

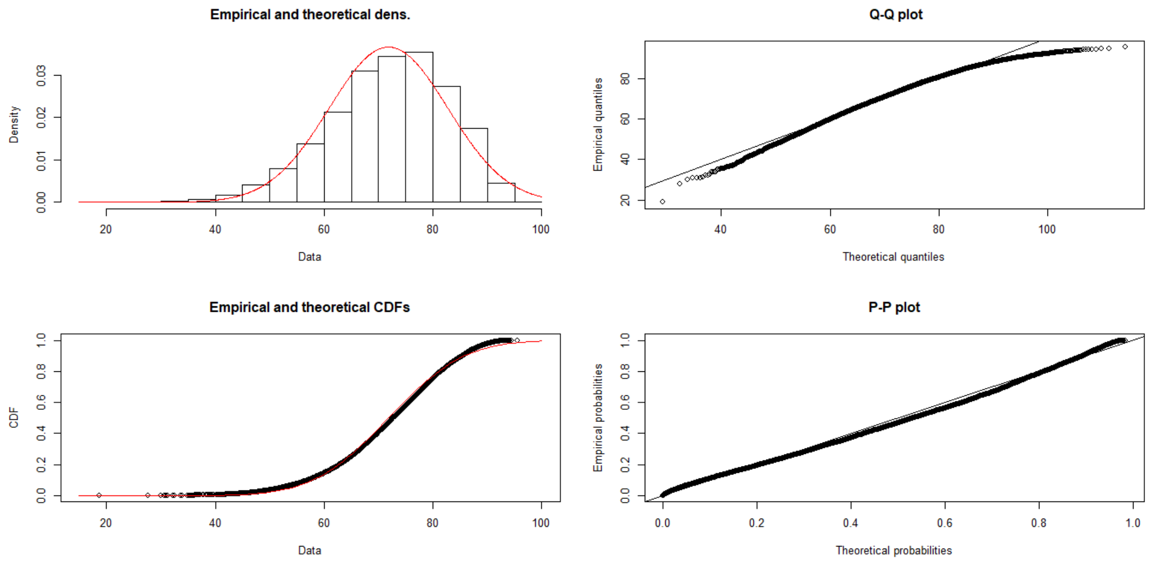


Figure 34 Goodness-of-fit plots (density, CDF, Q-Q plot and P-P plot) for the investment cost of the insulation system B

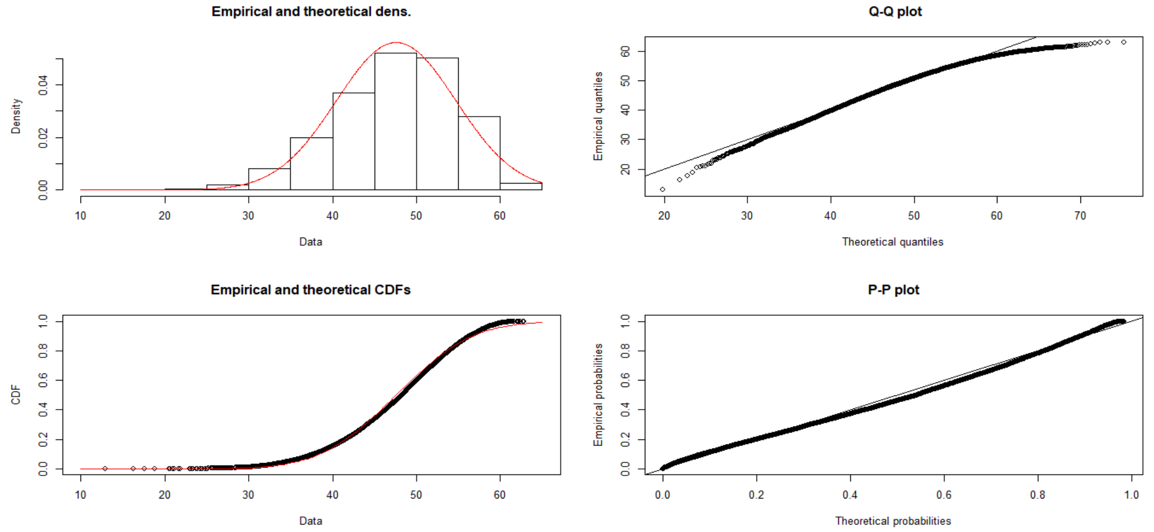


Figure 35 Goodness-of-fit plots (density, CDF, Q-Q plot and P-P plot) for the investment cost of the insulation system C

Table 16 summarizes the costs items considered.

Table 16 The cost items composing the insulation system investment costs for the insulation systems A, B.C

Insulation System		**Insulation Systems investment costs**				
		1. Sum of costs of each material belonging to the system [€/m²]	**type of installation**	**2. Labour cost PDF**	**3. Overheads (15%)**	**4. Enterprise profits (10%)**
A	10 cm EPS + plasterboard	22.414	On site composite insulating board (EPS+ plasterboard) directly fixed to the wall through a fixing mortar	Lognorm (meanlog=2.75, sdlog=0.03176)	15% (MT+MO)	10% (MT+MO+ OV)
B	12 cm Cork + rendering	59.048	Internal insulation composite system, finished with a mortar as surface rendering (similar to ETICS used in building facades) and fixed to the wall through a mortar	Lognorm (meanlog=2.75, sdlog=0.03176)	15% (MT+MO)	10% (MT+MO+ OV)
C	10 cm Mineral wool + plasterboard	33.104	On site composite insulating board (mineral wool + plasterboard) fixed to the wall through a metallic frame	Lognorm (meanlog=2.78, sdlog=0.03176)	15% (MT+MO)	10% (MT+MO+ OV)
		5. Discount PDF	**investment costs PDF [€/m²]**	**VAT (10%)**	**VAT (22%)**	**investment costs PDF (VAT 10% included)**
		Weibull (shape= 2.182935; scale= 26.819093)	Norm (mean=36.75, sd= 5.5896)	3.675	8.085	Norm (mean=40.425, sd= 5.5896)
		Weibull (shape= 2.182935; scale= 26.819093)	Norm (mean=71.8228, sd=10.91148)	7.18228	15.80102	Norm (mean=79.005, sd= 10.91148)
		Weibull (shape= 2.182935; scale= 26.819093)	Norm (mean=47.57, sd= 7.1218)	4.757	10.4654	Norm (mean=52.327, sd= 7.1218)

Insulation Systems maintenance cost

As specified in paragraph 2.5.2.1, only the maintenance of the interior finishing is taken into account, considering costs of painting with a specific frequency (15 years) for all the insulation systems. The same approach of investment costs, i.e. the same cost items, are considered for the maintenance costs. Material costs data come from a regional pricelist.

The PDFs obtained are normal distributions, of which the accuracy was checked through data-fitting and goodness-of-fit plots. As described in 2.5.2.1, maintenance costs are yearly distributed, based on an internal panting RSL (deterministic value) established as 15 years.

Heat transmission losses

The calculation of the heat transmission losses has been performed based on approach 3 (annual HDD), described in section 2.6.1 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 (Italy).

Building global efficiency for heating

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

Energy tariffs

According to the EU Energy Market legislation (Directive 2009/72/EC and Directive 2009/73/EC [81,82]), Member States shall ensure that consumers are free to buy electricity and gas from the supplier of their choice (free market), but at the same time regulated prices are set and established (regulated market) by a specific independent body (in Italy, the Italian Regulatory Authority for Electricity and Gas[28]). All prices include taxes.

The PDFs for the energy tariffs in the Italian context were established to be uniform distributions by considering:

- as mean value, the energy tariff for the energy source in the regulated market;
- as variability source, the energy tariff variability for the energy source in the free market.

4.1.3 Results

For the insulation systems, the output samples of the Global Costs (GC) in 30 years and of Payback Periods (PB) are obtained. Results are presented through the box-whiskers plots in Figure 36, and the Cumulative Density Functions (CDFs) in Figure 37. These graphs allow identifying the uncertainty ranges and the median values of the economic indicators for the insulation systems considered.

The GC median values is about 120 €/m² for the insulation system A (EPS), 158 €/m² for the insulation system B (Cork) and 132 €/m² for the insulation system C (mineral Wool). The PB median values are respectively 4.5, 5.8 and 8.3 years.

However, these results are associated with considerable uncertainty: the outcome included within the ranges of the blue box plots represents only a 50% probability. The whole uncertainty ranges of Global Costs, considering the box whiskers, vary from about 76 €/m² to 269 €/m² for solution A; from about 101 €/m² to 303 €/m² for solution B; and from about 87 €/m² to 280 €/m² for solution C.

[28] http://www.autorita.energia.it/it/inglese/about/presentazione.htm

What in general emerges is that solution A (EPS) is the one able to guarantee minor Global Costs and consequently minor Payback Period, followed by Solution C (mineral wool) and B (cork).

The difference among the solutions is mainly due to the different initial investment costs of the insulation materials while running costs are the same for the three solutions. In fact, the maintenance costs are assumed to be the same for the three solutions (periodic painting of the interior surface) and energy costs are almost the same, given the fact that the energy scenario is the same and the heat transmission losses through the renovated wall present very slight differences.

This is also highlighted by the cost shares, reported in the following Table 17, defined as:

- SHARE_inv = (investment cost + replacement cost – residual value)/(global cost);
- SHARE_maint = (maintenance cost)/(global cost)
- SHARE_energ = (energy cost post renovation)/(global cost)

For solution A, the investment cost share has an impact of about 34% on the GC, while the maintenance cost share contributes with 21%, and the energy cost share with 45%. Similarly, for solution C, the investment cost share has an impact about 40% on the GC, while the maintenance cost share contributes with 19% and the energy cost share with 41%. Differently, for solution B, the investment and maintenance costs shares have a major contribution on the GC (about 51%) compared to the energy cost share (about 33%) and the maintenance cost share (about 16%).

Table 17 Cost shares for the three insulation systems

	SHARE_inv	SHARE_maint	SHARE_energ
A	34%	21%	45%
B	51%	16%	33 %
C	40%	19%	41%

The representation of CDFs (Figure 37) is useful to compare the probability that a certain solution reaches an economic target. For instance, by fixing a GC of 160 €/m², there is a higher than 90% probability that solutions A and B reaches the target, while this probability falls at 60% for solution C.

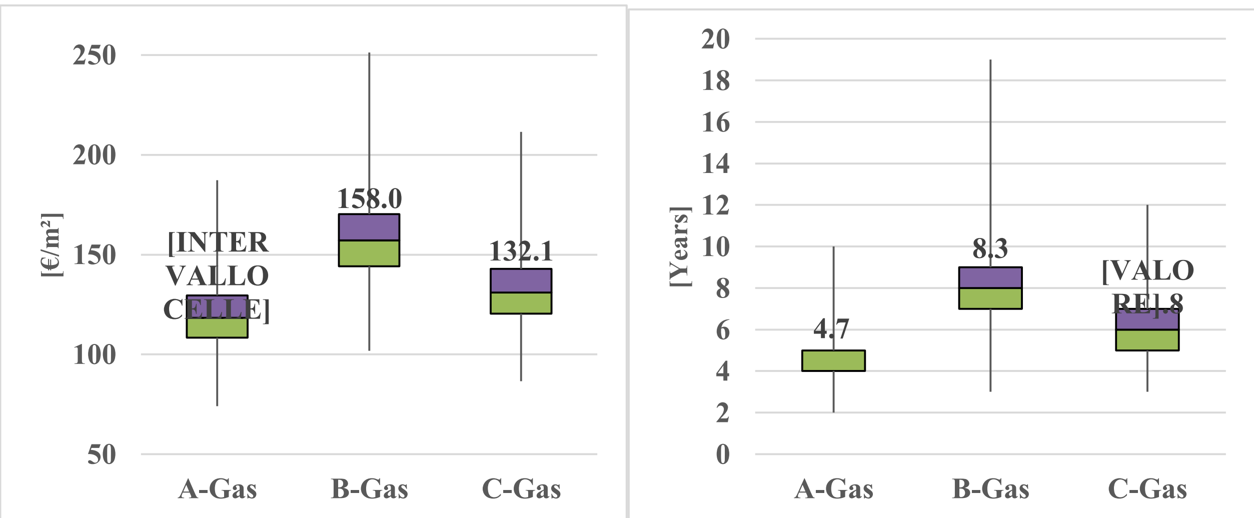


Figure 36 Box-whiskers plots of the Global Cost and Payback period for design options A, B, C, with natural gas as energy scenario, under a regular growth macro-economic scenario and a calculation period of 30 years

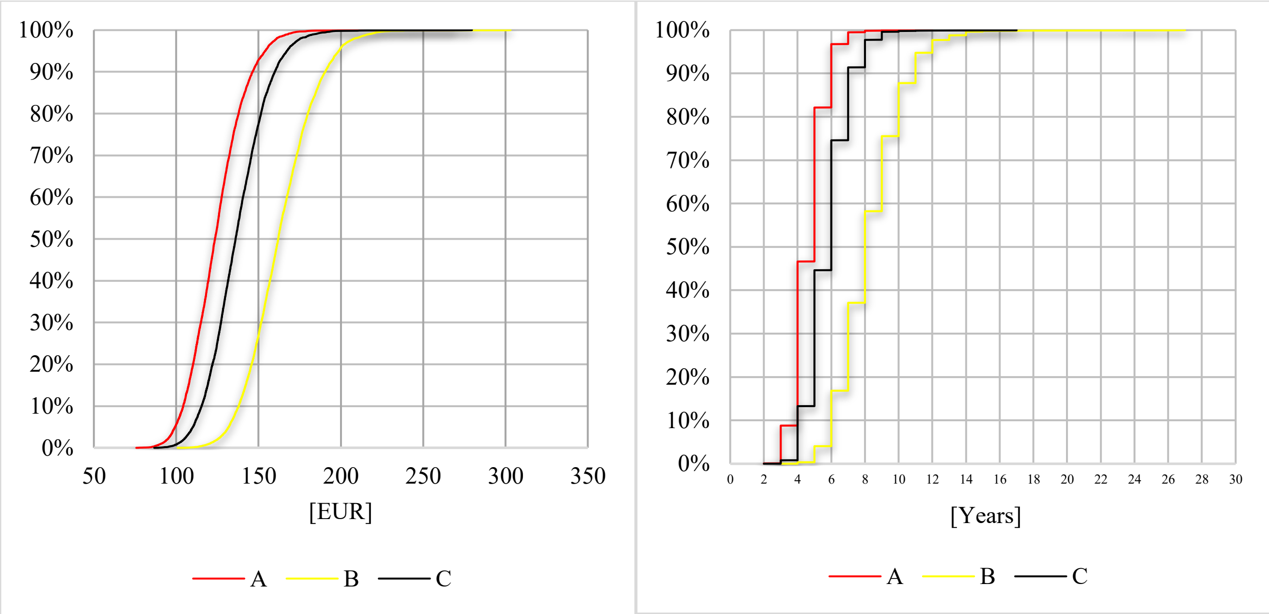


Figure 37 Cumulative distribution of the Global Cost and Payback period for design options A, B, C, with natural gas as energy scenario, under a regular growth macro-economic scenario and a calculation period of 30 years

4.2 Comparison of the economic performance of several design options under different scenarios for energy sources, calculation periods and macro-economic variables

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), four macro-economic scenarios and two calculation periods (30 and 45 years).

4.2.1 Definition of design options and simulation scenarios

The design options are the same as those of the previous case in section 4.1, namely insulation systems A (EPS), B (cork), C (mineral wool).

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;
- 2 calculation periods: 30 and 45 years;
- 3 energy scenarios: Natural gas, Electricity and Oil as heating sources;
- 4 macro-economic scenarios: Regular Growth, Intense Growth, Stagflation, Deflation.

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

4.2.2 Uncertainty characterisation and propagation

The PDFs of the parameters included in the LCC are the same of the previous case in section 4.1.

Concerning data on the two additional energy scenarios (electricity and gas), the following assumptions are considered.

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.

The PDFs for the tariffs of the electricity (uniform distributions) are established based on the same approach followed for gas (section 4.1.2).

The tariffs of the oil, on the other hand, have been evaluated through the elaborations of the Oil industry Union (that represents the oil companies working in the Italian market), based on monthly oil price observations by the Ministry of Economic Development[29]. These values have been used to establish the ranges for uniform distributions as PDFs of the oil tariffs. The prices are all taxes included.

As for the previous case in section 4.1, the uncertainty analysis is performed through the WP5 software tool under the same calculation assumptions.

4.2.3 Results

The Global Costs obtained assessing the three insulation solutions in all the scenarios combinations are shown in the following figures.

Figure 38 (a-b-c-d) reports the boxplots of the Global Costs of the insulation solutions for a calculation period of 30 years, under all the energy scenarios (gas, electricity, oil) and the macro-economic scenarios (Regular Growth, Intense Growth, Stagflation and Deflation). The same results are also presented in a mean-standard deviation space in Figure 39.

The median values of the GC are also reported in the graphs and in Table 18. The table also include the percentage differences of the median values of GC obtained in all the macro-economic scenarios compared to those of the regular growth scenario.

The results obtained highlight what follows:

- The general result that arose from the case-study described in section 4.1 -solution A-EPS guarantees minor global costs and Payback Period, followed by Solution C-mineral wool and B-cork- is confirmed under all the energy and economic scenarios;
- Considering the different macro-economic scenarios, the Stagflation scenario entail the minor median values of GC (from about -22% to -45% compared to Regular Growth one), while the Deflation scenario the highest ones (from +14% to +40%). This is due to the fact that in the Stagflation scenario, the inflation rate is very high and its average value is higher

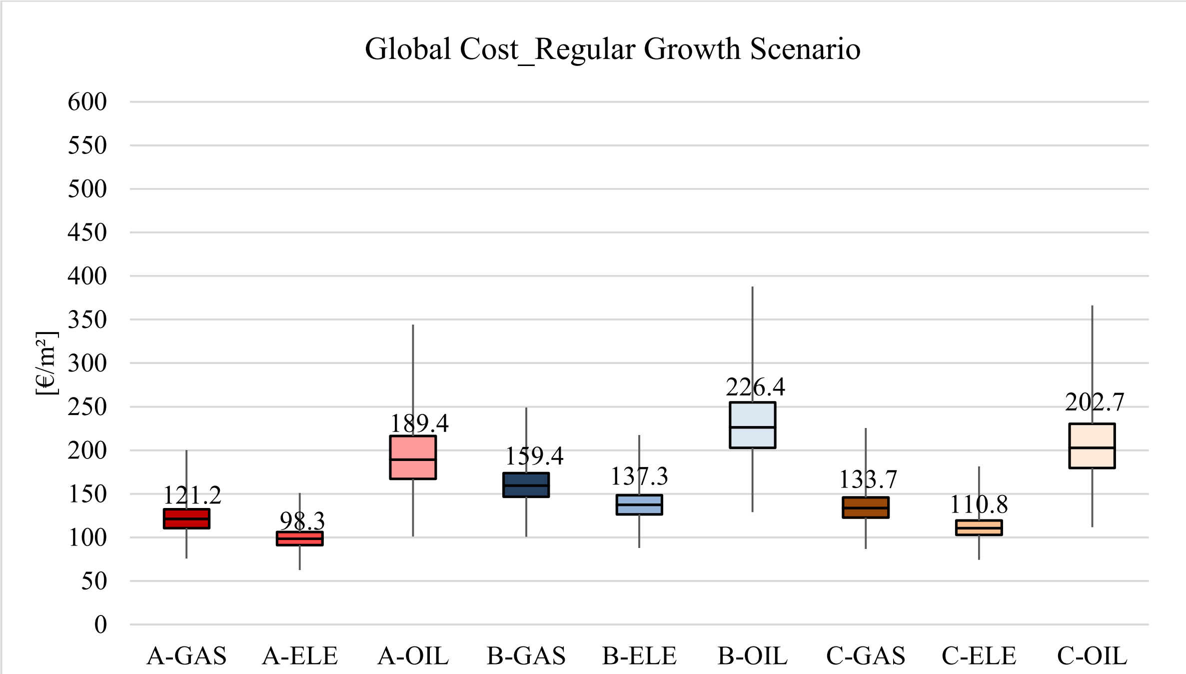
[29] http://www.unionepetrolifera.it/?page_id=948

than the nominal interest rate and the GDP. As a result, the escalation factors become less than 1, while the discount rate is lower than that of all other macro-economic scenarios. In contrast, in the Deflation scenario, since the inflation is very low (the lowest of all scenarios), discount rates and escalation factors are the highest ever.
Regular Growth and Intense Growth scenarios give rise to similar values for the GC (slightly lower in the second case, of around 3-8%).

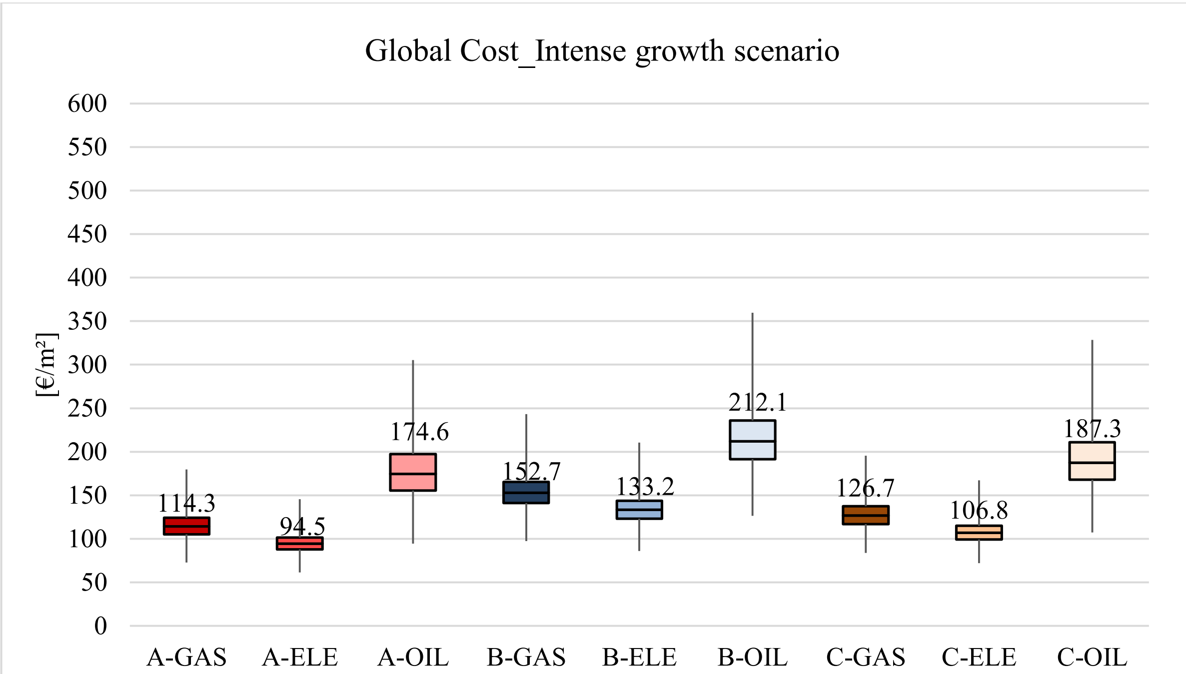
- For each insulation solution, under each macro-economic scenario, electricity is able to determine a minor global cost, followed by gas and oil. This is due to the low overall heating efficiency defined for the oil scenario and the high one for the electricity scenario, together with the different energy tariffs in Italy.
- Furthermore, in the electricity scenario the variations of the GC median values among the macro-economic scenarios are lower than in the other energy scenarios: until about 31%, compared to a maximum of 45% for the oil scenario and of 37% for the gas scenario.
- Results are associated with considerable uncertainty, as highlighted by the whiskers of the boxes, especially in the Deflation scenario.

Table 18 Summary of the GC median values of the insulation solutions for a calculation period of 30 years, under all the energy scenarios (gas, electricity, oil) and the macro-economic scenarios (Regular Growth, Intense Growth, Stagflation and Deflation).

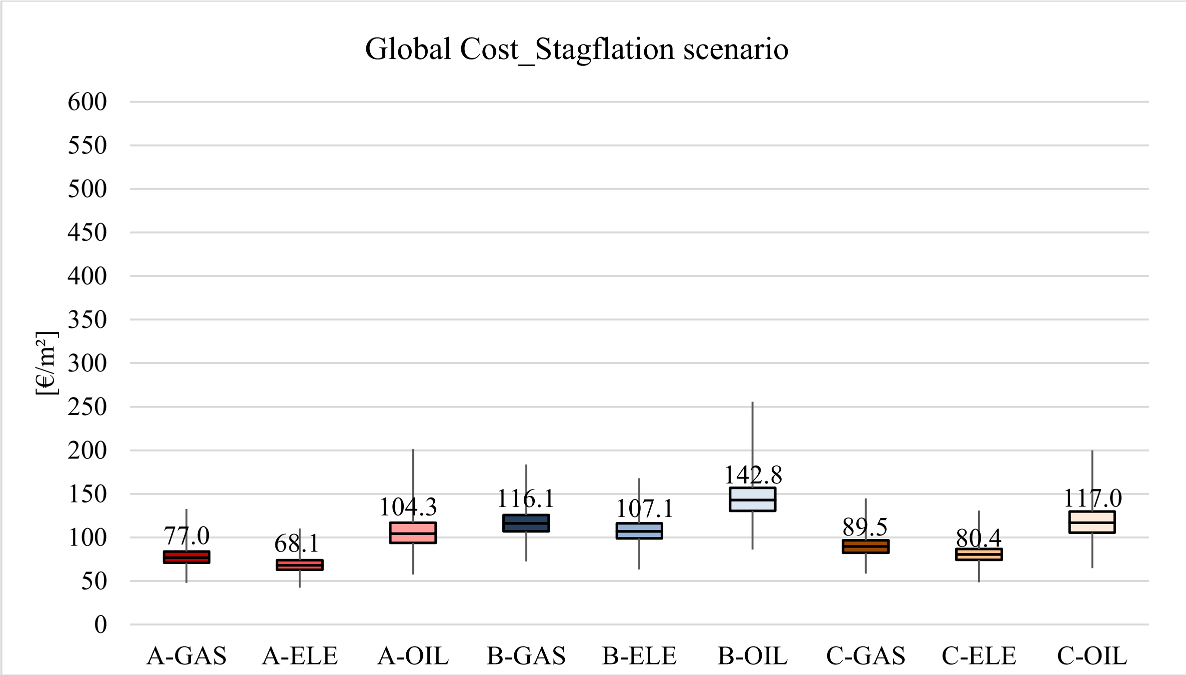
	A			B			C		
	Gas	**Electricity**	**Oil**	**Gas**	**Electricity**	**Oil**	**Gas**	**Electricity**	**Oil**
Regular Growth	121.26	98.37	189.40	159.43	137.31	226.41	133.72	110.82	202.73
Intense Growth	114.35	94.55	174.61	152.76	133.25	212.13	126.72	106.83	187.32
% difference with Regular Growth scenario	*-5.7%*	*-3.9%*	*-7.8%*	*-4.2%*	*-2.9%*	*-6.3%*	*-5.2%*	*-3.6%*	*-7.6%*
Stagflation	77.04	68.18	104.34	116.11	107.09	142.82	89.56	80.42	117.05
% difference with Regular Growth scenario	*-36.5%*	*-30.7%*	*-44.9%*	*-27.2%*	*-22.0%*	*-36.9%*	*-33.0%*	*-27.4%*	*-42.3%*
Deflation	154.39	118.23	264.73	192.24	156.38	300.14	166.87	130.36	277.81
% difference with Regular Growth scenario	*27.3%*	*20.2%*	*39.8%*	*20.6%*	*13.9%*	*32.6%*	*24.8%*	*17.6%*	*37.0%*


Global Cost_Regular Growth Scenario
600
550
500
450
400
350
300
250
200
150
100
50
0
[€/m²]
121.2
98.3
189.4
159.4
137.3
226.4
133.7
110.8
202.7
A-GAS
A-ELE
A-OIL
B-GAS
B-ELE
B-OIL
C-GAS
C-ELE
C-OIL

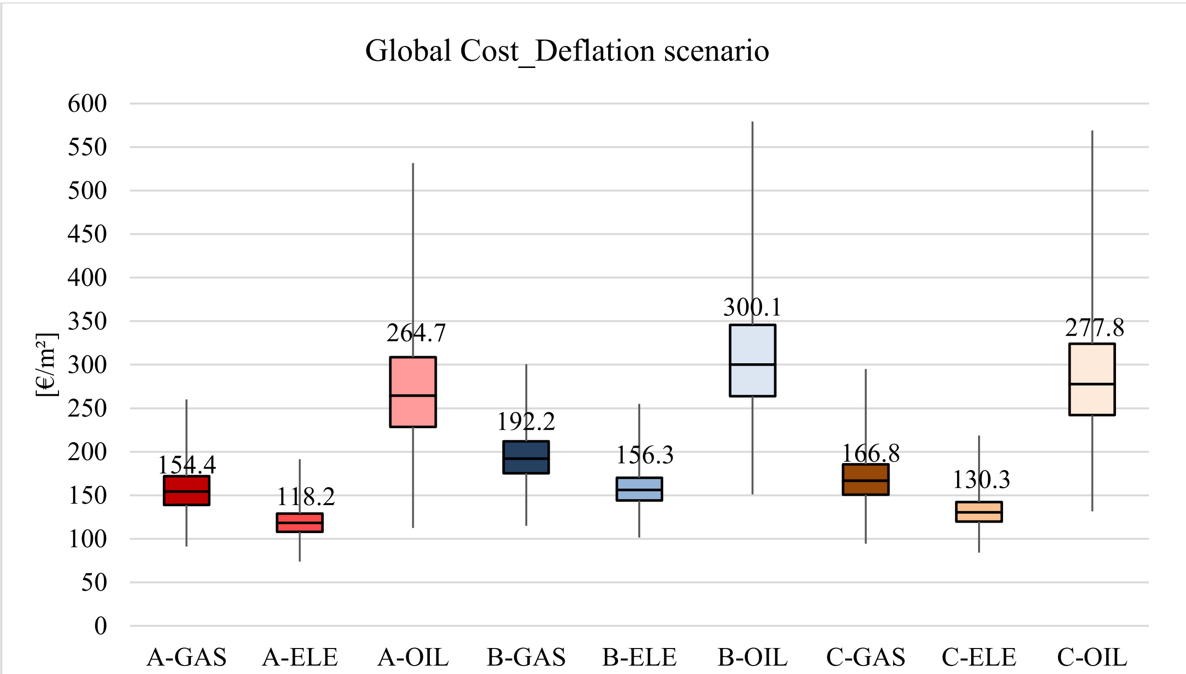
(a)


Global Cost_Intense growth scenario
600
550
500
450
400
350
300
250
200
150
100
50
0
[€/m²]
114.3
94.5
174.6
152.7
133.2
212.1
126.7
106.8
187.3
A-GAS
A-ELE
A-OIL
B-GAS
B-ELE
B-OIL
C-GAS
C-ELE
C-OIL

(b)



(c)



(d)

Figure 38 (a-b-c-d) Global Cost of Systems A, B and C, under electricity, gas and oil scenarios and the four macro-economic scenarios (calculation period of 30 year)

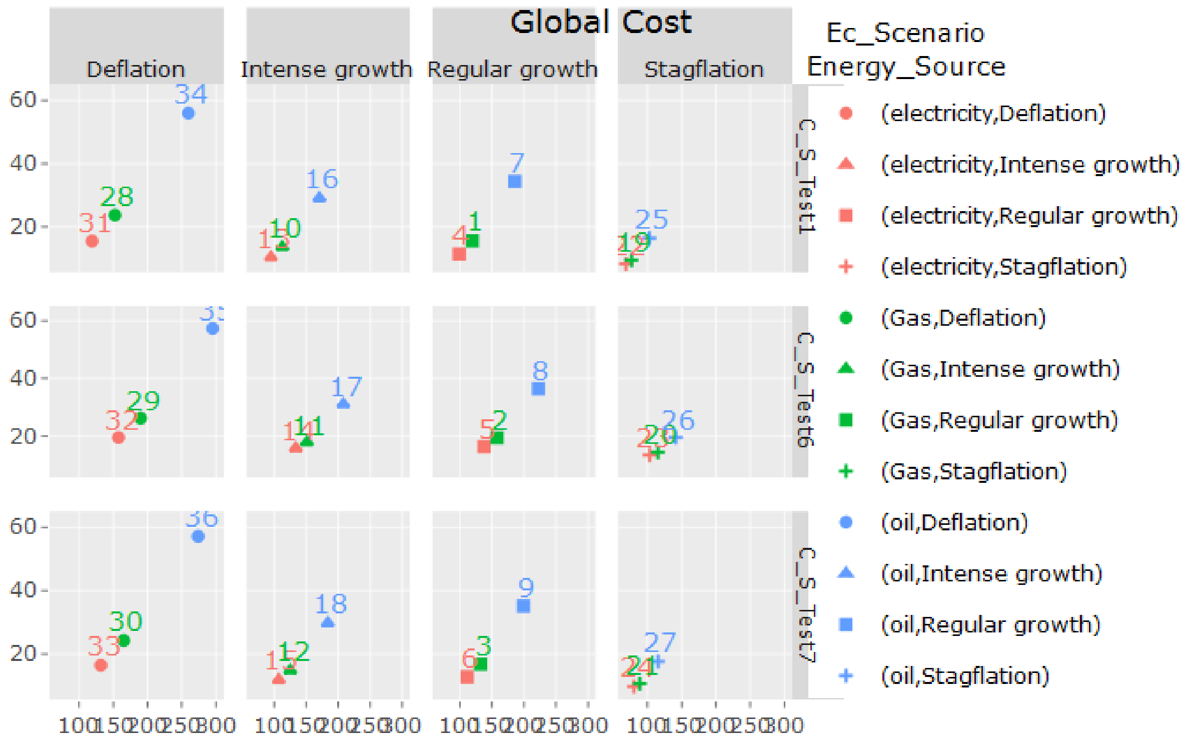
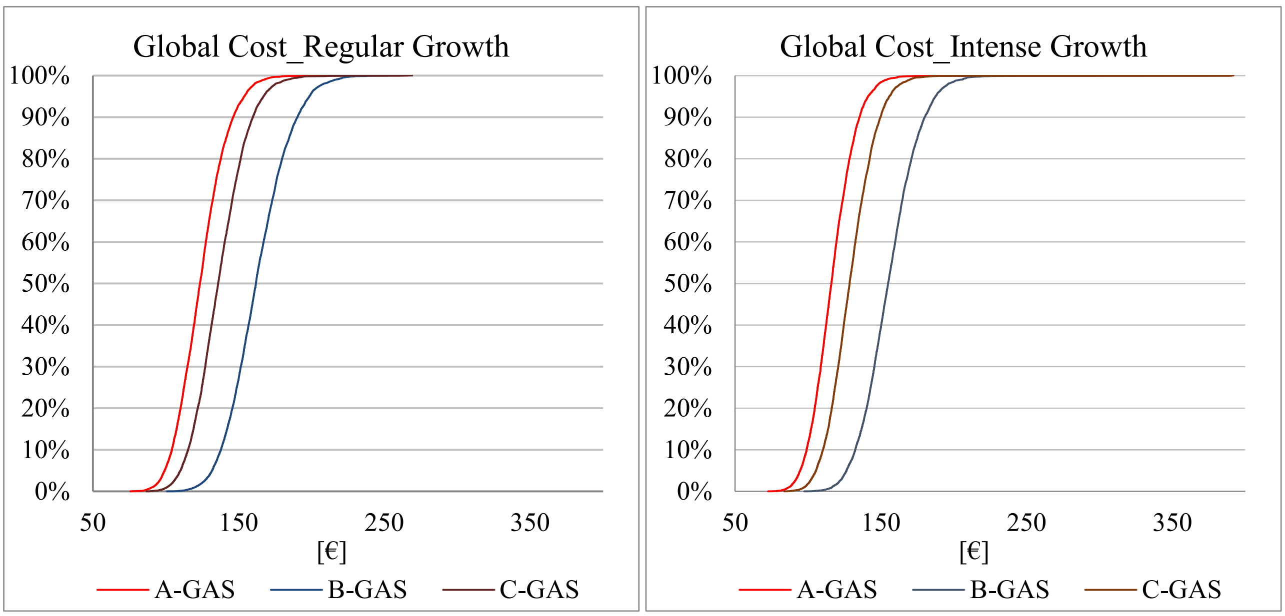
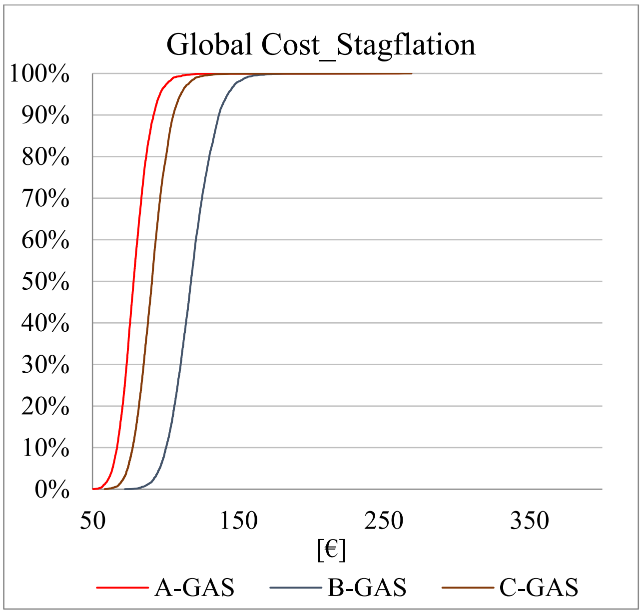


Figure 39 Global Cost of Systems A, B and C, represented in a space mean (x)-standard deviation (y), under electricity, gas and oil scenarios and the four macro-economic scenarios (calculation period of 30 year)

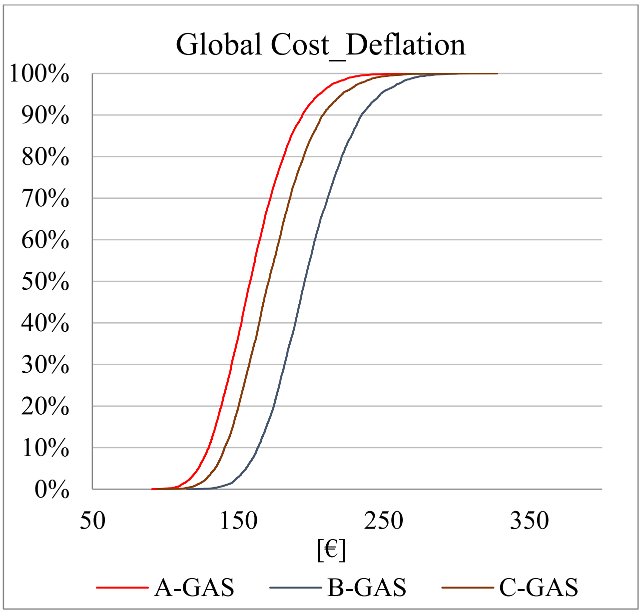
Figure 40 (a-b-c-d) shows the CDFs of the three design options under only one energy scenario (gas) and all the macro-economic scenarios in a calculation period of 30 years. This representation is useful to compare the probability that a certain solution reaches a global cost target or assess if a certain economic target is reached in any possible macro-economic scenario. E.g., by fixing a GC of 150 €/m² as economic target, there is a probability of 100% that GC of all solutions is below this level in the Stagflation scenario, while the probability decreases at less than 40% for solution A, 20% for solution C and 3% for solution B in the Deflation scenario.



(a) **(b)**



(c)

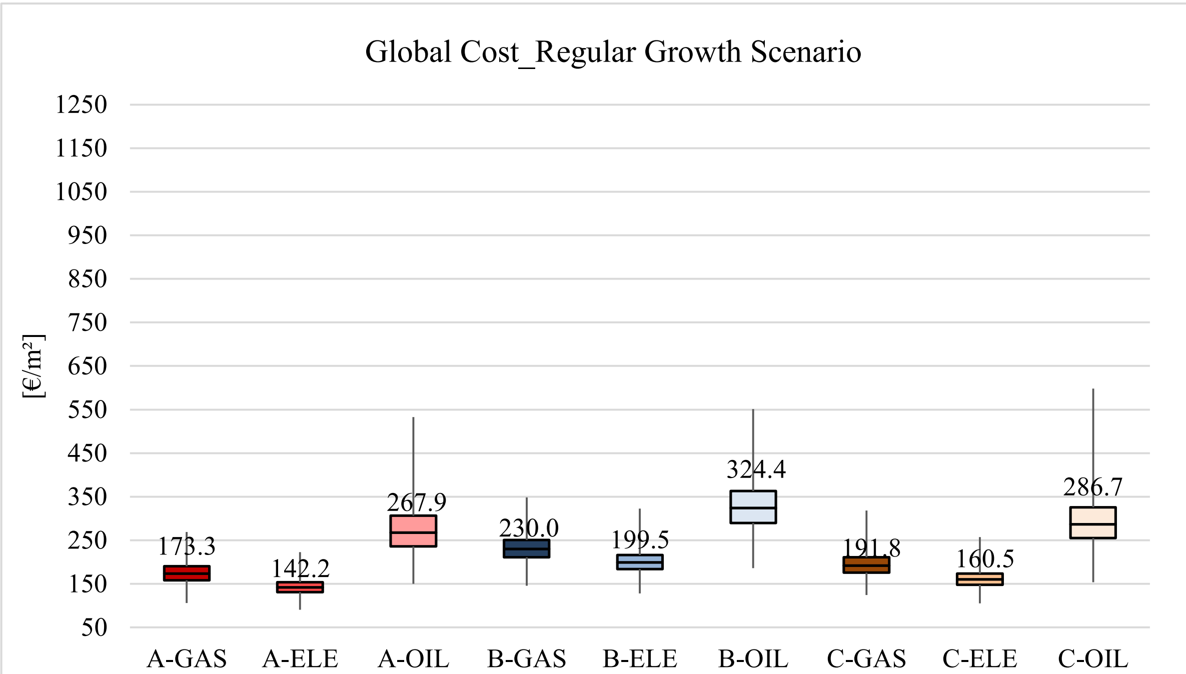


(d)

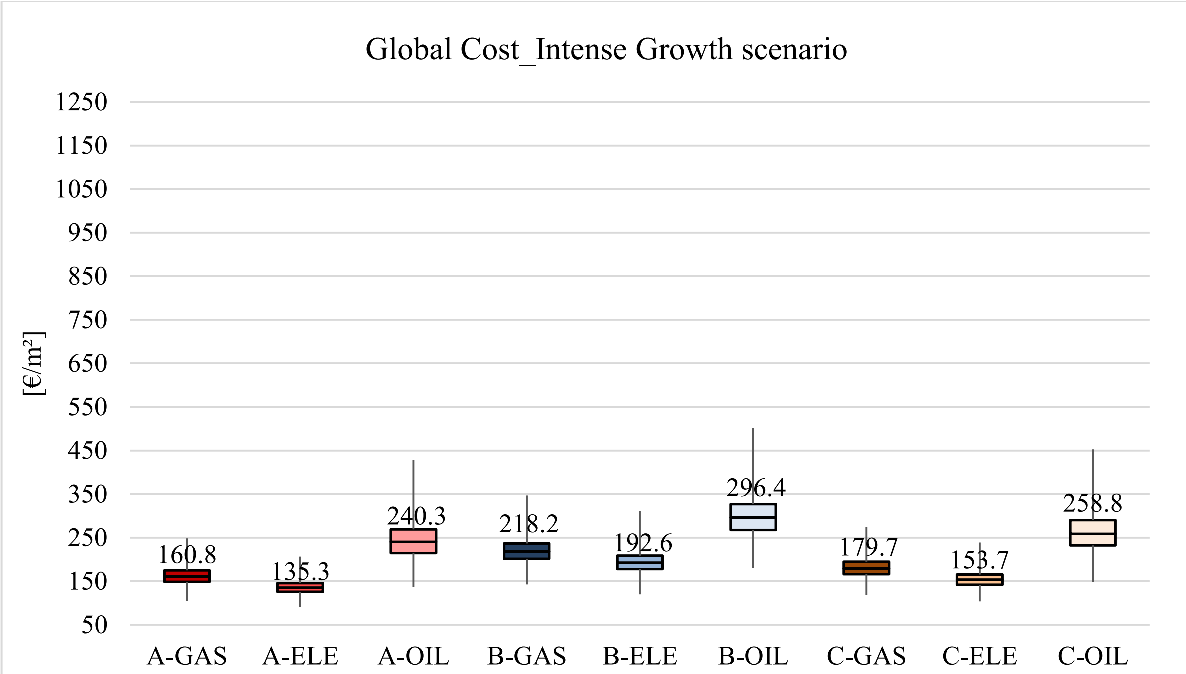
Figure 40 (a-b-c-d) Cumulative density functions of the Global Cost of Systems A, B and C, under gas scenario and the four macro-economic scenarios (calculation period of 30 year)

Figure 41 (a-b-c-d) report the boxplots of the Global Costs of the insulation solutions prolonging the calculation period up to 45 years, under the same energy (gas, electricity, oil) and macro-economic scenarios (Regular Growth, Intense Growth, Stagflation and Deflation). The median value of the GC is also reported in the graphs.

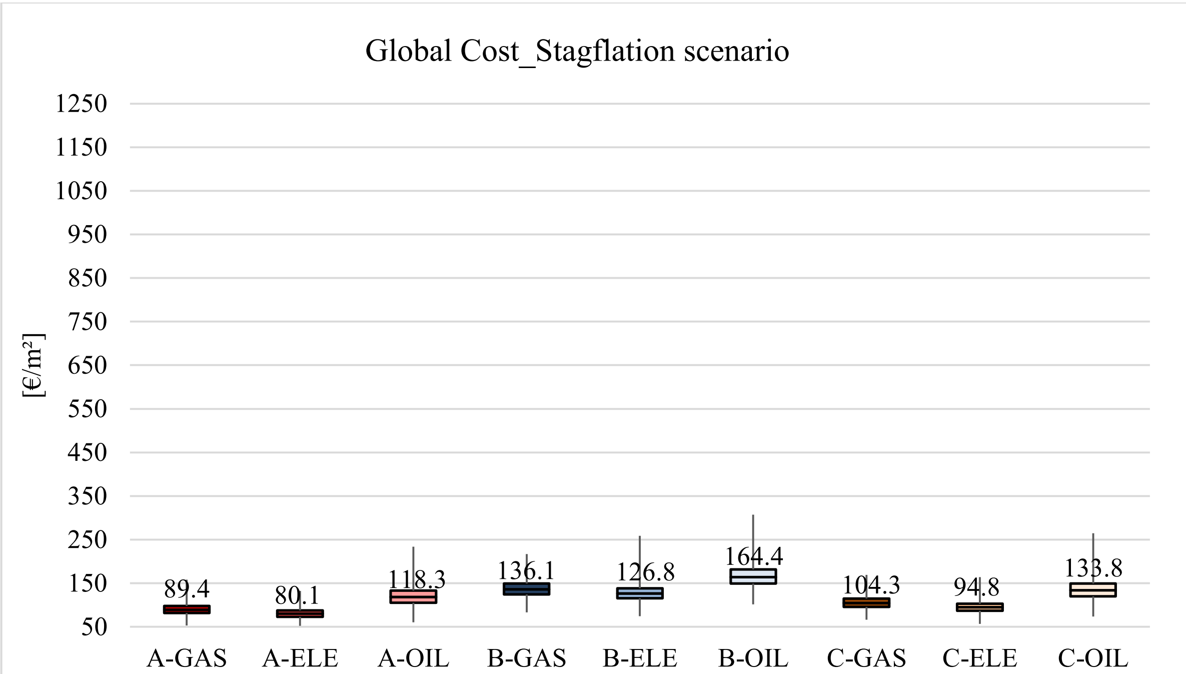
Of course, GC reaches in this case higher values due to the prolonged life-cycle considered. The general trends obtained for the GC in the different scenarios at 30 years are confirmed.



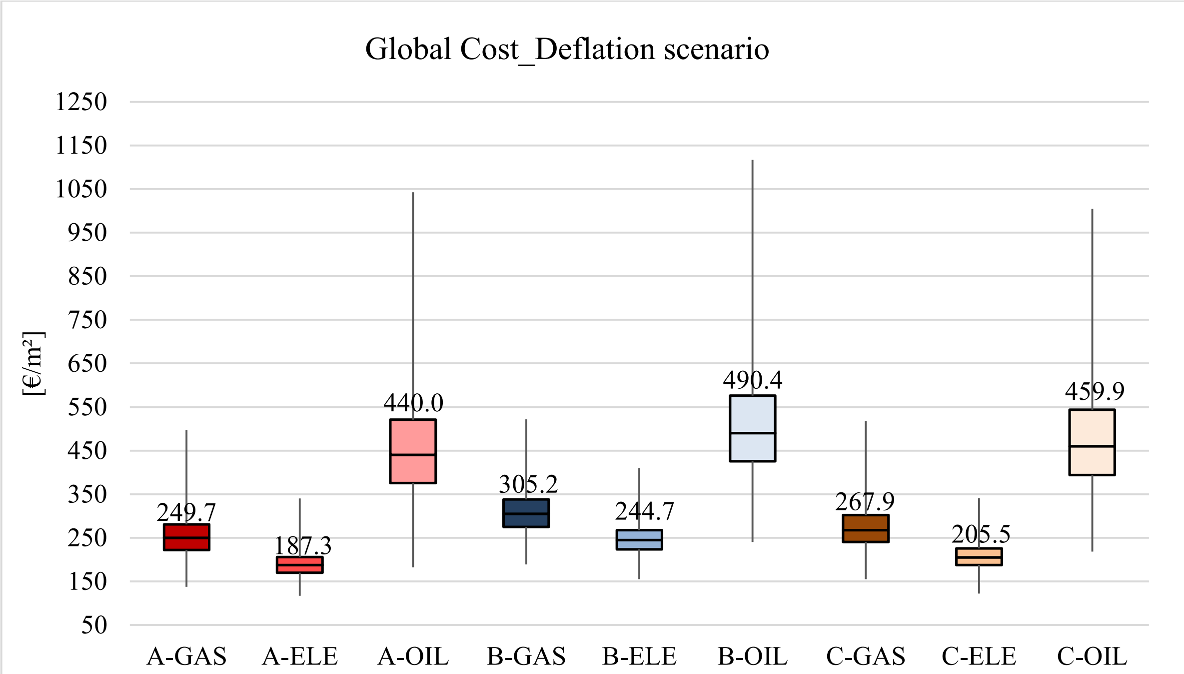
(a)


Global Cost_Intense Growth scenario
[€/m²]
1250
1150
1050
950
850
750
650
550
450
350
250
150
50
160.8
135.3
240.3
218.2
192.6
296.4
179.7
153.7
258.8
A-GAS
A-ELE
A-OIL
B-GAS
B-ELE
B-OIL
C-GAS
C-ELE
C-OIL

(b)


Global Cost_Stagflation scenario
[€/m²]
1250
1150
1050
950
850
750
650
550
450
350
250
150
50
89.4
80.1
118.3
136.1
126.8
164.4
104.3
94.8
133.8
A-GAS
A-ELE
A-OIL
B-GAS
B-ELE
B-OIL
C-GAS
C-ELE
C-OIL

(c)



(d)

Figure 41 (a-b-c-d) Global Cost of Systems A, B and C, under electricity, gas and oil scenarios and the four macro-economic scenarios (calculation period of 45 year)

4.3 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 the variance of the results.

The analysis is performed under the simulation assumptions established for the cases of sections 4.1 and 4.2 and previously described: the three insulation measures A,B,C are compared under three energy scenarios (Gas, Electricity and Oil as building energy sources), 5 macro-economic scenarios, and two calculation periods (30 and 45 years).

The Sensitivity Analysis has been performed in two ways, according to what has been reported in section 3.6. For both ways, total order indices (STi) are presented. The LCC input data included in the analysis are obviously those represented by distributions in the methodological approach of section 2.5.2, and here summarized:

- Qhpost = heat transmission losses through the wall after renovation;
- EnT= Energy tariff of the energy source considered
- ETAh = overall system efficiency for heating
- CI = insulation system initial investment cost
- CM = insulation system maintenance cost
- SL= insulation system service life
- GDP = nominal growth rate of GDP
- INF = inflation rate
- INT = nominal interest rate

4.3.1 Results

The following figures represent the STi of the LCC input data for the three insulation solutions, under the different energy and macro-economic scenarios and during a calculation period of 30 years[30].

Sensitivity Analysis - First way

In this case, the macro-economic variables, as the other stochastic LCC parameters, are all included in the SA. STi for each case study are represented by histograms from Figure 42 to Figure 45.

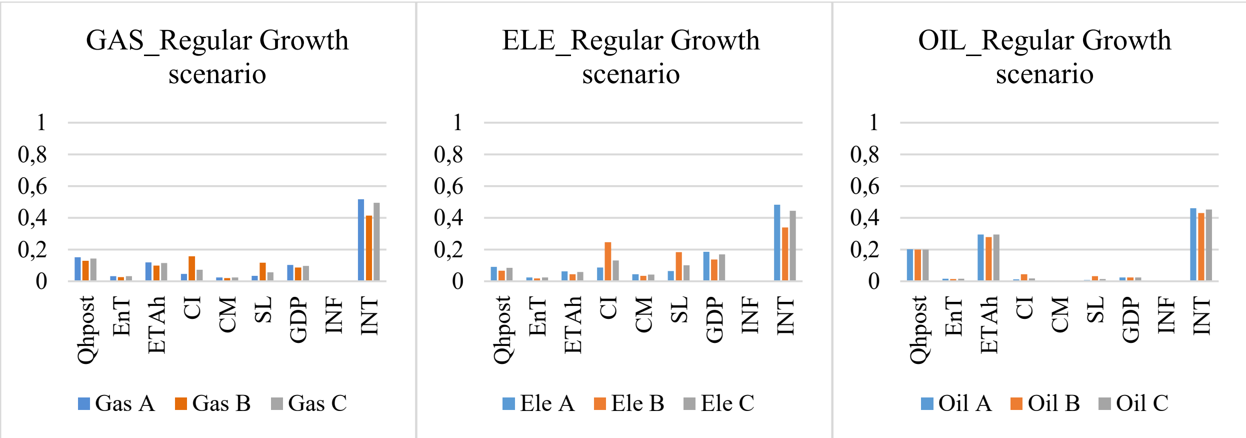


Figure 42 STi for Systems A, B, and C under gas, electricity and oil scenario in the Regular Growth macro-economic scenario and a calculation period of 30 years.

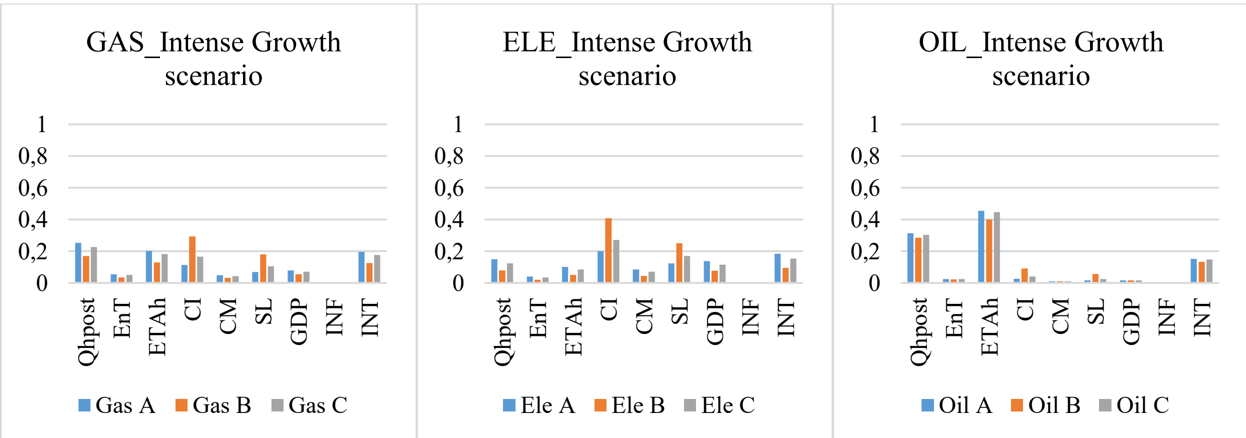


Figure 43 STi for Systems A, B, and C under gas, electricity and oil scenario in the Intense Growth macro-economic scenario and a calculation period of 30 years

[30] In the results obtained, the sum of the total order sensitivity indices of the LCC data inputs is always greater than 1, as requested by Sobol's method [74].

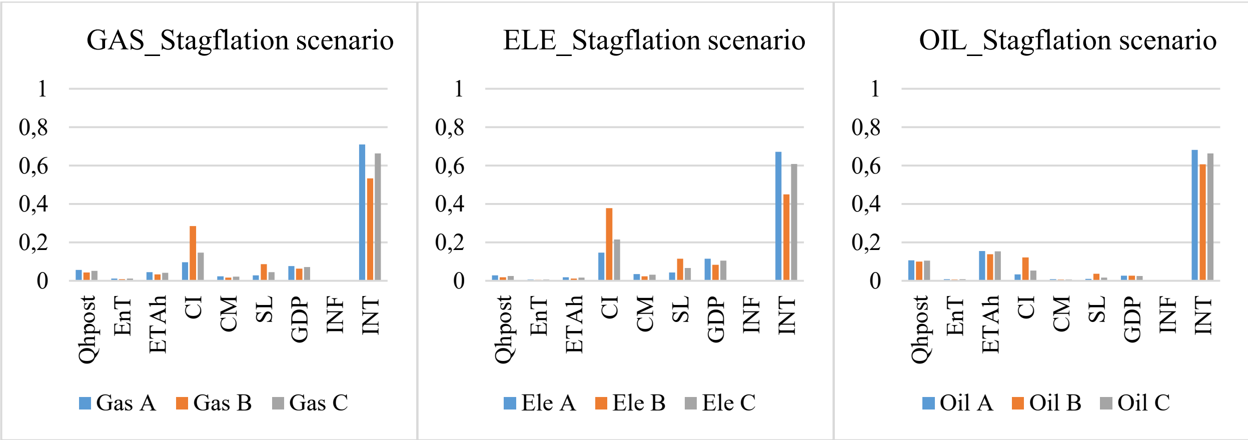


Figure 44 STi for Systems A, B, and C under gas, electricity and oil scenario in the Stagflation macro-economic scenario and a calculation period of 30 years

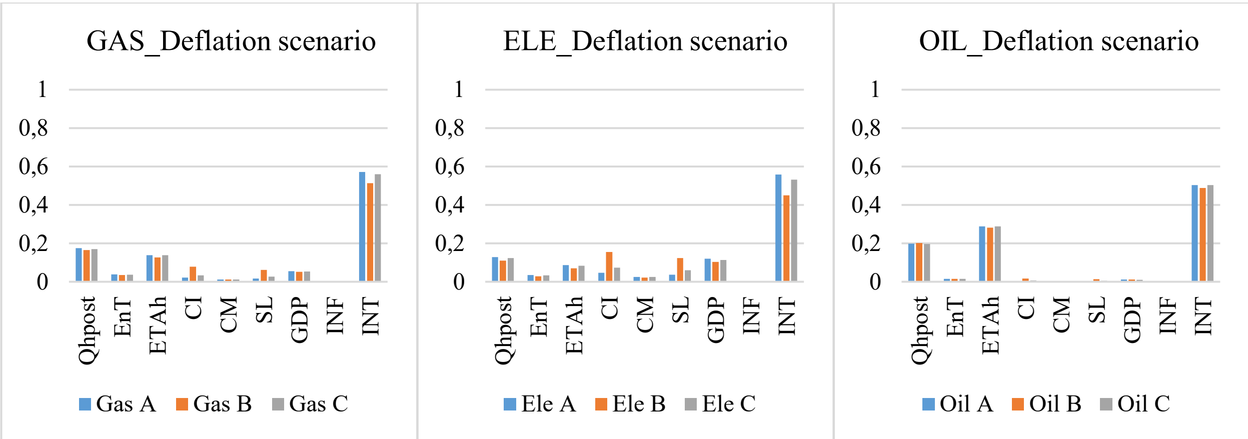


Figure 45 STi for Systems A, B, and C under gas, electricity and oil scenario in the Deflation macro-economic scenario and a calculation period of 30 years

From the graphs, it is evident how the input uncertainty impacts vary across the different energy and macro-economic scenarios, while a certain consistency is noticeable among the three insulation solutions (similar STi trends for A, B and C).

The main remarkable difference among the insulation systems STi is that solution B entails higher values for the investment costs (CI) and the service life (SL), being the most expensive solution. Consequently, the variation of the investment costs STi is quite notable among the different energy and economic scenarios. Insulation systems A and C investment cost uncertainties influence for less than 17% on the output variance, in the gas and oil scenarios and all the macro-economic scenarios. Considering the electricity scenario (which entail the lower energy costs), they impact until 27%. The investment cost STi for the insulation system B impacts for less than 30% the output variance in the gas and oil scenarios and all the macro-economic scenarios, reaching 41% in the electricity scenario with intense growth.

In all scenarios, the uninfluential parameters variances on the output variance (STi<0.1) are those of the inflation rate (INF) (the analysis is performed in real terms) and of maintenance costs (CM) (relative low cost share and weight).

The macro-economic variable Interest Rate (INT) is the most influential input parameter in almost all the macro-economic and energy scenarios, except for the Intense Growth scenario. It is responsible for 34-52% of the overall outcome variability in the Regular Growth scenario, 45-57% in the Deflation scenario and finally 45-71% in the Stagflation scenario (for this last, especially in gas and oil energy scenarios). Its contribution is lower in the Intense Growth scenario (10-20%), where the STi of other inputs increase.

From the comparison of the results obtained with the different energy sources in all macro-economic scenarios, it arises that:

- In the Electricity scenario, the insulation Investment Cost uncertainty entail a higher impact than that reached with the other energy sources, due to the limited energy consumptions (and costs) in this scenario. CI STi reaches 0.15-0.38 in the Stagflation scenario and 0.20-0.41 in the Intense Growth scenario, depending on the insulation system considered (B always entail higher CI STi, being the more expensive solution).
- In the Oil energy scenario, parameters related to the energy consumption, as Qhpost (heat transmission losses) and ETAh (overall efficiency for heating) show a certain influence especially in the Regular Growth, Deflation and Intense Growth and scenarios, where they are responsible together for respectively more than 48%, 49% and 69% of the output uncertainty. In the Stagflation scenario, they account for about 25%. This is due on the high uncertainty ranges of the heating efficiency set for the oil scenario.

From the comparison of the results obtained with the different macro-economic scenarios, it arises that:

- In the Intense Growth and oil scenario, Qhpost and ETAh are responsible together for 69-77% of the overall outcome variability depending on the insulation systems, due to the higher uncertainty ranges for the energy parameters in this scenario. While in the Intense Growth scenario with the other energy sources, the STi are quite balanced and the outcome uncertainty is due to several factors, which are more related to the energy consumption for the gas scenario and to the systems cost in the electricity scenario.
- In the Regular Growth scenario with gas and oil as energy sources, the highest STi, after that of Interest Rate, are those related to the energy performance, while in the electricity scenario they are those related to the system investment costs and to the service life and GDP that affect the replacement costs. Qhpost and ETAh are responsible together for 23-27% of the overall outcome variability in the gas scenario and 48-50% in the oil scenario, considering the different insulation systems. Investment cost, service life and GDP are responsible together for 34-57% of the overall outcome variability in the electricity scenario depending on the insulation systems (B entail higher investment costs).
- In the Deflation scenario, excluding the Interest Rate that is clearly the most influencing parameter; the other STi ranking is similar to that of the Regular Growth scenario.
- In the Stagflation scenario, facing a high impact of the Interest Rate uncertainty, the STi of the energy parameters are less important: under 0.10 in gas and electricity scenarios and under 26% in the oil scenario.

If a calculation period of 45 years is taken into account (from Figure 46 to Figure 49), the influence of the uncertainty of the Interest rate on the outcome uncertainty is even more evident, due to the highest running cost for the prolonged time period. It is responsible for 48-66% of the overall outcome variability in the Regular Growth scenario, 62-75% in the Deflation scenario and finally 70-81% in the Stagflation scenario. Its contribution is lower in the Intense Growth scenario (22-33%), where the STi of other inputs increase.

In this longer calculation period, GDP variance is also more influential, above all with gas and electricity as energy sources: STi for this parameter reaches 0.51 in the Stagflation scenario and 0.36 in the Regular and Intense Growth scenarios.

Inflation rate and maintenance costs variances are confirmed as uninfluential on the output variance in this calculation period (STi<0.05). Furthermore, also the energy tariff uncertainty decreases its importance and can be considered uninfluential (STi<0.03 in all scenarios).

Finally, in this calculation period, the investment cost variance is responsible at most for 23% of the overall outcome variability

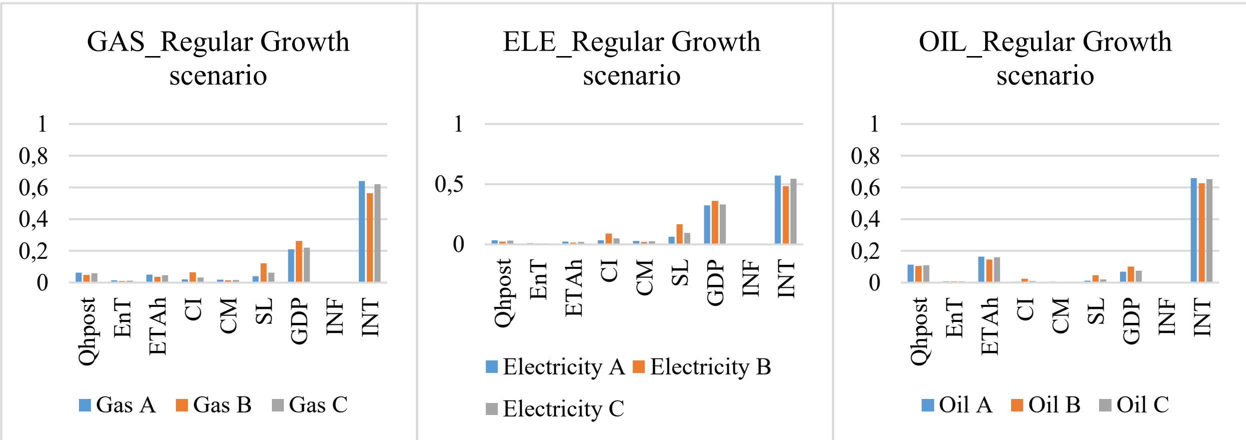


Figure 46 STi for Systems A, B, and C under gas, electricity and oil scenario in the Regular Growth macro-economic scenario and a calculation period of 45 years

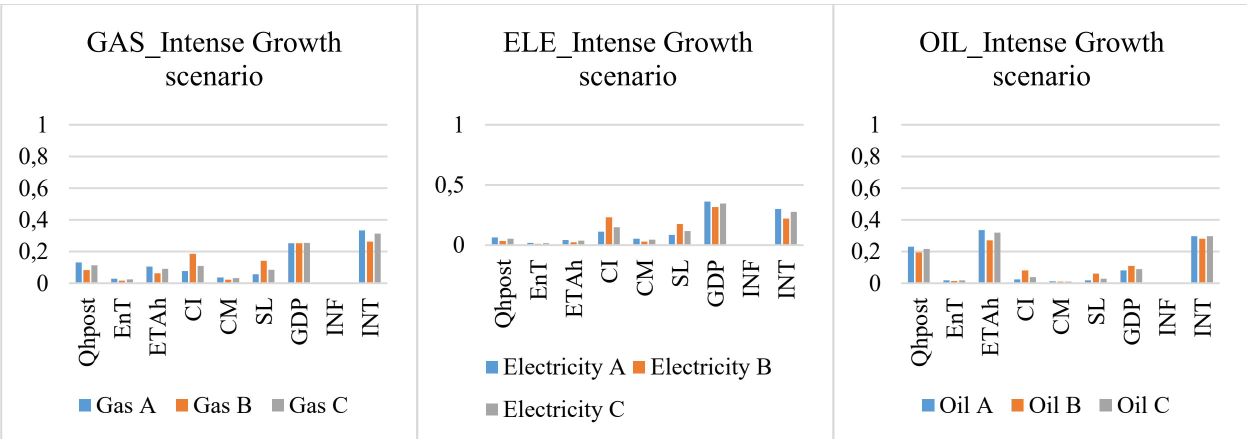


Figure 47 STi for Systems A, B, and C under gas, electricity and oil scenario in the Intense Growth macro-economic scenario and a calculation period of 45 years

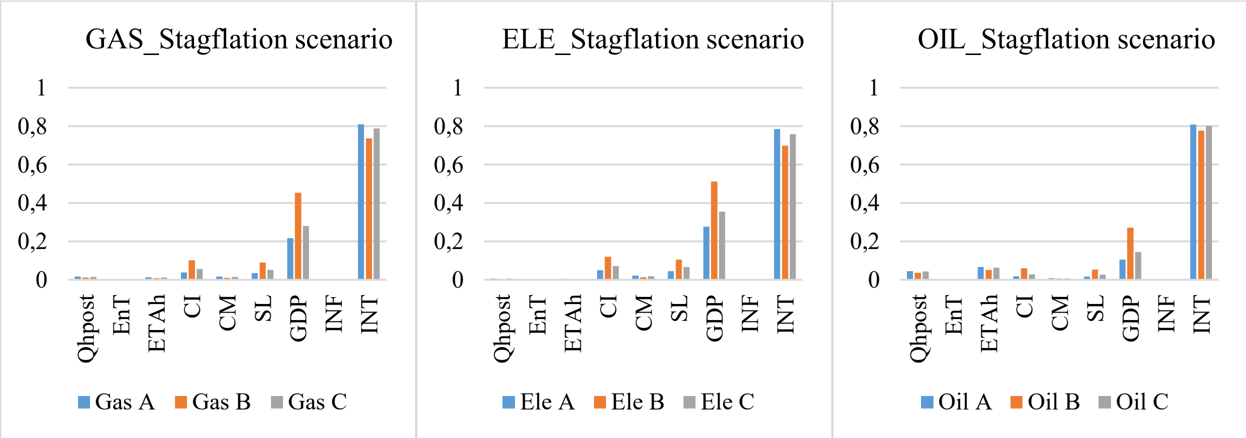


Figure 48 STi for Systems A, B, and C under gas, electricity and oil scenario in the Stagflation macro-economic scenario and a calculation period of 45 years

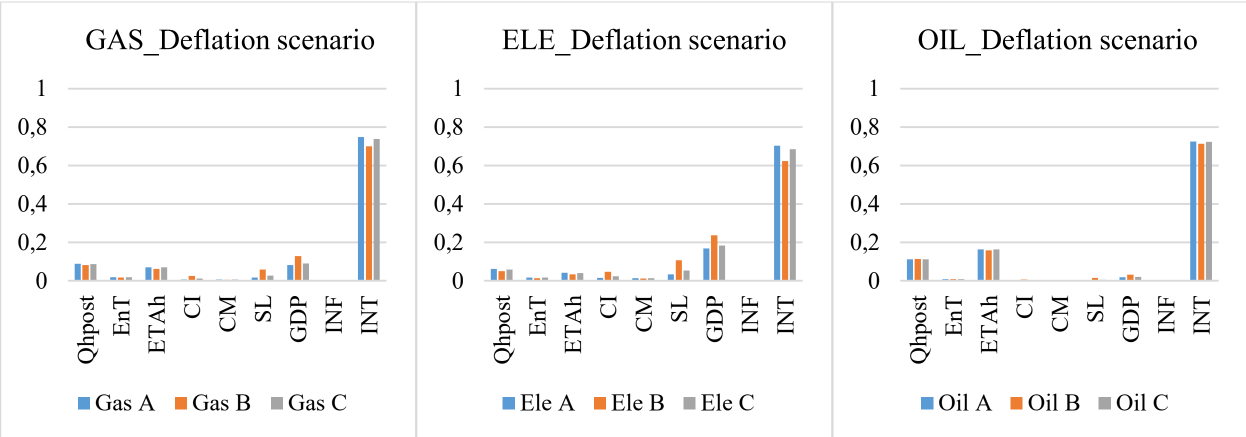


Figure 49 STi for Systems A, B, and C under gas, electricity and oil scenario in the Deflation macro-economic scenario and a calculation period of 45 years

Sensitivity Analysis - Second way

In this case, the macro-economic variables are excluded from the analysis, since SA is performed within each macro-economic scenario to assess the influence of the uncertainty of the other stochastic LCC parameters. STi are calculated for the Gas energy scenario and all the macro-economic scenarios and then represented as box-whiskers plots considering 50 alternative (deterministic) trajectories of the three macro-economic variables simulated (from Figure 50 to Figure 53).

From the graphs it arises that the variation of the STi over the different trajectories in all scenarios (except in the Stagflation scenario) is quite limited, so that the calculated mean value is well representative of the whole indices distributions.

In the Stagflation scenario (Figure 52), the various extractions that feed the sensitivity can generate results that are not always consistent as is the case of other scenarios, i.e. the price development rates can have opposite trends (one growing, the other one decreasing) and this creates greater variability in the sensitivity indices.

Furthermore, in all the economic scenarios, the variables related to the energy consumption (Qhpost, EnT and ETAh) are the most influential input parameters. In particular, Qhpost and ETAh are responsible together for about 90% of the outcome variance in all the macro-economic scenarios, except for the Stagflation scenario (70-83%) where the investment cost uncertainty, especially for the insulation solution B, gains a certain influence.

In all cases, maintenance cost and service life uncertainty are uninfluential on the output variance (STi always lower than 0.03).

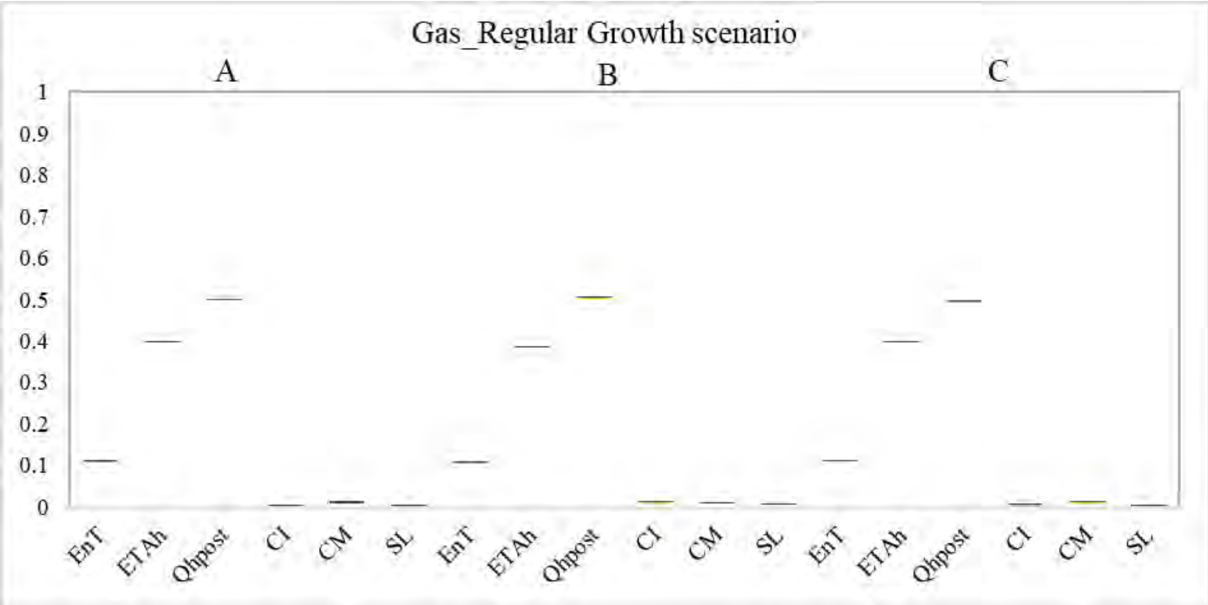


Figure 50 STi trend (50 economic predictions) for the Systems A,B,C in the GAS and Regular Growth scenario (30 year)

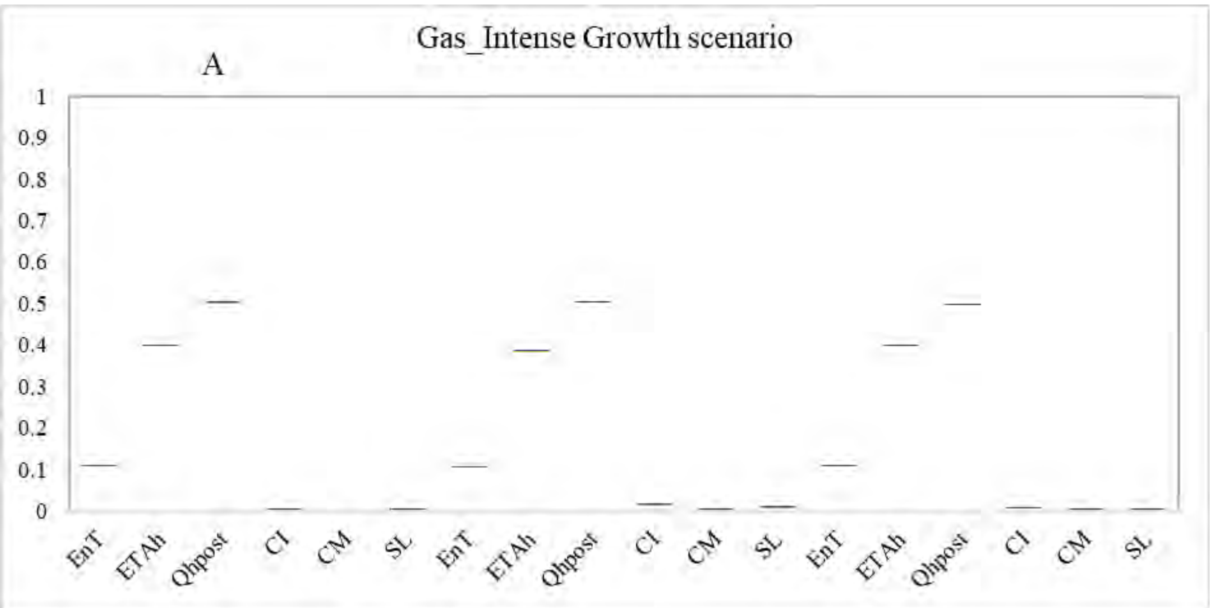


Figure 51 STi trend (50 economic predictions) for the Systems A,B,C in the GAS and Intense Growth scenario (30 year)

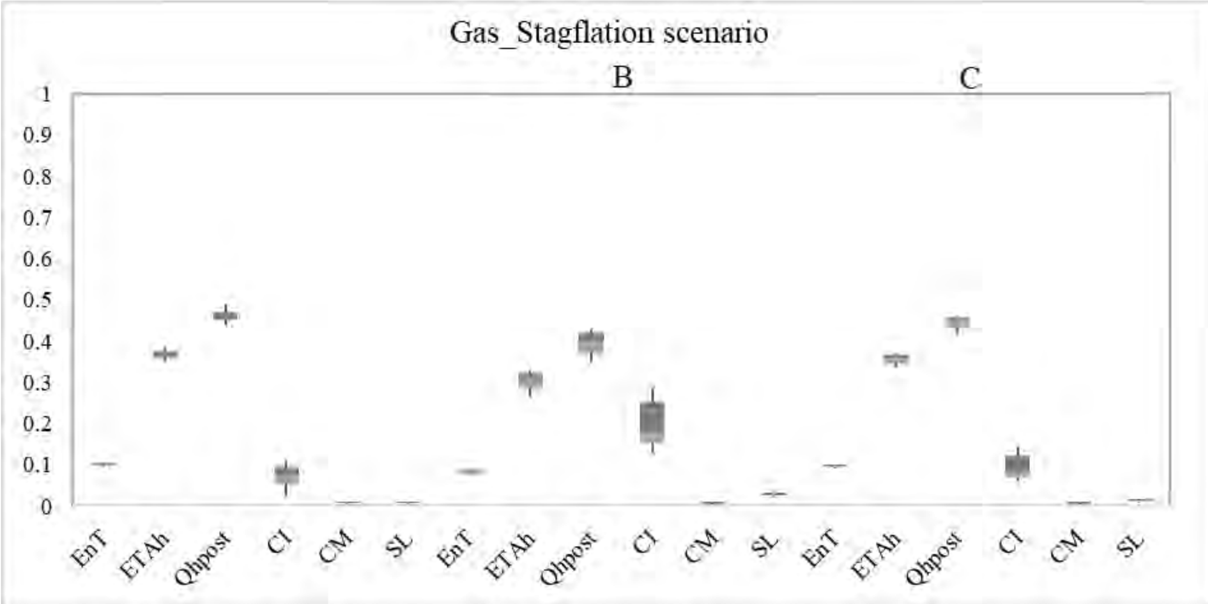


Figure 52 STi trend (50 economic predictions) for the Systems A,B,C in the GAS and Stagflation scenario (30 year)

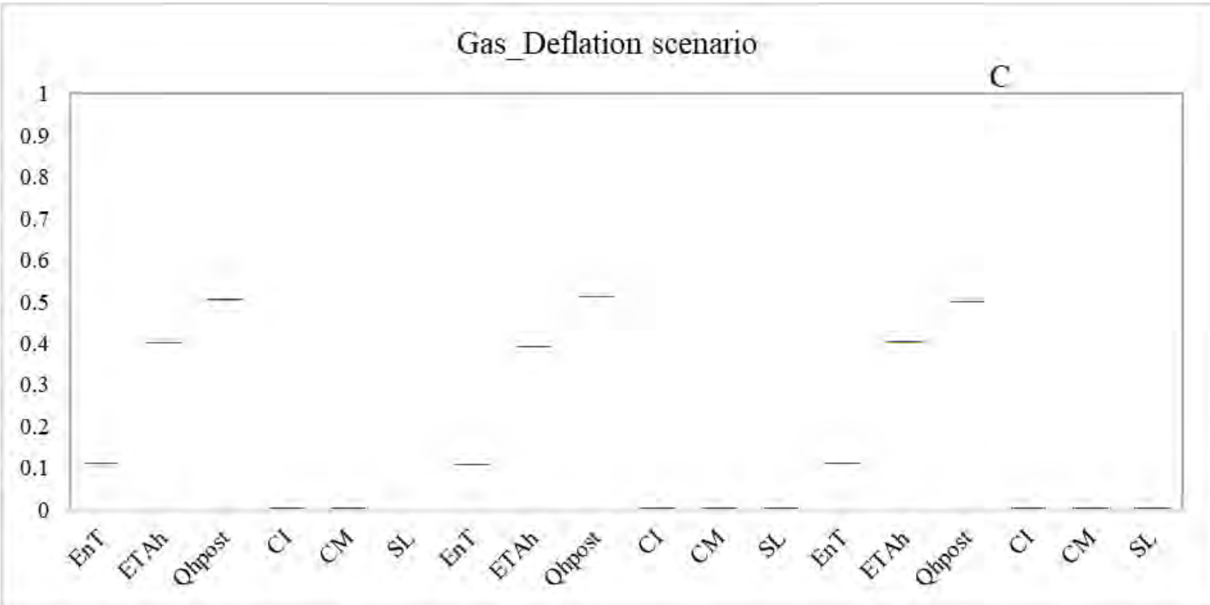


Figure 53 STi trend (50 economic predictions) for the Systems A,B,C in the GAS and Deflation scenario (30 year)

4.4 Conclusions

This section reported the exemplary case study run by UNIVPM according to the PM developed and using the WP5 software tool.

Probability distributions of Global Cost and Payback Period of three internal insulations typically used in Italy have been assessed in a specific wall/climate configuration, considering several assessment scenarios: three energy sources spread at national level, four future possible macro-economic scenarios, and two calculation periods.

The outcomes have been presented through box-whiskers plots and cumulative density functions, to easily compare the performance of the different options. For the current case study it can be concluded that solution A (EPS) is the one able to guarantee minor Global Costs and consequently minor Payback Period, followed by Solution C (mineral wool) and B (cork). The difference among the solutions is mainly due to the different initial investment costs of the insulation materials while running costs are almost the same for the three solutions (as a result of the input data set fort his case study). However, the results are associated with considerable uncertainty, as underlined by the distributions ranges.

The outcome is confirmed in all the energy and macro-economic scenarios, while the absolute values of GC and PB obviously vary according to the specific scenarios. E.g., for each insulation solution, under each macro-economic scenario, electricity is able to determine a minor global cost, followed by gas and oil, depending on the specific heating efficiency energy sources tariffs in Italy.

Considering the different macro-economic scenario, the Stagflation scenario entail the minor median values of GC, while the Deflation scenario the highest ones. In general, by varying the economic scenario, the GC obtained in the baseline reference scenario may vary until 45%. This underlines the importance of the economic variables characterisation in LCC procedures.

Furthermore, for all simulated cases, the sensitivity indices have been calculated to assess, for this case study, which input parameter uncertainty has more impact on results variance (Sensitivity Analysis).

The SA has been performed in two ways, according to the PM developed. In the first one, the macro-economic variables, as the other stochastic LCC parameters, are all included in the SA. With this method, it is possible to compare the importance of economic inputs across different macro-economic scenarios. Indeed, results highlight how the Interest Rate variance in all scenarios is the most influential on the outcome variance. In few cases, also the parameters related to the building energy performance or to the insulation system investment costs show high sensitivity indices, depending on the relative weight of the cost shares (investment or energy costs) in the life-cycle.

The SA performed in the second way allows focusing on the influence of the LCC inputs uncertainties, except for macro-economic variables. It essentially confirms the importance of the energy performance uncertainty on the output variance.

It should be noticed, however, that the evaluation of the sensitivity indices is strictly related to the characterisation of the input parameters for this case study and their relative weight on the outcome. E.g., the heating equipment efficiency, here modelled as a uniform distribution considering the typical values for both old and new systems in Italian historical buildings, could have a minor impact when a specific building case-study is assessed, i.e. when the efficiency is modelled as a "deterministic" input. Likewise, the insulation systems Service Life is here modelled considering the probabilistic factorial method, obtaining a normal distribution with quite low variance, thus entailing a low sensitivity index. In other cases, the user could characterise the SL through other methods (e.g. considering the results of hygrothermal assessments) thus obtaining a higher uncertainty range and supposedly a higher impact on the outcome variance.

In conclusion, the exemplary case performed mainly aims to illustrate the potential applications of the probabilistic LCC methodology developed rather than demonstrate absolute results. Future applications, e.g. in view of future progress of RIBuild guidelines or in general in building renovation projects, should carefully consider how the input parameters are characterised in order to effectively understand the results obtained.

5 Exemplary application of the "probabilistic" LCC: coupled probabilistic LCA and LCC of different interior insulation systems (*HES-SO*)

5.1 Introduction

This case study is a follow-up of the Swiss exemplary case study presented in the RIBuild deliverable D5.1 (section 3.1). In the previous case study, we presented the probabilistic environmental impacts' savings for three levels of assessment (screening, intermediate and detailed). Uncertainties were taken into account for the definition of input parameters (historic building context, insulation system properties, wall properties etc.) depending on the assessment type (Figure 54).

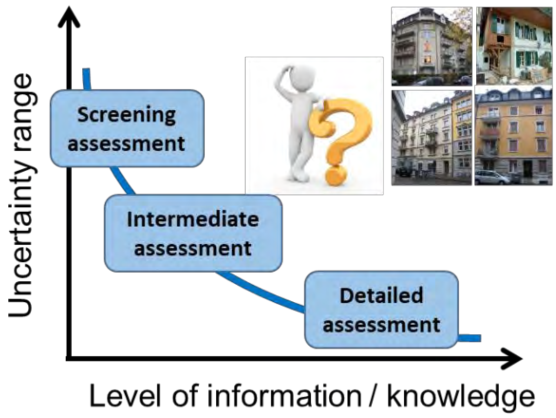


Figure 54 Illustration of the relationship between the uncertainty range and the level of information for different assessments in the renovation of a historic building

This aim of this new case study is to compare different insulation systems from a life cycle assessment and life cycle cost point of view, to identify cost-effective solutions (i.e. solutions able to minimize the life cycle costs but also the environmental impacts compared to the situation before renovation).

In the following case study, we do not consider anymore three levels of details. We assume to be in one level of details (intermediate assessment) with a combination of known and uncertain parameters. On the one hand, when available, we consider real data based on manufacturers' insulation properties (e.g., deterministic lambda values). On the other hand, the historic building wall properties and the boundary conditions (outdoor climate and interior temperature) are still supposed not to be known with confidence (as for the previous screening assessment).

Two situations often found in practice are considered in this exemplary case study conducted for one square meter of a historic building facade:

- Renovation of the building façade with interior insulation systems (cf. case study 1 in section 5.2)
- Renovation of the building façade with an interior insulation system coupled with the replacement of the old heating system (cf. case study 2 in section 5.3).

Other renovation measures exist to renovate a historic building (e.g., replacement of windows, renovation of other elements like the slab or the roof). However, these renovation measures can only be analysed together with the interior insulation measures in the case of a global building assessment of heating demand, LCA and LCC which is not in the scope of the study.

5.2 Renovation of the façade with interior insulation systems (case study 1)

This case study compares available insulation systems. To allow a global vision of the renovation measure, the heat transmission losses, as well as LCA impacts are calculated and presented next to the life cycle costs of the renovation measures. In the following sections, two renovation cases often found in historic buildings are considered, namely:

- Comparison of interior insulation systems for a defined U-value
- Comparison of interior insulation systems for a constant thickness

5.2.1 Design options

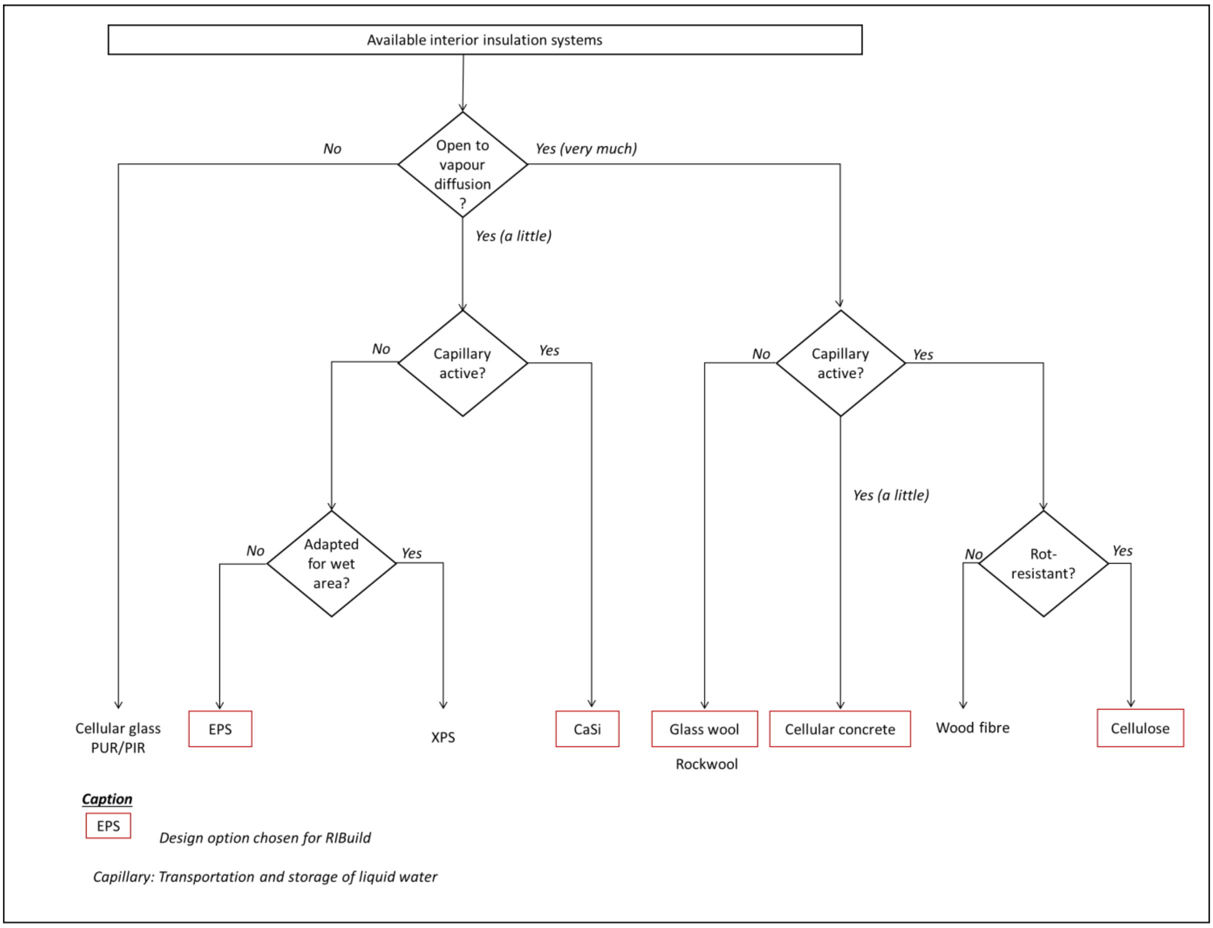


Figure 55 Classification of insulation materials according to their hygrothermal properties

In Switzerland ten insulation types are predominant on the market: cellular glass, polyurethane/polyisocyanurate (PUR/PIR), expanded polystyrene (EPS), extruded polystyrene (XPS), Calcium silicate (CaSi), mineral wool (including glass wool and mineral wool), cellular concrete, wood fibre and cellulose. In order to limit the number of design options in this exemplary case study, the systems were classified according to their hygrothermal properties.

Figure 55 gives a classification of these ten insulation materials according to their openness to vapour diffusion, capillarity and rot-resistance. The materials non-open to vapour diffusion are in the meantime non-capillary active. The problem of rot-resistance appears only for wood fibre. The colour frames point out the insulation systems chosen as design options for this case study. We discuss below the choice of these five design options.

Choice of design options

Vapour impermeable insulation materials such as cellular glass or PUR/PIR are not considered in this case study as design options. They are not open to vapour diffusion which increases the risk of water condensation in the interior wall.

EPS and XPS display similar hygrothermal properties: they are both capillary active and vapour permeable. Due to its complete resistance to liquid water, XPS is mainly used where the risk of liquid water presence is high, so either in buried construction or on exposed construction details (e.g. reveals of window, wall footers). On the contrary, EPS is mainly used as traditional insulation board against the wall. That is why only the most commonly used system (EPS) was chosen as design options.

Calcium silicate is a relative new insulation system made of blocks. It is a little open to vapour diffusion and is capillary active. It is included as one design option.

Mineral wools (rock wool, glass wool) are considered as one insulation system owing to their equivalent properties. These insulation materials are composed of fibres while cellular concrete is a block material. However, cellular concrete is defined separately from calcium silicate because of their different porous structure, which is responsible for the water transport mode through the structure.

Although they have equivalent hygrothermal properties, cellulose is rot-resistant while wood fibre is damageable by water. If humidity stagnates in the wall, there is a great risk to permanently loose the insulation abilities of wood fibre. For this reason, cellulose was preferred in this case study.

Layers composition

Finally, the considered systems are mineral wools, cellular concrete, cellulose, EPS and CaSi. These insulation systems can be divided in three main categories:

- block insulation with mortar
- blown insulation with wood lathing
- insulation board with wood lathing

Layers composition of the different insulation systems are defined based on the available commercial references in the Swiss market. For EPS, CaSi and cellulose all the recommended systems have the same layer composition. The properties of the insulating layer only vary from one product to another (e.g., thermal conductivity and density). For cellular concrete, the manufacturer only suggests one renovation option. For glass wool, there are three systems suitable for interior building renovation. The compositions of two of them, as well as the composition of insulation with rock wool, are similar. The last system is considered less representative and is not considered in this case study.

Regarding block insulation, if the wall presents too many irregularities on its surface, it is possible in many cases to apply a filler layer before the adhesive layer. However, it is a very context-specific situation and the filler is neglected in this study. Furthermore, only homogeneous layers were considered in the calculation. Therefore, in the case of insulating solutions requiring supporting structure, the impact of lathing in technical space or in insulation layer was neglected for the U-value and LCA calculations[31].

For calcium silicate, the reinforcing mesh included in the surface rendering was also neglected. Indeed, its function is to ensure that the system remain in place.

For mineral wool, the insulation layer close to the existing wall is normally composed of two glass wool panels. While it can be calculated as one layer for the transmission losses or the LCA, this particularity will be considered in the LCC calculation as it influences the labour costs.

5.2.2 Simulation scenarios and functional units

Simulations were carried out for a typical sandstone wall from the Swiss plateau with internal mineral coating. Sandstones represent more than 80% of the old building constructions in the Swiss midlands. The heating system is assumed to be an old oil boiler, the main represented heating system in historical buildings according to the Federal Register of Buildings and Dwellings of Switzerland [83]. The reference study period is set at 30 years, so a value closed to the service life of the insulation systems.

Case a: insulation for required U-value

In Switzerland, the SIA380/1 [84] standard defines requirements for the thermal performance of the building. Generally, a global assessment of the building is performed. Another solution is to assess each construction element separately. In the case of such a pointwise evaluation, the minimal U-value required for the renovation of external walls is 0.25 [$W.m^{-2}.K^{-1}$].

As a result, in the scenario 1, the insulation thickness for the five design options is scaled to reach that minimal value of 0.25 [$W.m^{-2}.K^{-1}$]. The five insulation design options presented in 5.2.1 are considered.

Case b: insulation with constant thickness

In the scenario 2, the facade is insulated with an insulation layer of 9 [cm] for each design option. This thickness was defined to not reduce too much the interior surface area and to reach a maximal U-value of 0.40 [$W.m^{-2}.K^{-1}$] for all insulation systems, except CaSi. In this scenario, it is assumed that it is possible to get an exemption to the SIA 380|1 standard (historic building renovation).

[31] It is however taken into account for the LCC (in the labour cost)

Where the SIA 380/1 standard deals with thermal performance, the SIA 180 standard gives guidelines in order to avoid moisture problems. A minimal heat transfer coefficient in of U=0.40 [W.m^{-2}.K^{-1}] is required. Most of the design options in this scenario therefore comply with SIA 180. Due to the high conductivity of the CaSi, it U-value for 9 [cm] oscillates between 0.30 [W.m^{-2}.K^{-1}] and 0.52 [W.m^{-2}.K^{-1}]. Moreover, this thickness affects only the insulation layer and not the global insulation system, thus excluding mortar, vapour barrier, technical space and finishing. This corresponds to a global thickness up to maximal 17 [cm] for all insulation system. Table 19 summarizes the design options and scenarios.

Table 19 Presentation of the general assumptions for the 2 situations

Functional unit	**Case study 1.a** U=0.25 [W.m^{-2}.K^{-1}]	**Case study 1.b** e= 9 [cm]
Design options	Mineral wool (glass wool) Cellulose Polystyrene (EPS) Cellular concrete Calcium silicate (CaSi)	
Context Historic wall type Location	stone wall representative of Swiss historic buildings representative of Swiss Midlands (Plateau)	
Scenarios for the LCA and LCC Heating system assumption Reference study period	existing oil boiler 30 years	

5.2.3 Uncertainty characterisation and propagation for the heat transmission losses

The insulation layer uncertainty considers the product choice proposed by the main insulation manufacturers in Switzerland. Most of the time, manufacturers recommend special cladding type or vapour barrier for their system. When it is the case, properties of this system, as well as given thickness, are set deterministic for the calculation (cf. Table 20). It is considered a part of the system definition. Indeed, in the case of a renovation, once the design option is chosen, it is assumed to be applied regarding the specific recommendation of the manufacturer. If manufacturers do not mention specific product properties or thicknesses, typical property uncertainties considered for each material type. These values take into account the generic value for density in the KBOB database [85] and density and conductivity in the SIA database [86] (respectively Swiss database for life cycle assessment of construction materials and Swiss database of construction materials properties). Table 20 summarizes the mathematical distributions and the assumptions considered for the heat transmission losses calculation.

Table 21 shows the characteristics and composition of the simulated historical wall from inside to outside. The main construction type in Switzerland is rubble stone. It represents different types of stones built with mortar joints. The conductivity of the rubble stone with mortar joints is likely to be a bit lower than the conductivity of the stone alone. However, this aspect is neglected in this study. The uncertainties of the conductivity, density and thickness are represented by uniform mathematical distributions.

Table 22 summarizes the five design options as well as their properties' values from the interior surface to the historical wall, according to the methodology described above. For calcium silicate board (CaSi), the thermal conductivity is rather high. Indeed, only the main distributed product is considered: a climate plate with a conductivity of 0.06 [W.m^{-1}.K^{-1}]. A new product mixed with polyurethane reaches a lambda value of 0.031 [$W.m^{-1}.K^{-1}$]. However, as it is a new product and not widely spread on the Swiss market, it was not considered in this study.

Finally, one assumed that the building is located on the Swiss plateau and that the interior temperature normally set at 20°C in SIA standards, can indeed fluctuate around this value from 18°C to 23°C depending on the historic buildings and the users' behaviour.

Monte Carlo simulations were conducted for 5000 runs using the HES-SO tool developed in the framework of RIBuild[32] to calculate the probabilistic monthly heat losses of interior insulation measures using the statistical software R.

Table 20 Uncertainty characterisation of heat losses parameters for monthly heat losses calculation

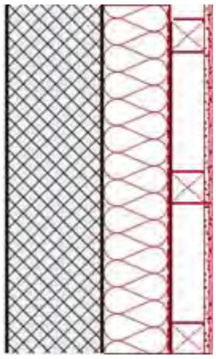
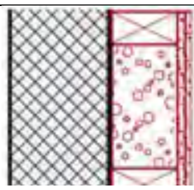
	Parameter description	Distributions and assumptions
Historic wall	Thickness of structural existing material	Uniform distribution (to consider the possible thickness changes from bottom to top of wall)
	Thermal conductivity of structural existing material	Uniform distribution (to consider the uncertainty of stone properties)
	Density of structural existing material	Uniform distribution (to consider the uncertainty of stone properties)
	U-value of the structural existing material	*Calculated value (from the thickness, density and thermal conductivity)*
Internal insulation system	Thickness of the insulation material	Variable to obtain required U-Value in scenario 1 or constant in scenario 2
	Thermal conductivity of the insulation material	Uniform distribution (account for the different available products from main manufacturer in Switzerland)
	Density of insulation material	Uniform distribution (account for the different available products from main manufacturer in Switzerland)
	Thickness of the additional materials (rendering or other)	Deterministic if define by manufacturer, otherwise uniform distribution which consider representative product of the Swiss market
	Thermal conductivity of the additional materials (rendering or other)	Deterministic if specific product mentioned by manufacturer, otherwise uniform distribution which consider representative product of the Swiss market
	Density of the additional materials (rendering or other)	Deterministic if specific product mentioned by manufacturer, otherwise uniform distribution which consider representative product of the Swiss market
	U-value of the wall (structural material + new internal insulation system)	Fixed value, as defined in the simulation scenario 1 or calculated value for scenario 2
Climate conditions	Climate conditions (external)	Equiprobability (choice between national weather stations of the Swiss Midlands)
	Internal temperature	Triangle (account for the uncertainty due to the user behaviour)
	Humidity level (internal)	-
Input parameter for the LCA and LCC (Use phase)	Annual transmission heat losses before renovation	*Calculated value*
	Annual transmission heat losses after renovation	*Calculated value*

[32] Developed based on "option 2" and described in RIBuild deliverable 5.1.

Table 21 Properties for the stone wall in the simulation

Stone wall layer	Conductivity [W.m^{-1}.K^{-1}]	Density [kg.m^{-3}]	Thickness [cm]
Mineral coating	0.4-0.8	1000-1600	0.5-2
Stone wall (sandstone)	1.7-2.3	2000-2600	40-60

Table 22 Characterisation of the five design options

Insulation type	Insulation system	Material Layers	Conductivity [W.m^{-1}.K^{-1}]	Density [kg.m^{-3}]	Thickness [cm]	Schematic representation of insulation systems
Board	**Polystyrene board** *(EPS)*	Plasterboard	0.21-0.25	700-1200	2.6	
		Technical space (air)	0.132-0.313	1.23	2.5-5	
		Vapour barrier	0.2	920-1100	0.15-0.35	
		EPS	0.029-0.033	25-30	Case a: variable Case b: 9	
	Mineral wool *(glass wool)*	Plasterboard	0.21-0.25	700-1200	2.6	
		Glass wool	0.032-0.035	20-29	Case a: variable Case b: 9	
		Vapour barrier	0.2	266	0.3	
		Glass wool	0.032-0.035	20-29	Case a: variable Case b: 9	
Block	**CaSi**	Lime cladding	0.57-0.68	1250-1500	0.2-0.3	
		CaSi	0.060	90-187	Case a: variable Case b: 9	
		Mineral mortar	0.60	1410	0.5	
	Cellular concrete	Plaster and lime cladding	0.4-0.7	1000-1400	1	
		Cellular concrete	0.042	90	Case a: variable Case b: 9	
		Mineral mortar	0.4-0.8	1000-1600	0.5	
Blown	**Cellulose**	Plasterboard	0.21-0.25	700-1200	1.3	
		Technical space (air)	0.132-0.313	1.23	2.5-5	

Insulation type	Insulation system	Material Layers	Conductivity [W.m^{-1}.K^{-1}]	Density [kg.m^{-3}]	Thickness [cm]	Schematic representation of insulation systems
		Vapour barrier	0.2	920-1100	0.15-0.35	
		Cellulose	0.038	50-55	Case a: variable Case b: 9	

5.2.4 Uncertainty characterisation and propagation for the LCA

Impact value for the LCA calculation are taken from the Swiss KBOB recommendation "Ökobilanz im Baubereich / Données d'écobilans dans la construction" [85]. This recommendation provides a list of construction materials and energy sources LCA data with three calculated indicators: the greenhouse gas emissions (GHG emissions), the cumulative non-renewable primary energy demand and the ecopoints according to the Ecological Scarcity Method (version 2013). It contains generic construction materials as well as product-specific values for the manufacturers selling their products in Switzerland. As for the thermal properties, if the LCA data are provided by a manufacturer, there are considered. Otherwise, generic LCA data for the construction materials are considered. From the deterministic value in the KBOB, lognormal distributions are calculated using the Pedigree matrix implemented in the ecoinvent database v2.2 (background database of the KBOB recommendations for the building sector). The uncertainty analysis was conducted with 5000 runs. Table 23 presents the uncertainty characterisation for LCA calculation.

Table 23 Uncertainty characterisation of parameters for the LCA

LCA Stage (EN 15978 nomenclature)		**LCA Parameter description**	**LCA distributions and assumptions**
Production Stage	**Material**	Mass of the materials composing the insulation system [kg]	*Calculated based on assumptions used for the heat losses calculations*
		Unitary environmental Impact of material [Unit of indicator]	Lognormal distribution (probabilistic KBOB[33] data of each material as implemented in ecoinvent v2.2.2016.12 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]	Normal distribution for internal insulated facade (mean=33.8, sd=14) (values based from an international database of service lives of building elements developed in the DUREE project [87])
	Energy Consumption	Heat transmission losses through the wall [kWh/year]	Calculated value (see Table 2)
		Building overall efficiency for heating, depending on the	Lognormal distribution (meanlog= 0.003268, sdlog= 0.091283)*

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

LCA Stage (EN 15978 nomenclature)		**LCA Parameter description**	**LCA distributions and assumptions**
		heating generator, distribution and regulation efficiency [-]	
	Energy Impact	Unitary environmental Impact of heating system [Unit of indicator]	Lognormal distribution using the probabilistic 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

*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

CaSi is a relatively new product and has not been yet referenced in the KBOB database. However LCA studies for the CaSi sold in Switzerland exist in the German Environmnetal Product Declaration (EPD) from IBU for two of the chosen indicators : greenhouse gas emissions and non-renewable primary energy for the production stage [88]. These EPD values are not strictly comparable with the KBOB methodology. In order to take into account the calculation differences between the EPD (calculated with the Gabi database) and the KBOB data (calculated with the ecoinvent database v2.2), the EPD impact values are increase of 2% to take into account the cut-off rules allowed by the SN EN 15804 standard. Similarly, we increase the primary non-renewable energy indicator of 5% to account for the difference in calorific values (gross calorific value (GCV) approach in Gabi and high calorific value (HCV) approach in Ecoinvent and KBOB). The values for the disposal at the end-of-life were considered equivalent to those of the cellular concrete. Finally, the ecopoints were approximated using a linear regression model between the cumulative energy demand and the ecopoints (Ecological Scarcity method) of all ecoinvent datasets for construction materials. This linear regression is based on the work conducted by Huijbregts et al [89][34]. We then apply to the three CaSi indicators the standard deviation (based on the Pedigree Matrix) of the cellular concrete. Table 24 summarizes the calculated impact values for CaSi. The LCA data for CaSi are probably not too much representative of the impact of the product due to the assumptions detailed above.

Table 24 Calculated deterministic LCA value for CaSi (production and end of life stages)

GHG emissions [kg CO_{2-eq}/kg]	Non-renewable primary energy [MJ/kg]	Ecological scarcity [UBP/kg]
2.09	28.09	1714

Monte Carlo simulations were conducted for 5000 runs using the HES-SO tool developed in the framework of RIBuild to calculate the probabilistic LCA of interior insulation measures using the statistical software R.

[34] The calculated ecopoints (in UBP/kg) for CaSi made has been checked in terms of ranking for a same additive thermal resistance of 5 [m^2.K/W] between the 5 insulation materials and for the three indicators (GHG emissions, primary non-renewable energy and the ecopoints). The ranking remains the same for the three indicators when using the calculated ecopoints for CaSi. When using only the calculated ecopoints for the 5 insulations, the ranking is still the same. So, no bias in terms of ranking is induced by our extrapolation. Only the cellular concrete and the glass wool are switched in the ecopoints' ranking compared to the GHG emissions and primary energy's ranking.

5.2.5 Uncertainty characterisation and propagation for the LCC

This section contains three parts: the determination of the investment costs for the insulation systems, the determination of the energy costs and finally the table with the characterisation of LCC parameters. In this section and in the following, all costs are given in Swiss Francs [CHF]. A conversion factor of 1:1 to euros [€] can be assumed when reading the results.

Determination on interior insulation investment costs

The investment costs for any insulation system comprise different parameters: the costs of the materials (the insulation and the other layers), the labour cost, and the other aspects such as the overheads and the profits of the company, the possible discounts given to the clients, and the VAT. Each parameter of the investment cost is likely to vary depending on the context of the renovation. Depending on the surface area of insulation ordered to the manufacturer, the cost of materials can be decreased due to a discount the manufacturer offers to its client. Similarly, the labour cost is likely to vary depending on the insulation execution; the geographical context (e.g., in Switzerland the labour cost is more expensive in cities like Zürich/Geneva than in the countryside). Getting real data on each of the parameters of the investment costs is not realistic. Some data exists (e.g., material costs) but other are confidential (e.g., enterprise profits). So, in this study, we rather used empirical investment costs based on interior insulation renovations observed over the last few years.

The investment costs of the insulation systems were defined based on empirical values taken from a database based on TEP Energy report [90]. This database gathers costs from building renovations whose owners applied for Swiss renovation subsidies in the framework of the "Programme Bâtiment /das Gebäudeprogramm"[91]. The renovations took place between 2006 and 2010. All building construction years were considered in order to collect enough case studies. In total, around 120 renovations with interior insulation were used for the determination of representative investment costs. As the evolution of labour costs for building renovation in Switzerland has not varied from 2010 to 2017 (variation of 0%), the investment costs were kept as such [92].

The variability on investment costs from the 120 renovations depends on many parameters and some were presented above. In the database, only three parameters are provided:

- the region of renovation within Switzerland;
- the area insulated;
- the applied insulation thicknesses.

An initial screening analysis of the investment costs within the database shows that the thickness does not represent a great percentage of the variability compared to other parameters. The difference between a thickness of 6.5 [cm] and a thickness of 25 [cm] is responsible of 4% of variation in the median investment cost. In opposite, when varying the insulated surface between 100 [m^2] (example of surface possible to find in a single-family house) to 1000 [m^2] (example of surface possible to find in a multi-family building), a variation of 27 [%] is found for the median investment cost. Concerning the region of renovation, no clear tendencies were found as not all the Swiss cantons are represented in the sample.

The resulting investment costs are presented in Figure 56. They represent the median cost and the interquartile range of costs available in the database after processing. They are considered to represent the investment costs of insulation for an external wall in order to reach U-values of 0.20 to

0.25 [$W.m^{-2}.K^{-1}$]. Indeed, these two U-values have close insulation thicknesses and the difference in investment costs is negligible. The chosen distribution is a triangle distribution (first quartile, third quartile, mean value) focusing on 50% of the available data. As the number of building renovations is variable (see number in brackets in the figure), these costs should only be interpreted as an empirical tendency and do not pretend to be representative of extreme situations.

For the scenario 2, the thickness reduction to 9 [cm] has been taken into account by reducing the investment costs by 4%, according to the variation on the median investment cost from U-values of 0.20 to 0.40 [$W.m^{-2}.K^{-1}$].

In the building renovations' sample from the "Programme Bâtiment/das Gebäudeprogramm" no renovation with calcium silicate are found. This product was not commonly used in Switzerland during the period when renovation data were collected (2006-2010). So, we used deterministic data for material and labour costs transmitted by the main reseller of CaSi in Switzerland. Based on these values, a rough percentage of variation of 10% was applied to create a theoretical triangle distribution. Unlike the other insulation systems, the cost of material for CaSi is not negligible. It represents 40% of the total investment cost. A linear regression enabled to determine the cost for each thickness according to the case study scenarios. The information provided by the manufacturer shows that the calcium silicate is usually applied in renovation with a low thickness up to 8-10 [cm]. Therefore the thickness of 21 [cm] needed to reach the required U-value of 0.25 [$W.m^{-2}.K^{-1}$] does not seem realistic and features higher costs due to the linear regression assumption.

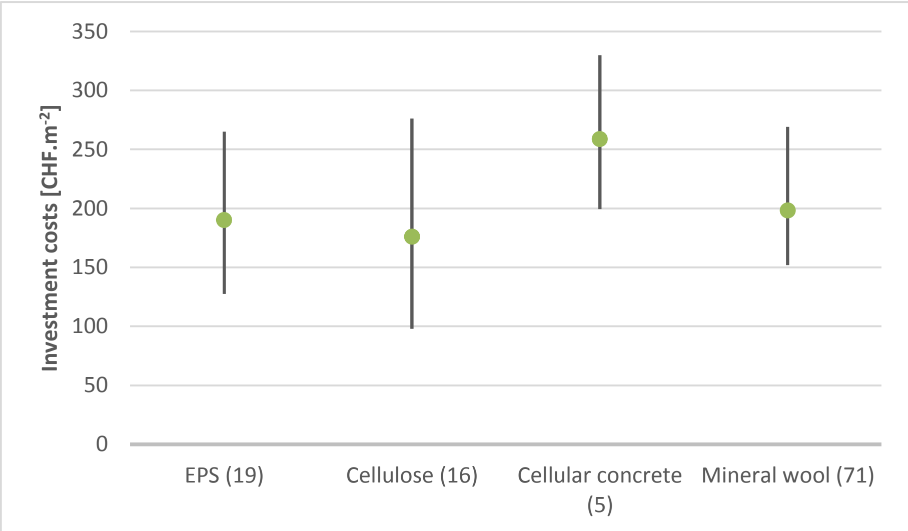


Figure 56 Cost of insulation systems for the four RIBuild design options, for U=0.25 [$W.m^{-2}.K^{-1}$] in brackets: number of case studies for each insulation

Determination on the energy costs

Energy cost for the LCC calculation is determined according to the definition in the EN 15459 standard for economic evaluation procedures for energy systems in buildings. Energy cost can be divided in four main costs: capital expenditure (CAPEX), operational expenditure (OPEX) taxes and external costs, as can be seen in Figure 57.

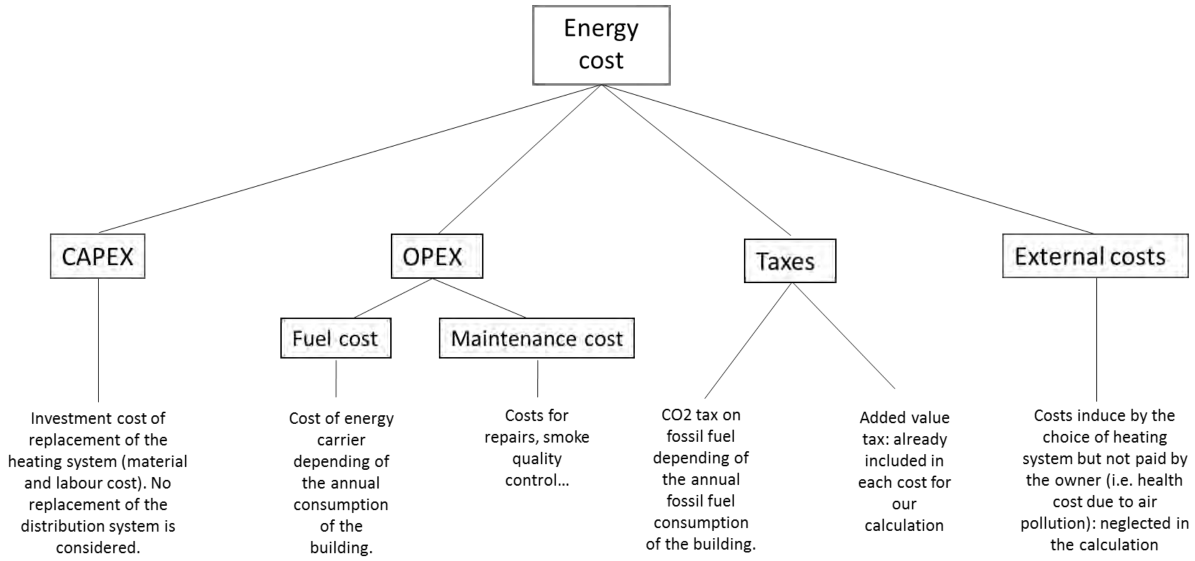


Figure 57 Decomposition of energy cost according to EN 15459

The energy costs expressed in [cCHF/kWhu] reflect the energy consumption of the building which is dependant of the size of a building and the level of insulation. The less heating consumption a building has, the higher will be the influence of the CAPEX.

The heating demand of a building after renovation is highly variable and depends on many parameters: energy performance targets for the renovation, compactness of the building, compliance to the limit value of SIA 380/1 renovation. For example, by considering a single-family house with a compactness factor of 2.50, the limit value of the heating demand according to SIA 380/1:2016 would be about 62 [$kWh.m^{-2}.a^{-1}$] in average conditions. For a house with a living area of 200 [m^2], it represents 7.3 litters of oil per square meter. As a comparison, the model of cantonal energy regulations (MoPEC), recommends a consumption of 4.8 [$L.m^{-2}$] of oil for buildings built in 2010 [93]. So, this reference building is assumed to be well insulated after renovation. In practice, it is likely that historic buildings after renovation may consume less or more than 62 [$kWh.m^{-2}$] depending on the chosen insulation thickness. Indeed, not all the renovations of historic buildings comply with the SIA 380/1 limit value, due to exceptions (architectural value). So heating demands far beyond the SIA 380/1 limit value are plausible. Finally, we consider a heating demand of about 70 [$kWh.m^{-2}.a^{-1}$] close to the limit value but not necessarily reaching it to represent the current historic building renovation situation (some renovations comply with eh limit value some other may not comply). This value only serves to fix the energy costs for 1 [m^2] of facade in this case study and will anyway not influence the ranking of the insulation system.

In this case study, the heating system is already in place and the boiler investment costs are assumed to be already amortised. Consequently, the CAPEX are not included. Moreover, the efficiency is defined lower than a new boiler's efficiency. According to the federal office of energy (SFOE) [94], the range of variation of efficiency varies from 75% to 80% (efficiency on higher calorific value) for an old oil boiler. The maintenance costs are as well neglected since only the vector cost in considered. Finally, the EN 15449 recommends only taking into account the price paid by the consumer for determining cost-optimal insulation solutions.

The fuel costs represent the minimum, maximum and mean costs payed by consumers over the three last years (2015-2017). Indeed the SIA 480 [95] recommends to choose the fuel cost as the mean cost over the last three years. The values are obtained from the Federal Office for Statistics of

Switzerland [96] according to the consumption of the building. The fuel cost includes the basic charge for oil and the value added tax. In addition, a CO_2 tax, introduced in 2015, is included in the fuel cost. It considers the CO_2 emissions from the use of fossil fuel boilers and changes every year. Therefore, it was deduced according to its annual amount and then considers with the value of 2018: 96 [CHF/tonne of CO_2]. This tax is normally fixed until 2020, but subject to rise after this date [90]. Finally, the uncertainty of the global cost of energy carrier for an oil boiler is given in Table 25.

Finally, Table 26 presents the assumptions for the LCC calculation.

Table 25 Oil price range for a boiler with a low efficiency

	Minimal cost [cCHF/kWh]	Maximal cost [cCHF/kWh]	Mean cost [cCHF/kWh]
Oil	11.07	14.41	12.91

Table 26 Uncertainty characterisation of LCC input parameters

LCC INPUTs			
LCC Stage		**LCC Parameter description**	**LCC assumptions**
Financial data	**Duration of the calculation**	Duration of the calculation [years]	30 years
	Financial rates	Inflation rate [%]	Regular growth macro-economic scenario
		Market interest rate [%]	Regular growth macro-economic scenario
	Rate of develop-ment of prices	Rate of development of prices [%]	Regular growth macro-economic scenario
System characteristics	**Component Investment cost**	Insulation systems Investment cost [€]	Triangle distribution (cf. insulation cost)
	Periodic costs for replacements	Insulation systems Service Life [years]	Normal distribution from the DUREE database [97] for internal insulated façade (mean=33.8, sd=14.0)
		Insulation systems replacement costs [€]	Updated insulation system investment cost
	Running Costs	Insulation systems annual Maintenance cost [€]	Deterministic=0 (included in the insulation system investment cost)
Energy Costs	**Energy consumption**	Heat transmission losses through the wall [kWh/y]	Normal distribution from heat transmission losses calculation
		Building overall efficiency for heating, depending on the heating generator, distribution and regulation efficiency [-]	Lognormal distribution (meanlog= 0.003268, sdlog= 0.091283)*
	Energy Costs	Energy source national tariff [€/kWh/y]	Triangle distribution (cf. energy cost in 5.2.5)

*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 5630 runs using the WP5 software tool.

5.2.6 Results for a wall U-value of 0.25 [W.m^{-2}.K^{-1}]

The results of the design options' comparison are represented for the heat transmission losses, the three LCA indicators and the global cost as boxplots with the whiskers representing the first and ninth decile of the distribution and the upper and lower parts of the boxplot representing the first and third quartiles. The median is represented by the horizontal black line in the middle of the boxplot. In addition to these comparative results, we also present for each design option, the share in terms of environmental impacts or in terms of global costs due to the insulation systems and the payback time of the renovation measure in years.

Figure 58 presents the results of the heat transmission losses before and after renovation (with the five insulation systems).

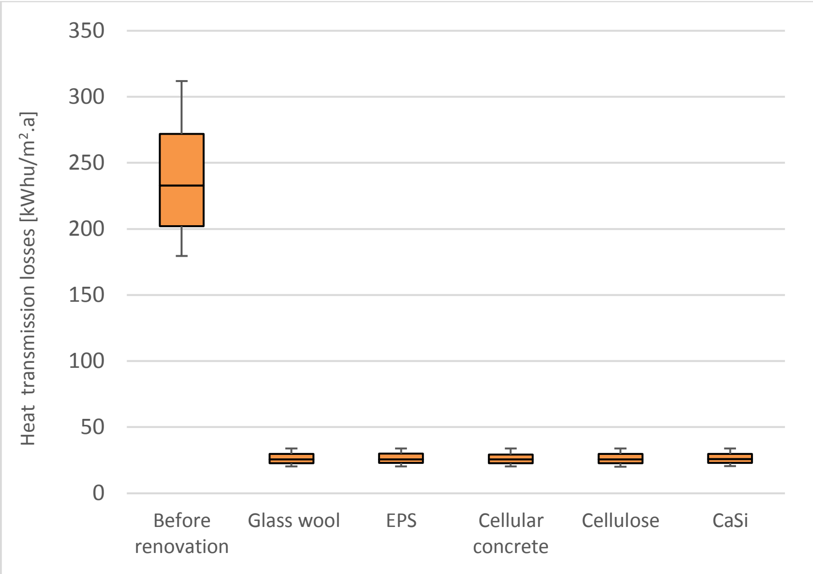


Figure 58 Heat transmission losses before renovation and after renovation for a wall U-value of 0.25 [W.m^{-1}.K^{-2}]

As the five design options allow to reach a U-value of 0.25 [W.m^{-2}.K^{-1}], they all significantly decrease the transmission losses from about 180 to 310 [W.m^{-2}.K^{-1}] before renovation to 25 to 40 [W.m^{-2}.K^{-1}] after renovation. The high variability of the heat transmission losses before renovation can be explained by the conductivity and thickness assumptions on the historical walls, which present a great variation range as we do not know in detail the wall characteristics in this assessment. After renovation, this variation range is less notable, because the impact of the insulation is predominant.

Figure 59 presents the results of each design option for the three LCA indicators (GHG emissions, cumulative non-renewable energy demand and ecopoints) and for the LCC indicator (Global costs).

The LCA results in Figure 59 (and in the following ones) are only presented as design options' comparison as the same trend as the one observed for the heat transmission losses is found i.e., the environmental impacts before renovation are higher than those after renovation. For example, the GHG emissions before renovation vary between 55 and 103 [kg $CO2_{eq}$.m^{-2}.a^{-1}] while they decrease to around 6.5 to 14.5 [kg $CO2_{eq}$.m^{-2}.a^{-1}] after renovation whatever the insulation systems. It is the same for the primary non-renewable energy. It varies between 223 and 421 [kWh oil_{eq}.m^{-2}.a^{-1}] before renovation and decrease after insulating the wall to around 27 to 57 [kWh oil_{eq}.m^{-2}.a^{-1}]. For the ecological scarcity, it varies between 11’500 and 22’700 [UBP.m^{-2}.a^{-1}] before renovation and drops to 5’050 to around 11’500 [UBP.m^{-2}.a^{-1}] after renovation. Insulating the facade considerably reduces the global environmental impacts.

Surprisingly, the global cost also decreases after insulating the wall. While it ranges from 759 to 1792 [CHF.m^{-2}.a-^{1}] before renovation, it drops to around 220 to 540 [CHF.m^{-2}.a^{-1}] for the glass wool, EPS, cellular concrete and cellulose and to around 600 to 1400 for the CaSi. In this last case, it is not obvious that the global cost after renovation is systematically lower.

In terms of environmental impacts, it is not possible to identify a best design option due to the uncertainties of the input parameters. However, EPS and CaSi solutions seem to have a slightly greater impact in median value compared to other insulations, particularly for the ecological scarcity. Due to the numerous assumptions, the uncertainty on the results of CaSi is substantial. In opposite, cellular concrete presents in median value lower values for all indicators.

Similarly, it is not possible to identify a better insulation system in terms of global costs. Glass wool, EPS, cellulose and cellular concrete show a similar cost variation between 220 and 650 [CHF.m^{-2}.a^{-1}], whereas CaSi presents higher global costs with a variation from 600 to 1690 [CHF.m^{-2}.a^{-1}]. This is due to its higher thermal conductivity (about 0.060 [W.m^{-1}.K^{-1}]), as well as its higher investment costs. Considering the new CaSi product mixed with polyurethane for which the thermal conductivity would be divided by a factor two (about 0.035 [W.m^{-1}.K^{-1}]), the installed insulation thickness will be much lower. Therefore, the global cost will most probably decrease consequently if we assume that its investment costs do not vary.

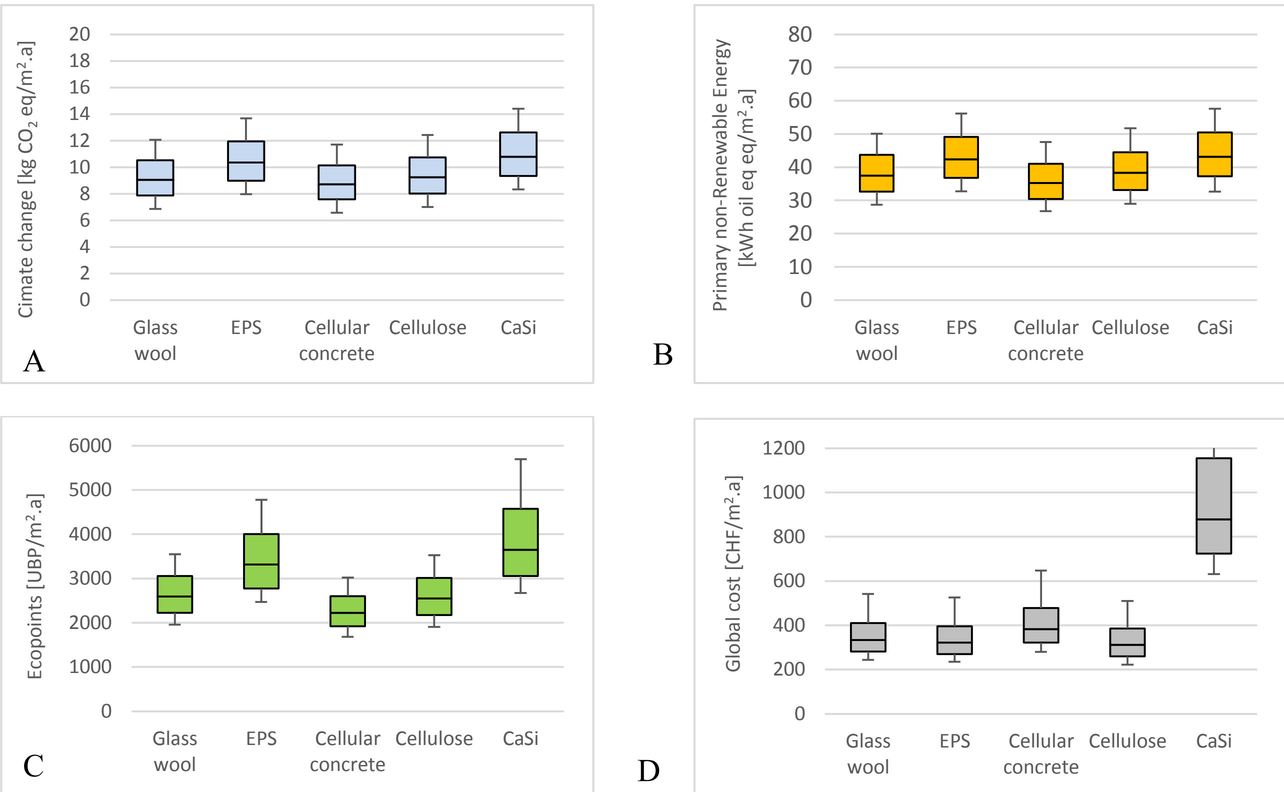


Figure 59 Probabilistic results for the wall after renovation with the different insulation systems with a resulting U-value of the wall of 0.25 [W.m^{-1}.K^{-2}] for climate change indicator (A), non-renewable primary energy (B), ecological scarcity (C) and global cost of the renovation (D)

Table 27 shows the share of environmental impacts and global cost due to the insulation system. For the three LCA indicators, the share of insulation material ranges from 2% to 39% of the total impact. So, it can be concluded that the environmental impacts are mainly driven by the operational energy use (heat losses) rather than by the additional insulation material. The share of the insulation material for the ecological scarcity indicator is a bit more important, generally less than 50% even if it can reach up in some cases 70% of the total ecopoints.

In opposite, the share of the insulation system in the global cost is much higher than for the GHG emissions or primary energy. It varies from 40% to 93% for all insulation systems. A higher share is found for the CaSi compared to the other systems. As a conclusion, the global costs are mainly driven by the investment costs of the insulation material rather than by the annual energy costs (due to the heat losses).

Table 27 Share of construction materials environmental impacts added during the historic facade renovation with a resulting U-value of 0.25 [W.m^{-1}.K^{-2}] and share of global costs

Share in % Construction materials		**Glass wool**	**EPS**	**Cellular concrete**	**Cellulose**	**CaSi**
LCA	Greenhouse gas emissions	5% to 15%	12% to 32%	3% to 10%	6% to 18%	13% to 38%
	Primary non-renewable energy	6% to 17%	12% to 33%	2% to 8%	6% to 20%	11% to 35%
	Ecopoints	6% to 20%	12% to 32%	4% to 12%	6% to 19%	13% to 39%
LCC	Global costs	44% to 78%	43% to 77%	50% to 82%	40% to 76%	76% to 93%

Table 28 presents the values of the payback times of the interior insulation measures for the different design options. The range of payback times is presented for the decile 1 and 9 respectively. They vary from 4 to 9 years for the insulation with glass wool, EPS or cellulose, and from 5 to 12 for cellular concrete. The situation of CaSi is again singular as the payback time varies from 14 to 37 for CaSi. These values should be interpreted according to the boundary conditions of this study. Only one square meter of the wall is considered and only the heat losses are considered. A similar study conducted at the building scale would provide different insights.

Table 28 Pay back times of the interior insulation measures with a resulting U-value of 0.25 [W.m^{-1}.K^{-2}]

		Glass wool	**EPS**	**Cellular concrete**	**Cellulose**	**CaSi**
LCC	Payback time (in years)	4 to 9	4 to 9	5 to 12	4 to 9	14 to 37

5.2.7 Results for a constant thickness insulation layer of 9 [cm]

Figure 60 presents the results of the heat transmission losses for an additional 9 cm thickness[35]. The same conclusions (heat losses reduction after renovation) as in the first case (U-value of 0.25 [W/m^2.K]) are observed. The heat transmission losses after renovation now vary around 30 [kWh$_u$.m^{-2}.a^{-1}] for glass wool, EPS and cellulose, around 40 [kWhu.m^{-2}.a^{-1}] for cellular concrete and 50 [kWhu.m^{-2}.a^{-1}] for CaSi.

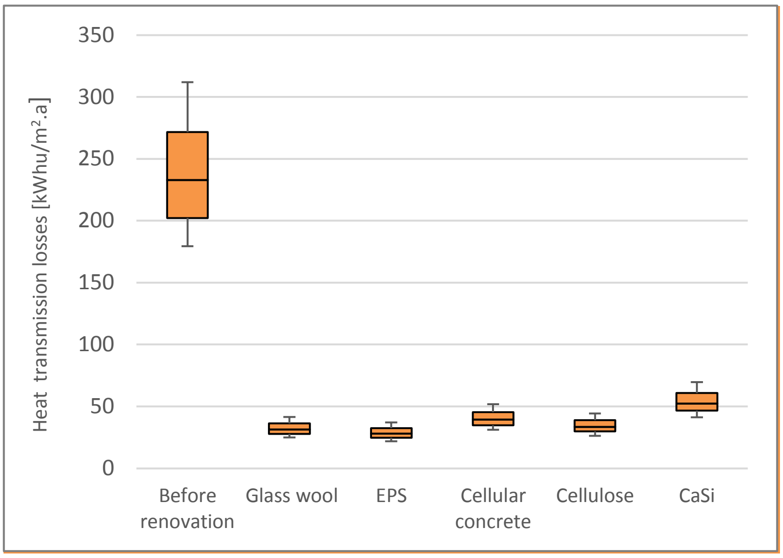


Figure 60 Heat transmission losses before renovation and after renovation for an insulation thickness of 9 [cm]

As for the previous case (U-value of 0.25 [W/m^2.K], a wall renovation with an insulation thickness of 9 [cm] allows an important reduction of the environmental impacts (correlated to the decrease of heat losses as seen in the figure above). Moreover, for all renovation design options, the annualized cost during the 30 years calculation period is lower than the running costs before renovation. Figure 61 now presents the impact of each design options for the three LCA indicators and for LCC.

For this functional unit of 9 [cm], different trends can be observed. The results for the LCA indicators are translated upwards in each graph depending i) on their thermal properties (density, lambda values) and ii) on the contribution of the insulation systems in the LCA results (generally below 39% for all indicators cf. Table 27). The physical properties seem to determine the ranking, with higher impacts for systems with higher conductivity and density, such as calcium silicate or cellular concrete.

The results for global costs do not change much for the glass wool, EPS, cellular concrete, cellulose systems. There are only slightly higher than for the first functional unit (U-value of 0.25 [W/m^2.K]). As explained in section 5.2.5, the insulation thickness does not have a great influence on the material costs. Therefore, the cost of energy due to higher transmission losses can explain this rise. Once again, CaSi is an exception. The use of a functional unit of 9 [cm] tighten the gap for the

[35] The heating demand of the building (single-family house) is supposed to be the same as in the previous case study 1.a for the energy cost calculation. Indeed, as we insulate only 9 [cm] and that the wall U-value is now higher, we assume that in parallel additional renovation measures for the building envelope are considered to remain compliant in this case study 1.b with the limit value of SIA 380/1 renovation.

global costs between the CaSi and the other design options. The decrease of the required insulation thickness considerably lower the CaSi material cost which then lead to a decrease of the global cost (as the material share in the global cost is important and about 75-90%). The global cost of CaSi remains still the most expensive solution in median value but is now closer to the other systems (around 600 [CHF.m^{-2}.a^{-1}] vs. 400 [CHF.m^{-2}.a^{-1}] in median value).

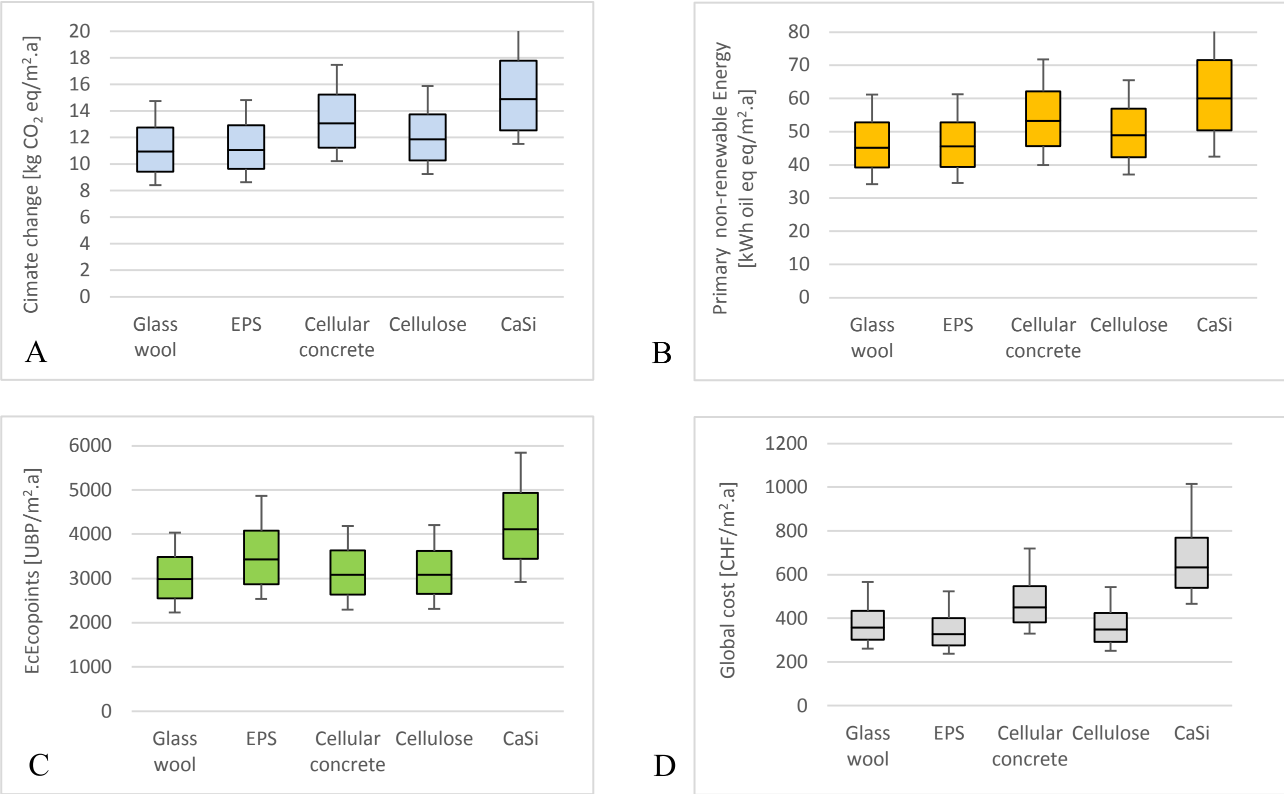


Figure 61 Probabilistic results due to the different insulation system for an insulation thickness of 9 [cm] for climate change indicator (A), non-renewable primary energy (B), ecological scarcity (C) and global cost of the renovation (D)

Table 29 shows the share of environmental impacts and global cost due to the insulation systems. At constant thickness, the share of the operational energy use (heat losses) depends on the heat transmission losses, variable for each design options. But the results still confirm that the share of insulation systems remains lower for the environmental impacts (GHG emissions, primary energy, ecopoints) than for the global costs.

For this renovation scenario the payback period varies from 4 to 9 years for insulation with EPS or cellulose, from 4 to 10 for glass wool, from 5 to 13 for cellular concrete and from 14 to 37 for CaSi. The payback period is therefore very similar than in the first case (U-value of 0.25 [W/m^2.K]) except for CaSi. For this last insulation system, the thickness of material contributes more in the global cost. So the lower the insulation thickness, the lower the payback time comparatively to the other systems (where the material cost is less influential).

Table 29 Share of construction materials environmental impacts added during the historic facade renovation for an insulation thickness of 9 [cm] and share of global costs

Share in % Construction materials		Glass wool	EPS	Cellular concrete	Cellulose	CaSi
LCA	Greenhouse gas emissions	4% to 12%	10% to 29%	2% to 5%	4% to 14%	6% to 19%
	Primary non-renewable energy	4% to 14%	10% to 29%	1% to 4%	5% to 15%	5% to 17%
	Ecopoints	5% to 16%	10% to 29%	2% to 7%	4% to 15%	6 to 20%
LCC	Global Cost	38% to 73%	39% to 74%	39% to 74%	33% to 69%	42% to 75%

Table 30 Pay back times of the interior insulation measures for an insulation thickness of 9 [cm]

		Glass wool	EPS	Cellular concrete	Cellulose	CaSi
LCC	Payback time (in years)	4 to 10	4 to 9	5 to 13	4 to 9	7 to 20

6.1.1. Intermediate conclusion

The comparison of the two cases confirms that in terms of LCC, it is more cost-effective to insulate a building wall with a thickness according to the SIA 380/1 standard. Indeed for the four insulation systems (excluding the case of CaSi), the costs vary between 220 [CHF.m^{-2}.a^{-1}] and 650 [CHF.m^{-2}.a^{-1}] for an insulation thickness complying with a U-value of 0.25 [W.m^{-2}.K^{-1}] and between 237 [CHF.m^{-2}.a^{-1}] and 719 [CHF.m^{-2}.a^{-1}] for a thickness of 9 [cm]. This difference can be explained by the fact that in the case of a renovation with a lower thickness, the costs of energy are not reduced enough to balance the costs induced by the installation of an insulation system (nearly identical whatever the thickness).

5.3 Interior insulation renovation coupled with the replacement of the heating system (case study 2)

5.3.1 Design options

The results of the case study 1 showed that the interior insulation systems have similar environmental impacts after renovation. It is not obvious to identify the most beneficial option for reducing the environmental impacts and the associated global costs. In parallel, during a building renovation, a building owner has the choice to renovate the envelope (e.g. the facades) but he also has the possibility to replace the old heating system. This solution can also help reducing the GHG emissions by removing old oil boilers often found in historic buildings in Switzerland.

As a result, a new case study will associate an internal insulation renovation associated to the replacement of the heating system will be considered. The aim is to assess the influence of the replacement of different heating systems. Therefore, the study will only be done for one insulation system as the trends would be similar for the other ones.

5.3.2 Simulation scenarios and functional units

The insulation thickness is the same as the one in case study 1.b, described in chapter 5.2.2 (with 9 [cm]). This choice limits the part of the living area lost when renovating from the inside. Besides this practical aspect, a limited thickness can also in some cases be a good compromise concerning hygrothermal issues. But in this case study, as the aim is more to assess the influence of heating system replacement, other thicknesses or U-values could also be considered.

The replacement of the heating system includes four scenarios: replacement by an oil boiler with good efficiency, a gas boiler, a wood pellet boiler and an air-to-water heat pump. Table 31 summarizes the design options and scenarios of this section.

Table 31 Design options and scenarios identified in this exemplary case study

Functional unit	**Case study 2** e= 9 [cm]
Design options	- Cellulose
Context	
Historic wall type	- stone wall representative of Swiss historic buildings
Location	- representative of Swiss Midlands (Plateau)
Scenarios for the LCA and LCC	
Heating system choices	- new oil boiler - new gas boiler - new wood pellet boiler - new air-to-water heat pump
Reference study period	- 30 years

5.3.3 Uncertainty characterisation and propagation for the heat transmission losses

The same assumptions as the ones presented in section 5.2.3.

5.3.4 Uncertainty characterisation and propagation for the LCA

The same assumptions as the ones presented in section 5.2.4.

5.3.5 Uncertainty characterisation and propagation for the LCC

In the next sections, we only present the modifications of assumptions and uncertainty characterization used in the previous case study. For all other, there are taken as the ones presented in section 5.2.5 and are not presented again.

To consider the replacement of the heating system, the cost of energy vector was calculated including the amortization of the heating system. The method used is the one already described in section 5.2.5. Three parameters neglected in the first case study are now considered: the initial investment cost of the heating system, the maintenance cost of the heat producer per year and the heating system service life. Table 32 summarizes the parameters taken into account in the previous case study for the cost of the vector only, and the parameters considered for the cost with amortization of the heating system.

Table 32 Uncertainty characterisation of parameters for the heating cost in the case study 2 (recall of the assumptions used in case study 1)

Heating cost Parameters	Parameter description	Case study 1 (recall)	Case study 2 assumptions
Energy consumption of the heating system	Heating consumption of the building [kWh/m^2]	Deterministic (70 [kWh/m^2.an])	
	Calorific power [kWh/fuel unit]	Deterministic (similar to definition in KBOB [98])	
	Efficiency of the heating system [-]	Variation range according to [94]	
Characterisation of the heating system	Heating system service Life [years]	-	Deterministic (20 years) according to MoPEC [93]
	CO_2 content of the fuel [kg CO_2/kWh] (To calculate the value of the CO_2 tax)	Deterministic (OFEN values [99])	
Costs	Investment cost [CHF/m^2] (material and labour cost)	-	Mean of reseller values (HOVAL[100], Viessmann [101] and Planair [102])
	Energy carrier cost [CHF/m^2]	Variation range of three years according to [96]	
	Maintenance cost [CHF/m^2]	-	Mean of reseller values (ECO réno [103], TOBLER [104], Elcotherm [105] and Planair [102])
	CO_2 Tax	Calculated with the value of 2018, 96 [CHF/tonne CO_2]	
	Added value Tax	Included in each cost	
	External cost	Neglected	

The heating demand of the building (single-family house) is supposed to be the same as in the previous case study 1.a. However, as we insulate only 9 [cm], we assume that additional renovation measures for the building envelope are considered to remain compliant with the limit value of SIA 380/1 renovation.

When replacing the heat generator, initial investment costs are important. Amortization of the heat generator will be considered in the annual cost. Capital cost is set deterministic as few data are available on investment cost of boilers. It is a mean value of reseller's prices. As for the capital cost of boiler, maintenance cost is set deterministic as a mean value of four sources.

Service life is fixed at 20 years according to the model of cantonal energy regulations (MoPEC) [93]. The influence of service life on the resulting cost could have a great impact. Indeed, an international service life database developed during the research project DUREE funded by the Swiss Federal Office for Energy (SFOE) [97] shows that the service life observed in some literature sources for heat pump is shorter than for boilers. Considering different service lives for each heat producer would probably reduce the cost advantages for the air-to-water heat pumps.

For the energy carrier cost, special fuel tariff can be available e.g., for heat pumps. However, as these special tariffs depend on facility offers and are not always available, they are not considered here.

The resulting cost per useful kilowatt-hour for each system can be seen in Figure 68.

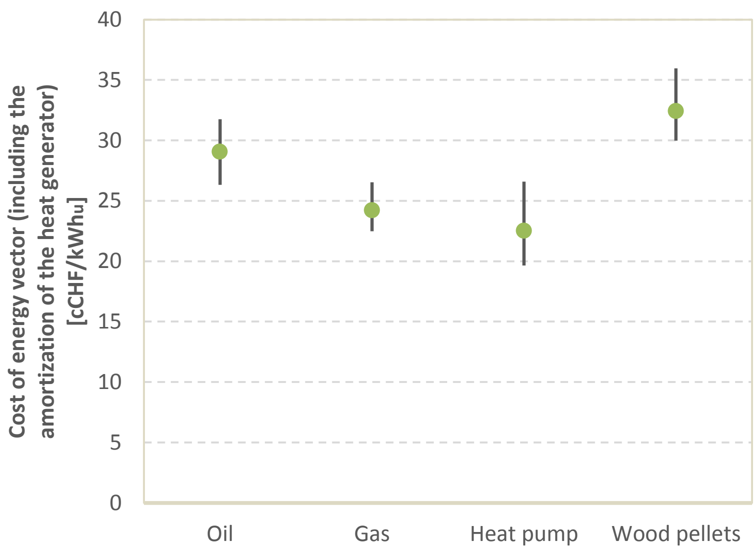


Figure 62 Cost of energy carrier with amortization of heat generator

In median value, the cost per useful kilowatt-hour for the heat pump is the lowest, followed by the cost of heating through gas, oil and wood pellets. This reflects the ordering of the investment costs except for the heat pump.

5.3.6 Results

The transmission losses results are the same as the ones presented in the case study 1.b. As for the previous case studies, the impacts after renovation compared to before renovation are reduced by around 6 times for the GHG indicator with the replacement with an oil boiler, around 7 times for the replacement with a gas boiler and even more for the replacement with a wood pellet boiler and with a heat pump. In terms of global costs, all renovation measures have in mean values, lower annualized costs than before renovation. However, the highest value for oil boiler (819 [$CHF.m^{-2}.a^{-1}$]) and wood pellet boiler (973 [$CHF.m^{-2}.a^{-1}$]) can show similar costs as the one before renovation (from 759 to 1792 [$CHF.m^{-2}.a^{-1}$]).

Figure 63 now presents the impact of each design option for the three LCA indicators and for LCC.

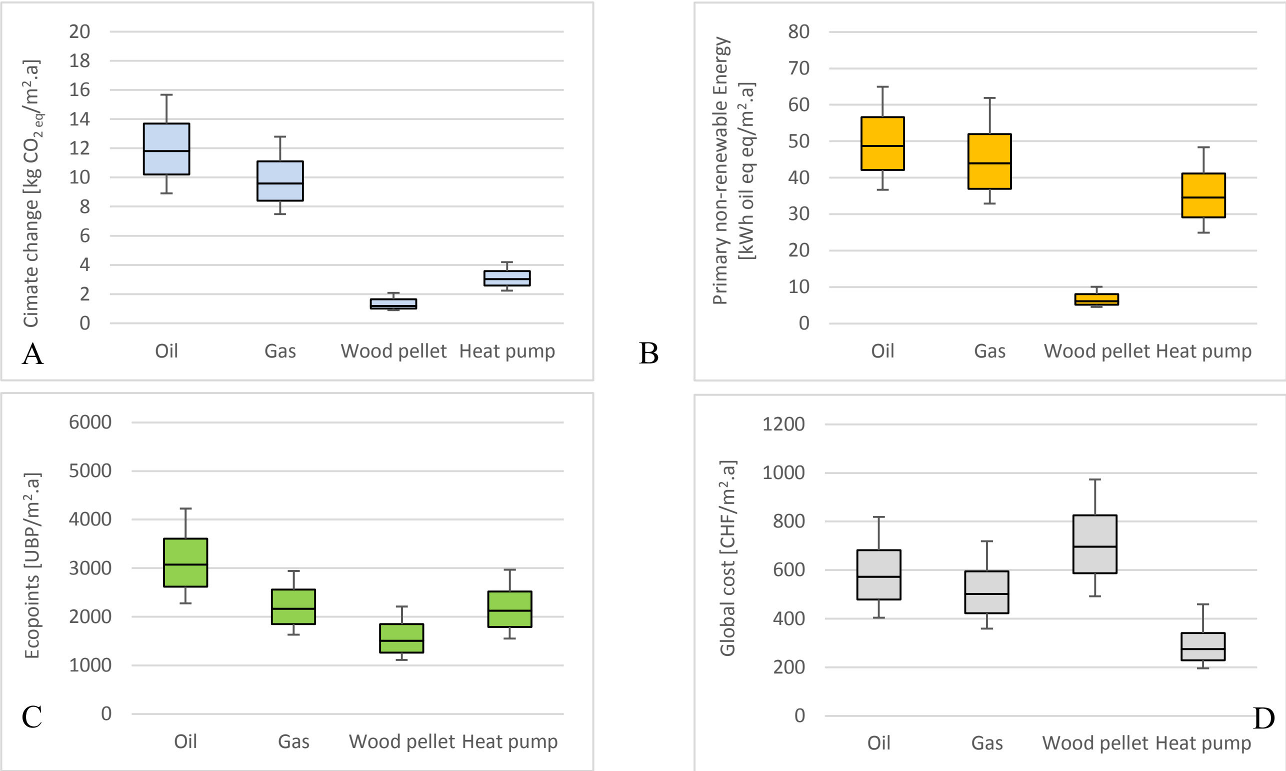


Figure 63 Probabilistic results for the wall after renovation with an additional insulation thickness of 9 [cm] and the replacement of different heat generators for climate change indicator (A), non-renewable primary energy (B), ecological scarcity (C) and global cost of the renovation (D)

The GHG emissions for a new oil boiler vary from 9 [kg CO_2 eq.$m^{-2}.a^{-1}$] to 15.5 [kg CO_2 eq.$m^{-2}.a^{-1}$], for a gas boiler from 7.5 to almost 13 [kg CO_2 eq.$m^{-2}.a^{-1}$], for a wood pellet boiler from 0.9 to 2 [kg CO_2 eq.$m^{-2}.a^{-1}$] and for heat pump from 2 to 4 [kg CO_2 eq.$m^{-2}.a^{-1}$]. The primary energy varies from 32 to 65 [$kWh.m^{-2}.a^{-1}$] for oil and gas boilers, 25 to 48 [$kWh.m^{-2}.a^{-1}$] for heat pump and 5 to 10 [$kWh.m^{-2}.a^{-1}$] for the pellets. For the ecopoints, oil boiler have an important impact from 6’780 to 12’620 [$UBP.m^{-2}.a^{-1}$] whereas gas boiler, and heat pump have similar variation range from around 4’200 to 8’500 [$UBP.m^{-2}.a^{-1}$] and wood pellet a lower variation range from 2’680 to 4’950 [$UBP.m^{-2}.a^{-1}$]. These LCA results confirm that the wood pellets and heat pump solutions allow a greater reduction of the GHG emissions compared to the fossil fuel solutions (oil and gas boilers). The GHG emissions ranking is robust as for the 5000 simulations the wood pellets is always better than the heat pump and these two are always better the fossil fuel solutions. Similarly, the wood pellets also allow a drastic reduction of the primary non-renewable energy. For the ecopoints with the uncertainties, it is not obvious to identify the best heating system as the uncertainties lead to some unclear ranking. However, in median values, the wood pellet has lower ecopoints that the others.

In terms of global costs, they vary for the oil boiler from 405 to 819 [$CHF.m^{-2}.a^{-1}$], for the gas boiler from 359 to 719 [$CHF.m^{-2}.a^{-1}$], for the wood pellet boiler from 493 to 973 [$CHF.m^{-2}.a^{-1}$] and for the heat pump from 196 to 460 [$CHF.m^{-2}.a^{-1}$]. Moreover, the global cost of the renovation increases compared to the global costs of the first case study where only the insulation was added excepted for the replacement with a heat pump.

Table 33 presents the share of construction materials (insulation systems) in the three environmental impacts and global costs.

Table 33 Share of construction materials environmental impacts added during the historic facade renovation for an insulation thickness of 9 [cm] and replacement of the heat generator and share of global costs

Share in % Construction materials		**Oil**	**Gas**	**Wood pellet**	**Heat pump**
LCA	Greenhouse gas emissions	4% to 14%	5% to 17%	54% to 82%	18% to 47%
	Primary non-renewable energy	5% to 16%	5% to 17%	47% to 78%	6% to 22%
	Ecopoints	4% to 15%	7% to 22%	12% to 34%	7% to 23%
LCC	Global Cost	18% to 51%	21% to 56%	15% to 44%	45% to 79%

The share of construction materials for oil boiler in the LCA is the same to the case study 1.b (see Table 29). For the replacement with a gas boiler, the share is similar to the one of the oil boiler, varying from 5% to 17% for the two indicators GHG emissions and primary non-renewable energy. For replacement with a wood pellet boiler, the share of insulation is more important, varying from 47% to 82% for the same two indicators. This is due to the reduction of the energy impacts in comparison to the fossil fuels variants. This leads to an increase of the contribution of the material share. Similarly, for the heat pump, the share of GHG is higher than in the fossil fuels cases. However, similar trends to these cases are observed for primary non-renewable energy due to the primary energy non-renewable due to the primary non-renewable electricity required for the heat pump.

In this case study, the energy cost is more important due to the inclusion of capital and maintenance costs in the energy tariff. As presented in Figure 62, the energy cost is now 24 [$cCHF/kWh_u$] in mean value while it was about 14 [$cCHF/kWh_u$] in the case study 1. The increase of energy cost leads to an increase in the contribution of operational energy use compared to the material share. For example, the share of insulation system in the global cost for the oil boiler decreases from 33%-69% for the case study 1.b to 18%-51% in this case study. The results are similar for the other fossil solution (gas boiler). The wood pellet global cost's share of insulation is slightly lower but remains in the same order. For the air-to-water heat pump, the insulation contribution is higher as the energy cost of this solution is lower as the other one.

For this renovation, it is also important to precise that the payback period cannot be calculated. Indeed, we have now an investment cost within the energy cost that influence the results of the payback time of the insulation systems. As it is not relevant anymore, we do not discuss it.

Finally, we notice that this renovation measure allows the greatest reduction of environmental impacts if the heating system is replaced by a wood pellet boiler or an air-to-water heat pump in addition to insulate the facade. This choice is robust i.e., the wood pellet has systematically lower primary energy and GHG emissions than the other solutions.

5.4 Discussion

These exemplary case studies conducted on a representative stone facade of a historic building assumed to be heated with an old oil boiler draw different conclusions:

- the importance of insulating a historic building facade (reduction of heat losses, GHG emissions and primary energy consumption);
- the environmental impacts after renovation are more driven by the operational energy use (heat losses) while for the global costs it is more the investment costs;
- the investment costs of insulation systems are less variable due to the thickness than due to the surface area applied;
- in terms of design options, when comparing insulation systems, it is not possible to choose one best solution based on the study' assumptions. In a historic building renovation, the limiting factor will probably be the hygrothermal aspect;
- when considering a replacement of the heating system, important environmental impact savings are found for the wood pellet and heat pump scenarios.

In the next sub-sections, we discuss some of the parameters of these case studies and their influence on the results.

5.4.1 Influential parameters for the LCA and LCC

Using Sobol analyses as a Global Sensitivity Analysis (GSA) method allow determining the sensitivity of parameters used for the heat transmission losses, for the LCA and for the LCC. In this section, we discuss the sensitivity of parameters by calculating the Sobol indices in the HES-SO probabilistic LCA tool based on a monthly heat losses calculation[36] and based on the WP5 tool for the probabilistic LCC. The parameters taken into account for the heat losses calculation are represented in detail in the Sobol analysis for LCA. In the WP5 tool for LCC calculations, the heat losses are represented by a normal distribution based on the calculation of the heat losses in the HES-SO tool.

In the following, we only present the results for one design option (cellular concrete) of the case study 1 as an illustration.

Sobol analysis of the heat transmission losses and LCA parameters

Different parameters are used in the heat losses and LCA: the thicknesses of materials (historic building facade, interior insulation system as described in Table 22), the unitary impacts of

[36] The monthly heat losses calculation (*Option 2)* has been implemented by HES-SO in a proof-of-concept tool to perform HAM assessments in comparison with results of option 1 (WP4 activities) and to obtain the heat losses for the Swiss case study. This approach is documented in deliverable report 5.1.

materials, the insulation system lifetime, the climate conditions, interior temperature, the heating production system, its efficiency, and its unitary impact.

Figure 64 presents an illustration of the Sobol indices for the heat losses and LCA parameters for the cellular concrete design option and greenhouse gas emissions. The first and total order for the Sobol indices is represented for each parameter. Sobol indices calculated for primary non-renewable energy are not presented as they present the same trends as for the GHG emissions' ones.

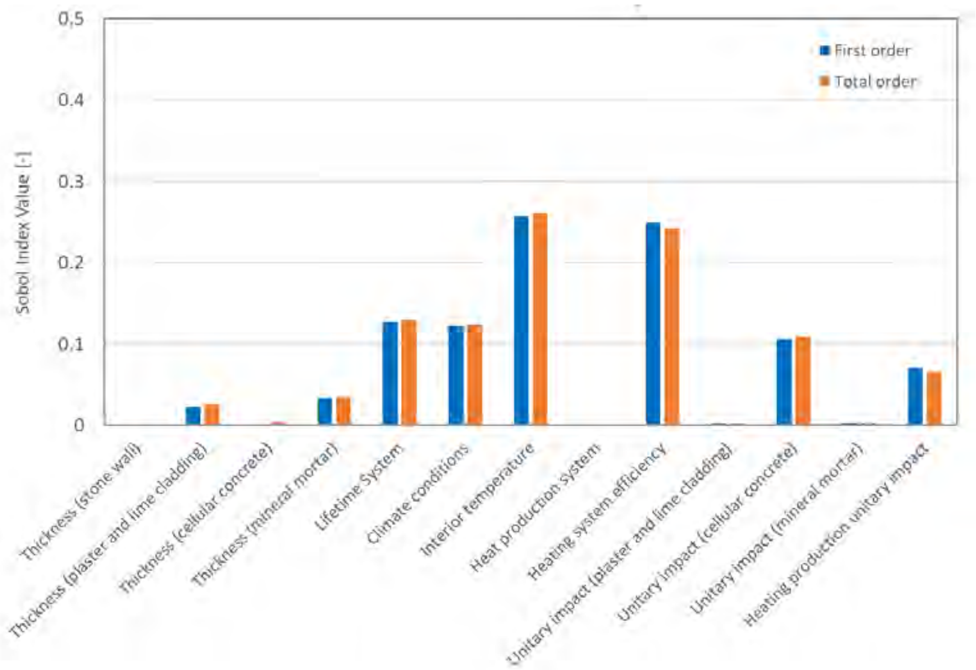


Figure 64 Total Sobol indices for the design option cellular concrete for case study 1 for combined heat losses and LCA parameters (calculated for GHG emissions)

Results show that the parameters that have the biggest influence on the output results (impacts) are, by order of importance:

- The interior temperature (total index of 0.26)
- The heating system efficiency (total index of 0.24)
- The insulation system lifetime (total index of 0.13)
- The climate conditions (total index of 0.12)

Then, other parameters related to the unitary impact value of GHG emissions of cellular concrete (total index of 0.11) and heating production (0.07) are found significant. To a lower extent, the uncertainty to the thickness of rendering on which side of the insulation system (total index around 0.02-0.03) are the next influencing parameters.

All other parameters have no or a very low influence on the GHG emissions' variabilities. It has also to be noticed that first order and total order indices have similar values which means that the joint influences of parameters are non-influent. Moreover, the calculation sometimes leads to slightly smaller total indices compared to first order indices. This observation is only due to the calculation procedure, it is possible to assume that both (i.e first order and total order) have similar values.

Sobol analysis of the LCC parameters

Ten parameters are used in the LCC: heat transmission losses through the wall after renovation (Qhpost) without the details of input parameters (as shown in the Sobol analysis for LCA parameters), energy tariff (EnT), energy source conversion factor (EnFc), overall efficiency for heating (Etah), insulation system initial investment cost (Sys_1_CI), insulation system maintenance cost (Sys_1_CM), insulation system service life (Sys_1_SL), nominal growth rate of gross domestic product (GDP), inflation rate (INF) and nominal interest rate (INT). Figure 65 gives the Sobol indices for one design option (cellular concrete) for the case study 1 with insulation of the facade only.

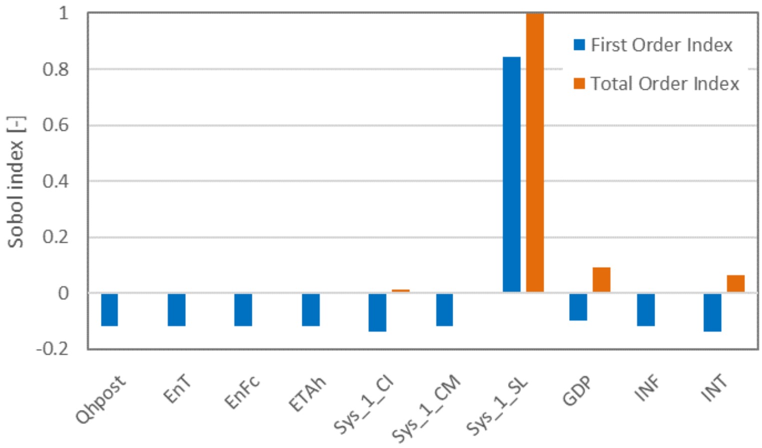


Figure 65 Total Sobol indices for the design option cellular concrete for case study 1 for LCC

It shows that the most influential parameter in the LCC calculation is the service life of the insulation system. This can be explained by the underlined assumptions in the methodology and case study. As it is the main influencing parameter, it also explains why the first order indices are slightly negative for the other parameters. Sobol results can be mostly explained by the assumptions on service life standard deviation. The value is about 14 years (while the mean value is at 34 years). So, for each 5000 simulations and a 30 years calculation period, we have either zero or one replacement. This situation is also stressed by the replacement rate calculation in the tool. The rate is rounded up to the next whole number. So, it increases the difference of LCC results between zero and one replacement. The investment costs representing a large share of the LCC results, that is the reason why Sobol identifies the lifetime as the most sensitive parameter.

For the Sobol indices, the other influent parameters (with values below 0.10) are then, the nominal growth rate of development of the prices for human operations (GDP), the nominal interest rate (INT), the investment costs of the insulation systems (CI) and the heat transmission losses after renovation (Qh_{post}). The other parameters have very little or no influence on the variance of the results (global costs).

Further GSA carried out for reference study periods beyond 30 years (40 and 50 years) show that the weight of the service life remains similar in the calculation. Indeed, in any calculation period, there is always a variable whole number of replacement (0 or 1 replacement for the 30 and 40 years calculation periods and 1 or 2 replacements for the 50 years' calculation period).

Influence of input parameters definition on the Sobol indices

Finally, it is important to recall that this section only illustrates the use of GSA (with Sobol approach) to identify the influencing parameters to the output results. The level of details of parameters has certainly a major influence on the Sobol indices. For instance, in the LCC, the heat losses were taken in the WP5 tool as a normal distribution without calculating them in detail. In opposite, in the HES-SO tool for probabilistic LCA, heat losses are calculated using mass, thickness, thermal conductivity and unitary impact of each material layer among other parameters. So, by changing the number of input parameters in the LCA and LCC calculations, the Sobol indices' values and ranking are likely to change.

Similarly, the distribution of the lifetime of the insulation system has a strong influence especially in the LCC results. In this exemplary case study for Switzerland, we define a distribution based on literature's data for insulation of the external walls. The value of the lifetime is found more uncertain (standard deviation of 14 years) as for the case study in section 4, where a standard deviation of 3 years is found. This only input parameter's difference has a strong influence on the results. In the present case study, the replacement rate is likely to never be the same for the 5000 Monte-Carlo simulations while for the case study in section 4 the replacement rate can be constant e.g., for a study period of 40 years.

The average value and the dispersion of the data points are very sensitive to the number of data. Additional data collection is likely to change the mean value but also the dispersion of the minimal and maximal lifetimes. This extreme value will then influence the replacement rate as found in Sobol indices for the LCC depending on the chosen distribution types. Indeed, the lifetime of the insulation system could also be defined with other distribution types. For instance, in case of a lower number of data points, normal and lognormal distributions are not relevant, and uniform or triangle distributions may be favoured.

5.4.2 Uncertainties in comparative assessment

In this study, the uncertainty analysis was run for each design option and we then compared the results. The reader can get an estimate of the range of environmental impacts and global costs for each individual design option. The reader can also look at comparative results. However, in case study 1, it is not easy to rank the design options and finally choose the best one. Looking at the uncertain parameters, many of them have the same values and distributions for all the design options. For example, it is the case for the outdoor climate, the indoor temperature and the historic building facade thermal properties. So, it may be possible that for a comparative LCA, the uncertainties displayed in the results are lower if only the residual uncertainties between two design options are considered. The uncertainties of identical parameters would be offset, and the only remaining uncertainty could highlight the differences between the design options.

5.4.3 Subsidies incentives for a U-value of 0.20 [W/m^2.K] and its relevance for historic building façade renovation

When renovating a building in Switzerland, building owners are encouraged to install enough insulation to reach a U-value of 0.20 [W.m^{-2}.K^{-1}] to get subsidies. This effect can influence the global costs. The subsidies are applicable per square meter of insulated facade and are dependent on the 26 Swiss cantons. In the Vaud canton (region of Lausanne), it amounts to 70 [CHF.m^{-2}] of installed insulation so about 25% of the investment costs of some insulation systems. This value can therefore be deduced from the initial investment costs of the insulation systems and helps improving the payback time of the renovation measure. Indeed, if the building owner aims at a U-value of 0.25 [$W.m^{-2}.K^{-1}$] (cf. situation of the case study 1), the subsidies encourage him to add a bit more thickness to reach the U-value of 0.20 [$W.m^{-2}.K^{-1}$] opening the subsidies.

However, it is not clear yet if a facade should be insulated from the interior with such a high thickness given the increasing risk in terms of mould growth and other damages over the lifetime of the measures (i.e., over the 30 to 40 years). It is maybe why public policies and energy efficient labels' recommendations in Switzerland do not give clear recommendations for historic building wall interior insulation.

However, it may be critical to apply interior insulation thickness allowing achieving a wall U-value of 0.20 [$W/m^2.K$]. First, for insulation systems open to vapour diffusion, the heat losses will not be the same depending on the relative humidity. This aspect is not considered in the monthly calculations of heat losses in the two case studies. Second, the benefit of the subsidies (i.e., lowering the initial investments costs) can be counter balanced some years later if damages occur on the inside part of the wall (deterioration of the insulation systems, frost damage in the wall etc.).

Insulation manufacturers have also conducted monitoring activities to follow these risks in real conditions (see e.g., the RIBuild WP3 Monitoring case study "Brüttelen" for Switzerland where a glass wool system was applied to reach a wall U-value of 0.20 [$W.m^{-2}.K^{-1}$] and has been monitored as part of the MOFEINN project).

So further research combining hygrothermal simulations and on-site monitoring is needed to clarify this paradox between a situation in favour of low thickness combined to low energy savings and low assumed moisture risk and a situation encouraging higher thicknesses combined to higher energy savings but also higher potential damages (frost damage, moisture etc.).

5.5 Conclusions

This comparative study of different interior insulations was limited to a square meter of a historic stone facade. It represents existing limestone facades in Switzerland without accurately modelling the quantity and properties of the mortar in-between the stones. In this study, thermal bridges created by the interior insulation were also not considered and the heat losses were only approximated by the heat transmission losses. It is a very simple model, easy to use, but not enough to draw robust conclusions at the scale of a full historic building renovation.

In further studies, it is thus relevant to apply the same LCA and LCC methodologies to a full building case study to better estimate the potential impact savings and payback times of these interior insulations.

6 Exemplary application of the "probabilistic" LCC: assessment of different insulation systems assuming several building energy source scenarios (*DTU*)

6.1 Introduction

The Danish case study assumed the insulation solutions presented in Table 34 and the energy supply solutions presented in Table 35. The case studies rely on two sets of scenarios (see also Table 37):

- One set of scenarios disregarding amortization and maintenance (DK1-DK8)
- One set of scenarios accounting for amortization and maintenance (DK9-DK15)

The case study seeks to illuminate the payback period under the 4 different economic scenarios embedded in the WP5 methodology: stagnation, regular growth, intense growth and deflation.

Table 34 Summary of the Danish insulation scenarios. Qhpost = heat loass through the wall after renovation, Qhpre = heat loss through the wall before renovation

Insulation scenario	Insulation material	Qhpost [kWh/year]	Qhpre [kWh/year]
CS8	Kingspan 25mm	116,8	138,6
DCS9	Kingspan 60mm	110,7	138,6
CS10	IQ-Therm 30mm	108,7	129,5

Table 35 Amortization and maintenance costs for the Danish energy supply scenarios

Heat source	Amortization [Euro/yrs.]			Maintenance and service [Euro/yrs.]
	Min		Max	
Wood pellet furnace	381			469,8
District heating	354	-	885	214,8
Heat pump (air->air)	163	-	218	174,5
Heat pump (air->water)	817	-	1199	228,2
Heat pump (geothermal->water)	973	-	1239	228,2
New natural gas furnace	354	-	442	214,8
New Oil furnace	310	-	442	161,1
Old oil furnace	0			161,1

The system purchase prices, fuel prices, average annual consumption of the various Danish energy supply solutions are presented in Table 36.

By combining the insulation scenarios and the 4 economic scenarios, 12 different scenario groups are obtained, each with 15 possible energy supply scenarios disregarding/taking into account amortization and maintenance. These gives rise to 180 simulation cases (Table 37).

The following sections are dedicated to the assessment of the optimum energy supply system for each of the 3 insulation solutions, through identification of the heat supply system providing the lowest payback period and hence the optimum combination of heat supply system and insulation system.

Table 36 Summary of the Danish energy supply scenarios including prices for new system and gross energy price. Annual consumption in an average Danish single-family house and heating expense are provided as example

Heat source	Price new heating system [Euro]			Gross energy price		Annual consumption avg. House		Annual consumption avg. House (MWh)	Heating expense [Euro/yr.]
	Min		Max						
Wood pellet furnace	4698			0,28	Euro/kg	3715	kg	18,6	1047,18
District heating	5369	-	13423	102,68	Euro/MWh	18,1	MWh	18,1	1858,59
Heat pump (air->air)	2013	-	2685	0,21	Euro/kWh	3620	kWh	3,62	753,15
Heat pump (air->water)	10067	-	14765	0,21	Euro/kWh	5170	kWh	5,17	1075,64
Heat pump (geothermal->water)	14765	-	18792	0,94	Euro/kWh	4525	kWh	4,53	4233,46
New natural gas furnace	5369	-	6711	1,34	Euro/m3	1630	m3	56,2	2187,92
New Oil furnace	4698	-	6711	1,34	Euro/liter	1880	liter	18,8	2523,49
Old oil furnace	0			0,21	Euro/liter	2420	liter	24,2	503,49

Table 37 Overview of the Danish insulation/heat supply system/economic specific scenarios

Insulation systems		**Economic scenarios**											
		Deflation (DF)			Regular growth (RG)			Intense growth (IG)			Stagflation (SF)		
		Insulation scenario											
		CS8	CS9	CS10	CS8	CS9	CS10	CS8	CS9	CS10	CS8	CS9	CS10
Energy supply solutions disregarding amortization/maintenance	DK1	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S12	S12
	DK2	S13	S14	S15	S16	S17	S18	S19	S20	S21	S22	S24	S24
	DK3	S25	S26	S27	S28	S29	S30	S31	S32	S33	S34	S36	S36
	DK4	S37	S38	S39	S40	S41	S42	S43	S44	S45	S46	S48	S48
	DK5	S49	S50	S51	S52	S53	S54	S55	S56	S57	S58	S60	S60
	DK6	S61	S62	S63	S64	S65	S66	S67	S68	S69	S70	S72	S72
	DK7	S73	S74	S75	S76	S77	S78	S79	S80	S81	S82	S84	S84
	DK8	S85	S86	S87	S88	S89	S90	S91	S92	S93	S94	S96	S96
Energy supply solutions including amortization/maint.	DK9	S97	S98	S99	S100	S101	S102	S103	S104	S105	S106	S108	S108
	DK10	S109	S110	S111	S112	S113	S114	S115	S116	S117	S118	S120	S120
	DK11	S121	S122	S123	S124	S125	S126	S127	S128	S129	S130	S132	S132
	DK12	S133	S134	S135	S136	S137	S138	S139	S140	S141	S142	S144	S144
	DK13	S145	S146	S147	S148	S149	S150	S151	S152	S153	S154	S156	S156
	DK14	S157	S158	S159	S160	S161	S162	S163	S164	S165	S166	S168	S168
	DK15	S169	S170	S171	S172	S173	S174	S175	S176	S177	S178	S180	S180

6.2 Case study 1

The subchapter presents the probabilistic LCC results obtained for the Danish case study on Kingspan 25 mm (insulation CS8) for each of the 4 different economic scenarios.

6.2.1 Economic scenario – intense growth

For CS8 under intense growth, Figure 66 and Figure 67 reveal that some of the energy supply systems yield distinct low payback periods. Disregarding amortization and maintenance the best performing energy system in combination with insulation CS8 under intense growth is DK5 with an average payback period of 7 years. Taking into account amortization and maintenance the best performing energy system in combination with CS8 is DK12 with an average payback period of 4 years.

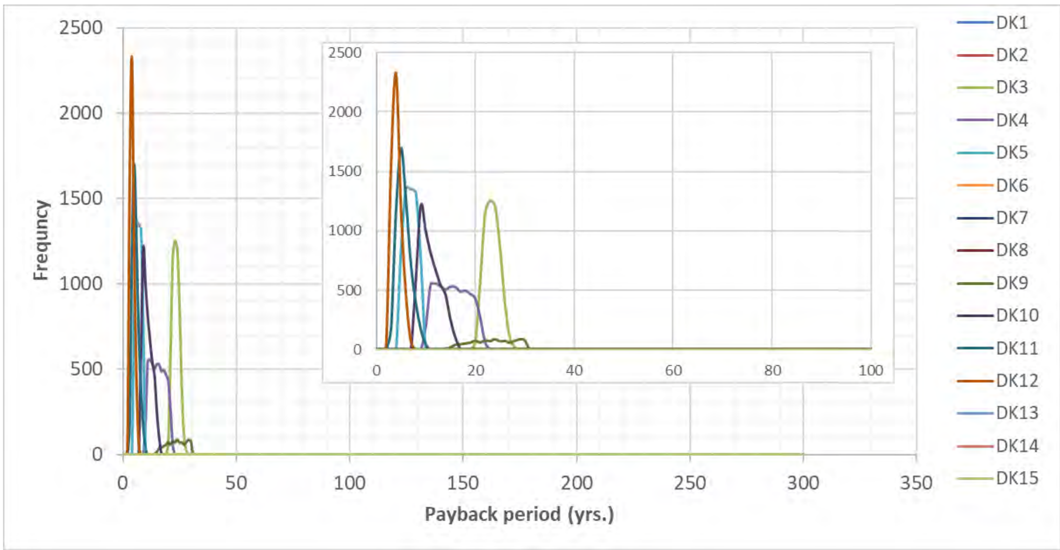


Figure 66 Frequency diagram illustrating the frequency of the payback period for the CS8 insulation system under intense growth for the 15 energy supply systems

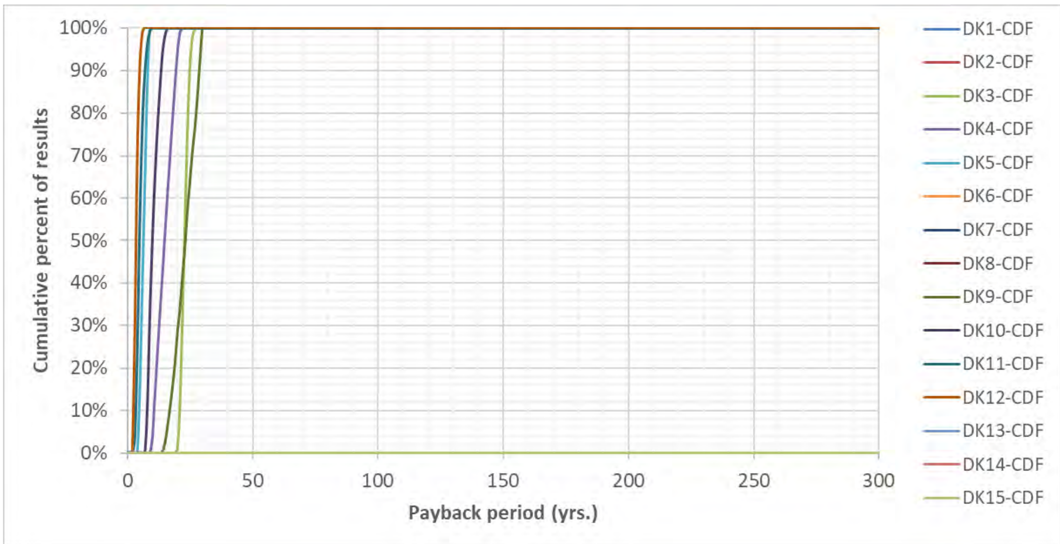


Figure 67 Cumulative frequency distribution diagram illustrating the cumulative frequency of the payback period for the CS8 insulation system under intense growth for the 15 energy supply systems

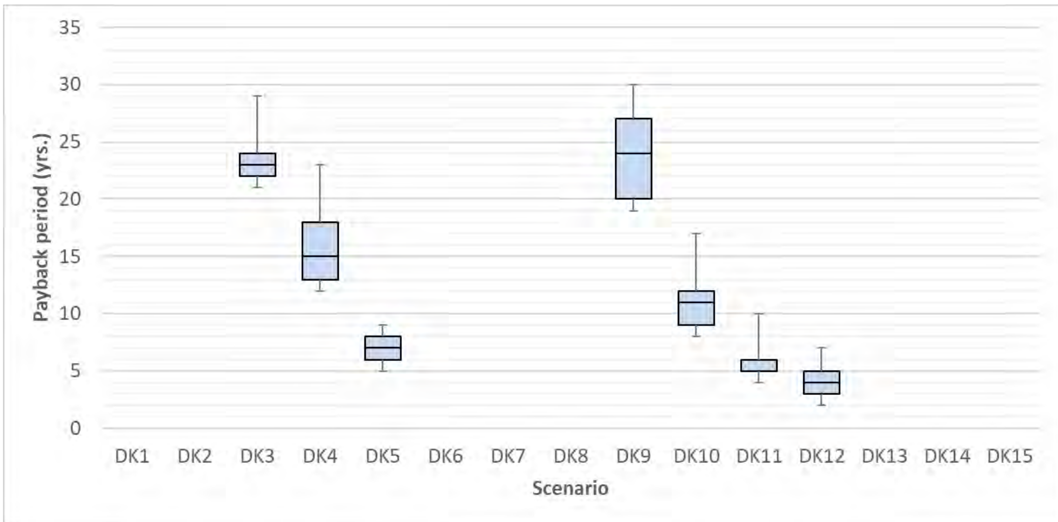


Figure 68 Boxplot depicting the distribution (min, max, 1 st quartile, 3rd quartile and median) of the payback period for the 15 energy supply systems in combination with insulation system CS8 under intense growth.

6.2.2 Economic scenario – stagflation

For CS8 under intense growth Figure 69 and Figure 70 reveals that some of the energy supply systems yield distinct low payback periods. Disregarding amortization and maintenance the best performing energy system in combination with CS8 under stagflation is DK5 with an average payback period of 10 years. Taking into account amortization and maintenance the best performing energy system in combination with CS8 is DK12 with an average payback period of 5 years.

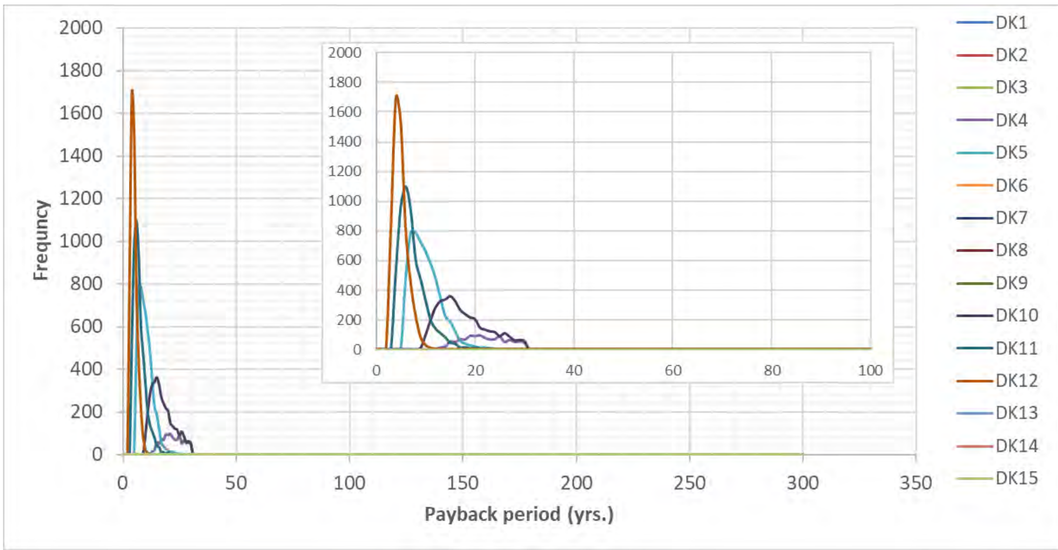


Figure 69 Frequency diagram illustrating the frequency of the payback period for the CS8 insulation system under stagflation for the 15 energy supply systems

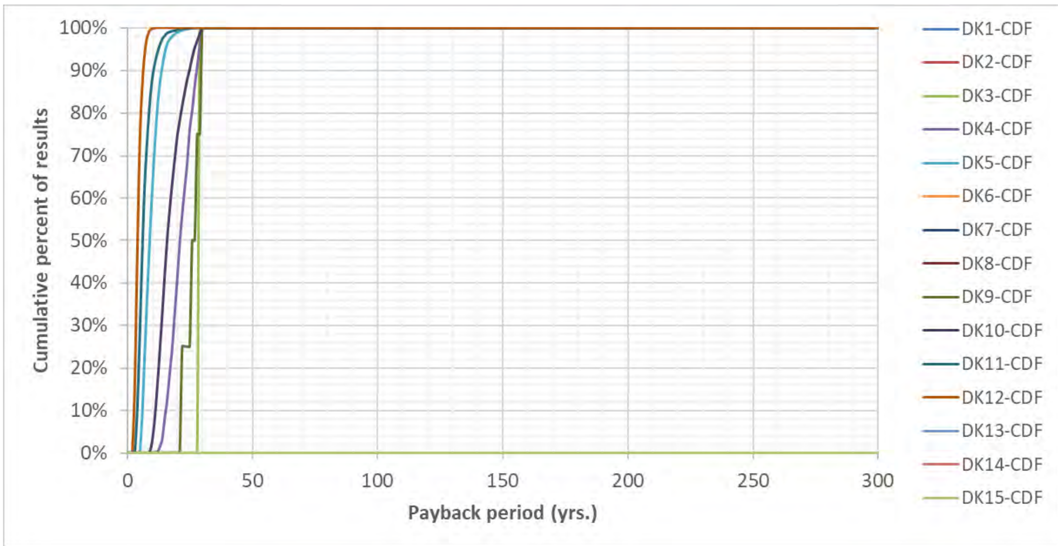


Figure 70 Cumulative frequency distribution diagram illustrating the cumulative frequency of the payback period for the CS8 insulation system under stagflation for the 15 energy supply systems

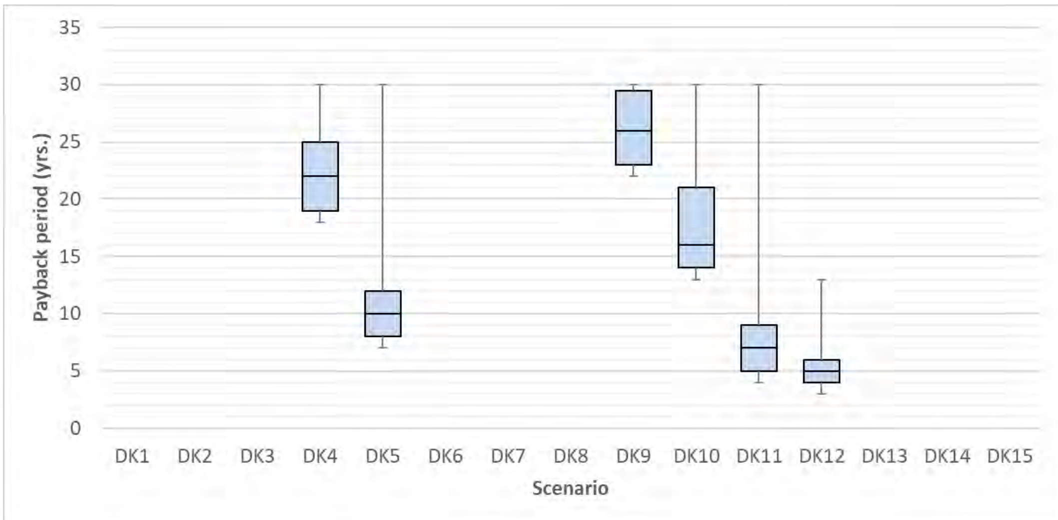


Figure 71 Boxplot depicting the distribution (min, max, 1 st quartile, 3rd quartile and median) of the payback period for the 15 energy supply systems in combination with insulation system CS8 under stagflation.

6.2.3 Economic scenario – deflation

For CS8 under deflation, Figure 72 reveals that some of the energy supply systems yield distinct low payback periods. Disregarding amortization and maintenance the best performing energy system in combination with CS8 under deflation isDK5 with an average payback period of 6 years. Taking into account amortization and maintenance the best performing energy system in combination with CS8 is DK12 with an average payback period of 4 years.

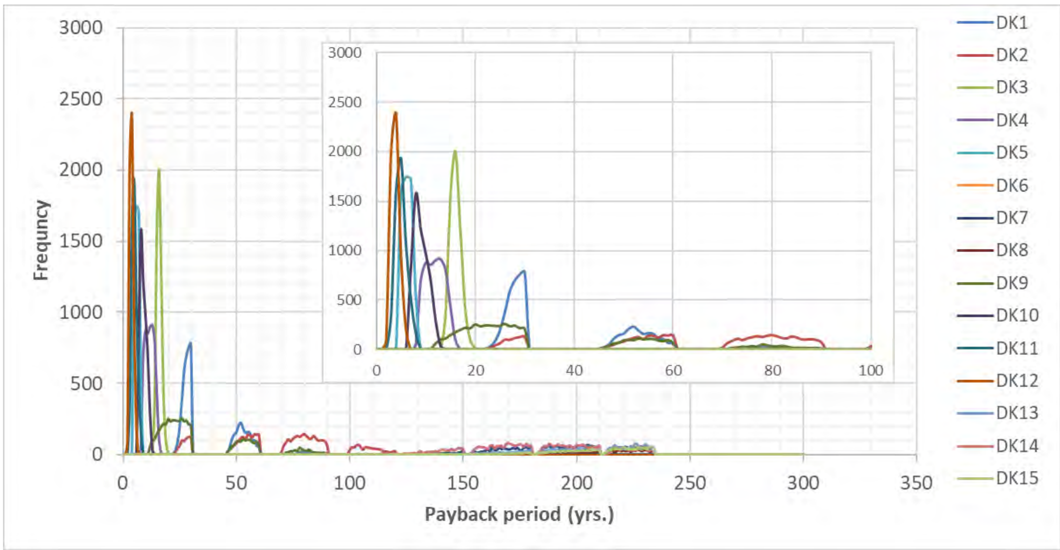


Figure 72 Frequency diagram illustrating the frequency of the payback period for the CS8 insulation system under deflation for the 15 energy supply systems

6.2.4 Economic scenario – regular growth

For CS8 under regular economic growth, the following figure reveals that some of the energy supply systems yield distinct low payback periods. Disregarding amortization and maintenance the best performing energy system in combination with CS8 under regular economic growth is DK5 with an average payback period of 7 years. Taking into account amortization and maintenance the best performing energy system in combination with CS8 is DK12 with an average payback period of 4 years.

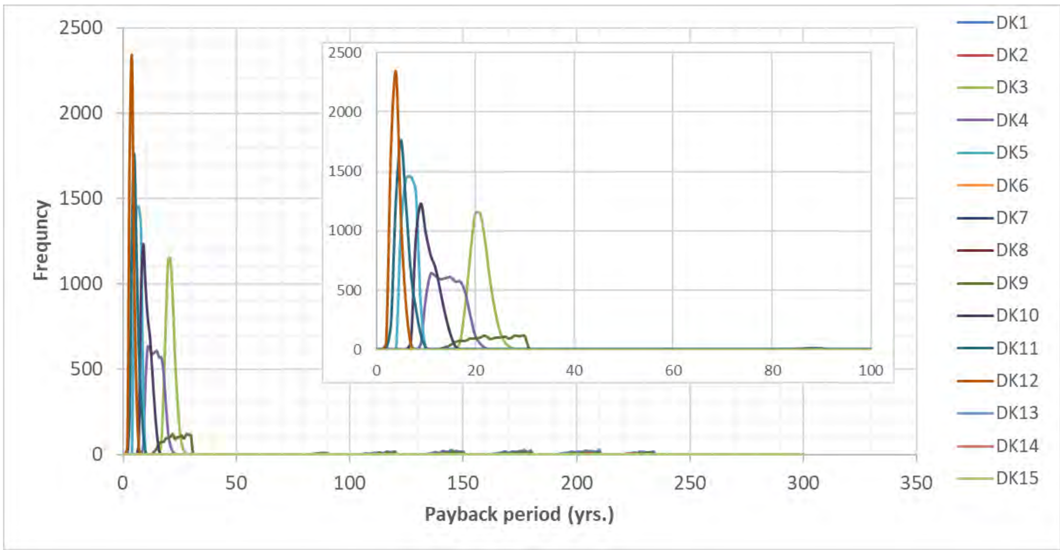


Figure 73 Frequency diagram illustrating the frequency of the payback period for the CS8 insulation system under regular economic growth for the 15 energy supply systems

6.3 Case study 2

This subchapter presents the probabilistic LCC results obtained for the Danish case study on Kingspan 60 mm (insulation CS9) for each of the 4 different economic development scenarios.

6.3.1 Economic scenario – intense growth

For CS9 under intense growth, Figure 74 and Figure 76 reveals that some of the energy supply systems yield distinct low payback periods. Disregarding amortization and maintenance the best performing energy system in combination with CS9 under intense growth is DK5 with an average payback period of 6 years. Taking into account amortization and maintenance the best performing energy system in combination with CS9 is DK12 with an average payback period of 4 years.

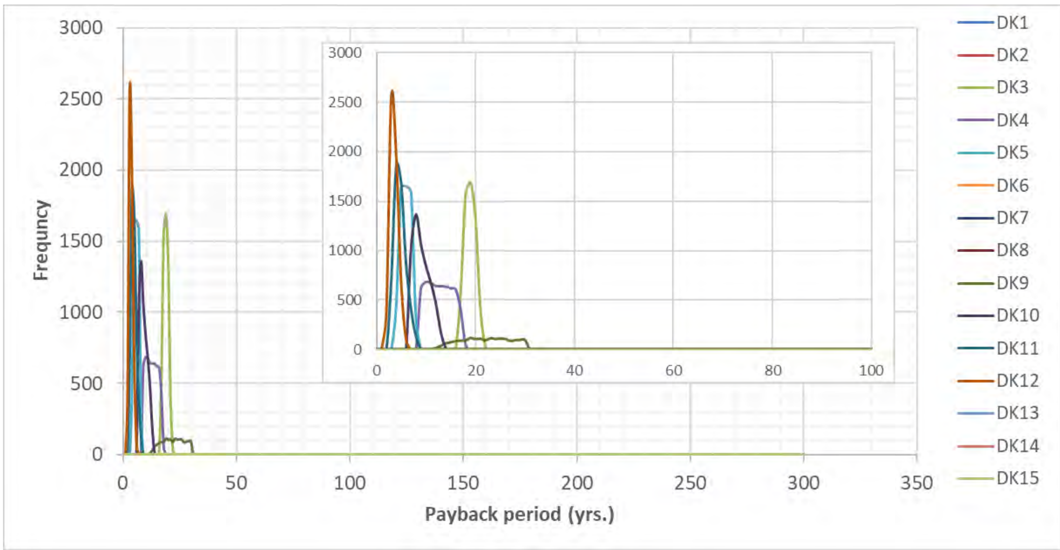


Figure 74 Frequency diagram illustrating the frequency of the payback period for the CS9 insulation system under intense growth for the 15 energy supply systems

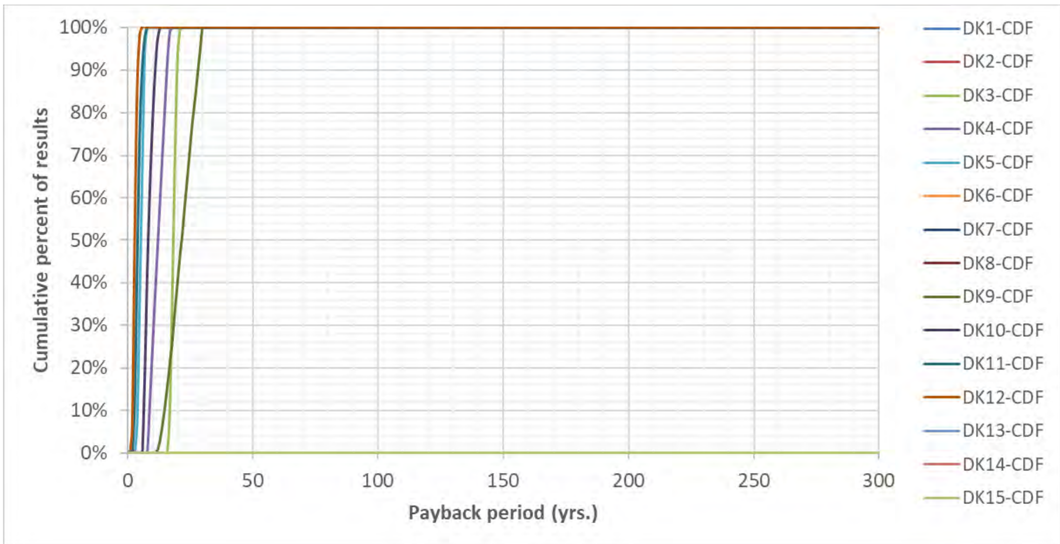


Figure 75 Cumulative frequency distribution diagram illustrating the cumulative frequency of the payback period for the CS9 insulation system under intense growth for the 15 energy supply systems

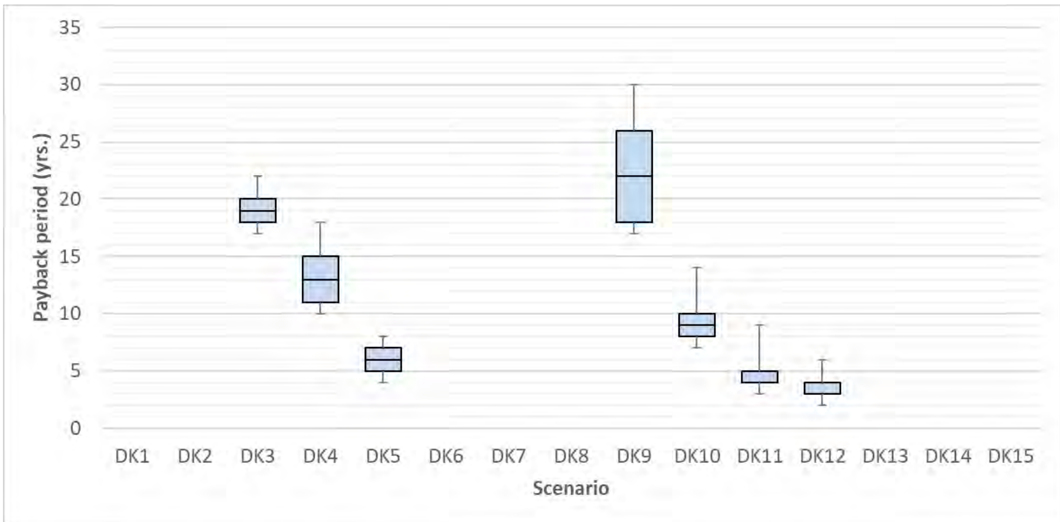


Figure 76 Boxplot depicting the distribution (min, max, 1 st quartile, 3rd quartile and median) of the payback period for the 15 energy supply systems in combination with insulation system CS9 under intense growth

6.3.2 Economic scenario – stagflation

For CS9 under stagflation, Figure 78 and Figure 79 reveal that some of the energy supply systems yield distinct low payback periods. Disregarding amortization and maintenance the best performing energy system in combination with CS9 under intense growth is, DK5 with an average payback period of 8 years. Taking into account amortization and maintenance the best performing energy system in combination with CS9 is DK12 with an average payback period of 4 years.

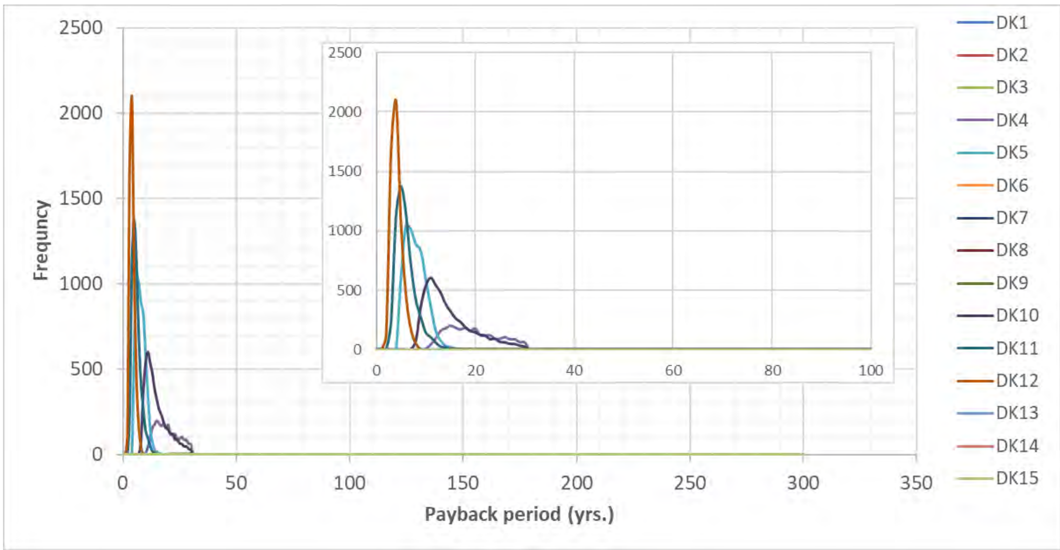


Figure 77 Frequency diagram illustrating the frequency of the payback period for the CS9 insulation system under stagflation for the 15 energy supply systems

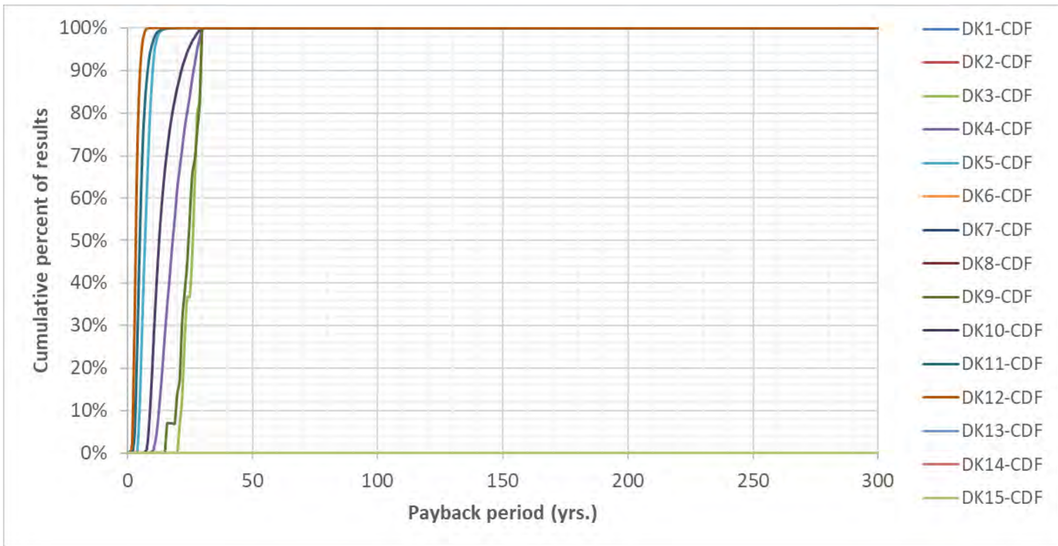


Figure 78 Cumulative frequency distribution diagram illustrating the cumulative frequency of the payback period for the CS9 insulation system under stagflation for the 15 energy supply systems

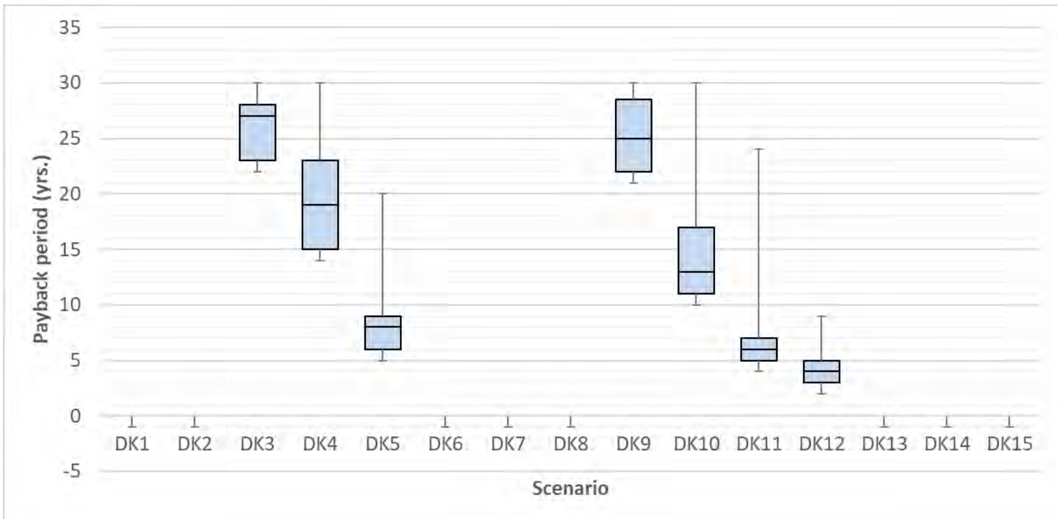


Figure 79 Boxplot depicting the distribution (min, max, 1st quartile, 3rd quartile and median of the payback period for the 15 energy supply systems in combination with insulation system CS9 under stagflation

6.3.3 Economic scenario – deflation

For CS9 under deflation, Figure 80 reveals that some of the energy supply systems yield distinct low payback periods. Disregarding amortization and maintenance the best performing energy system in combination with CS9 under deflation is DK5 with an average payback period of 5 years. Taking into account amortization and maintenance the best performing energy system in combination with CS9 is DK12 with an average payback period of 3 years.

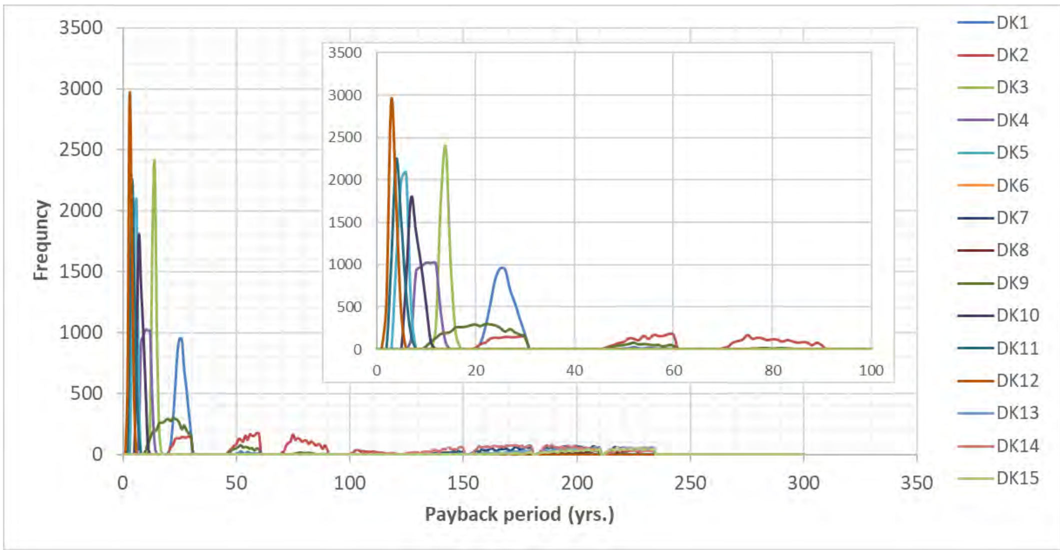


Figure 80 Frequency diagram illustrating the frequency of the payback period for the CS9 insulation system under deflation for the 15 energy supply systems

6.3.4 Economic scenario – regular growth

For CS9 under regular economic growth, Figure 81 reveals that some of the energy supply systems yield distinct low payback periods. Disregarding amortization and maintenance, the best performing energy system in combination with CS9 under regular economic growth is DK5 with an average payback period of 6 years. Taking into account amortization and maintenance the best performing energy system in combination with CS9 is DK12 with an average payback period of 3 years.

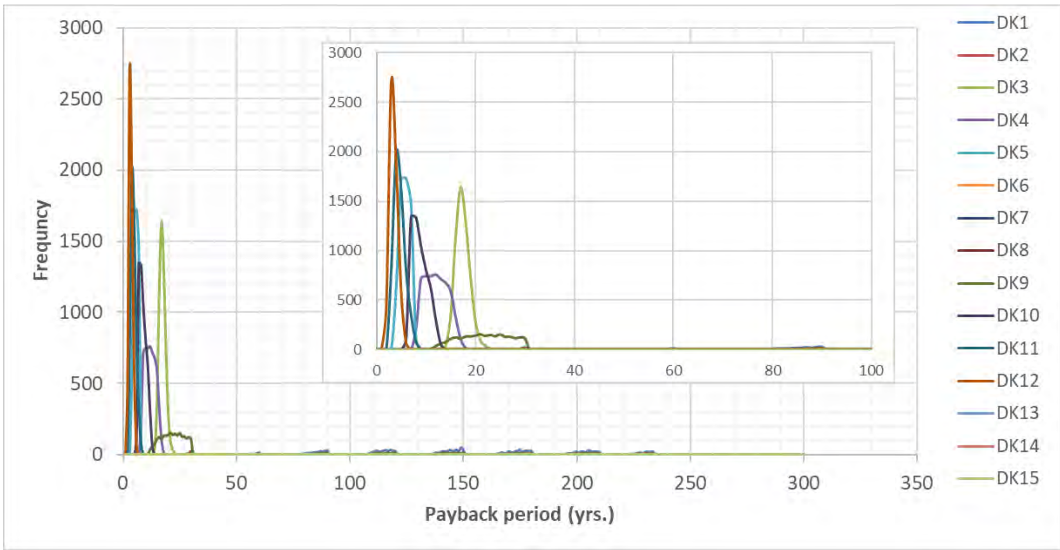


Figure 81 Frequency diagram illustrating the frequency of the payback period for the CS9 insulation system under regular economic growth for the 15 energy supply systems

6.4 Case study 3

This subchapter presents the probabilistic LCC results obtained for the Danish case study on Kingspan 60 mm (insulation CS10) for each of the 4 different economic scenarios.

6.4.1 Economic scenario – intense growth

For CS10 under intense growth, Figure 82 and Figure 83 reveal that some of the energy supply systems yield distinct low payback periods. Disregarding amortization and maintenance the best performing energy system in combination with CS10 under intense growth is DK5 with an average payback period of 14 years. Taking into account amortization and maintenance the best performing energy system in combination with CS10 is DK12 with an average payback period of 8 years.

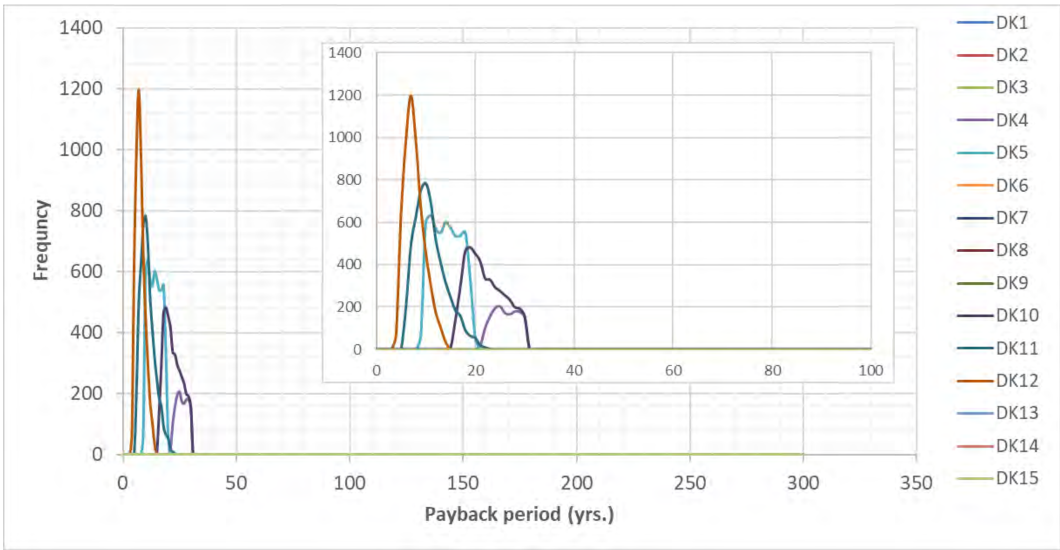


Figure 82 Frequency diagram illustrating the frequency of the payback period for the CS10 insulation system under intense growth for the 15 energy supply systems

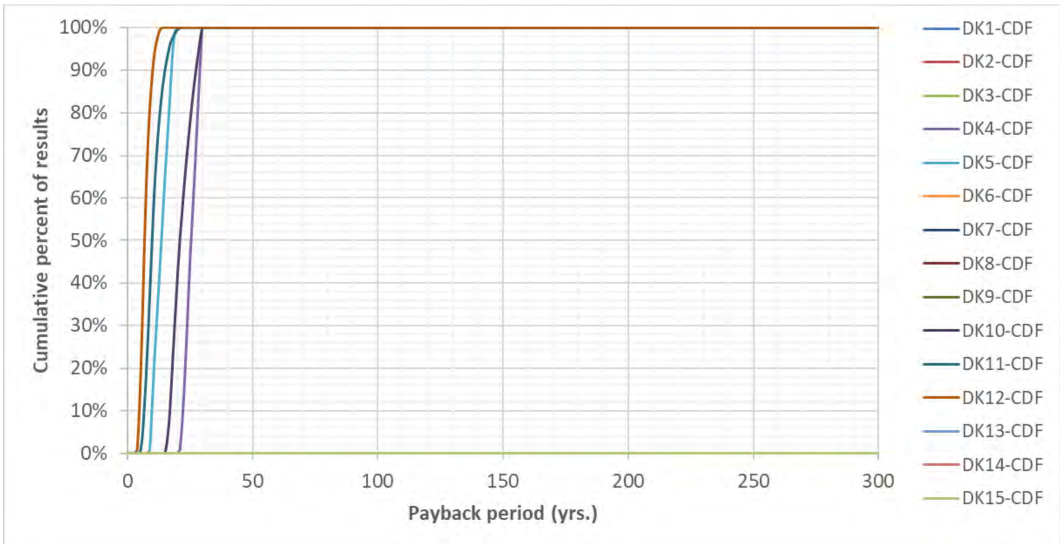


Figure 83 Cumulative frequency distribution diagram illustrating the cumulative frequency of the payback period for the CS10 insulation system under intense growth for the 15 energy supply systems

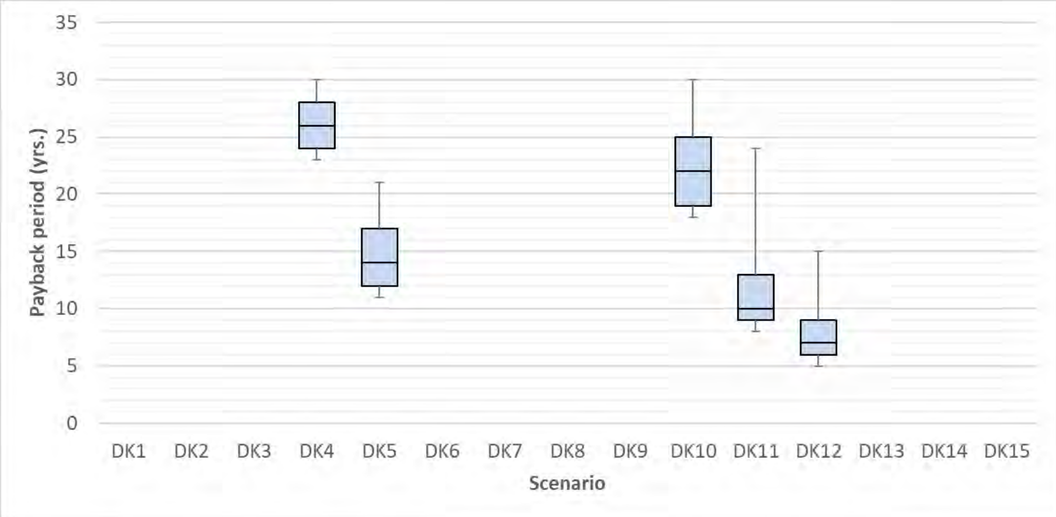


Figure 84 Boxplot depicting the distribution (min, max, 1 st quartile, 3rd quartile and median) of the payback period for the 15 energy supply systems in combination with insulation system CS10 under intense growth

6.4.2 Economic scenario – stagflation

For CS10 under stagflation, Figure 85 and Figure 86 reveal that some of the energy supply systems yield distinct low payback periods. Disregarding amortization and maintenance the best performing energy system in combination with CS10 under intense growth is DK5 with an average payback period of 21 years. Taking into account amortization and maintenance the best performing energy system in combination with CS10 is DK12 with an average payback period of 12 years.

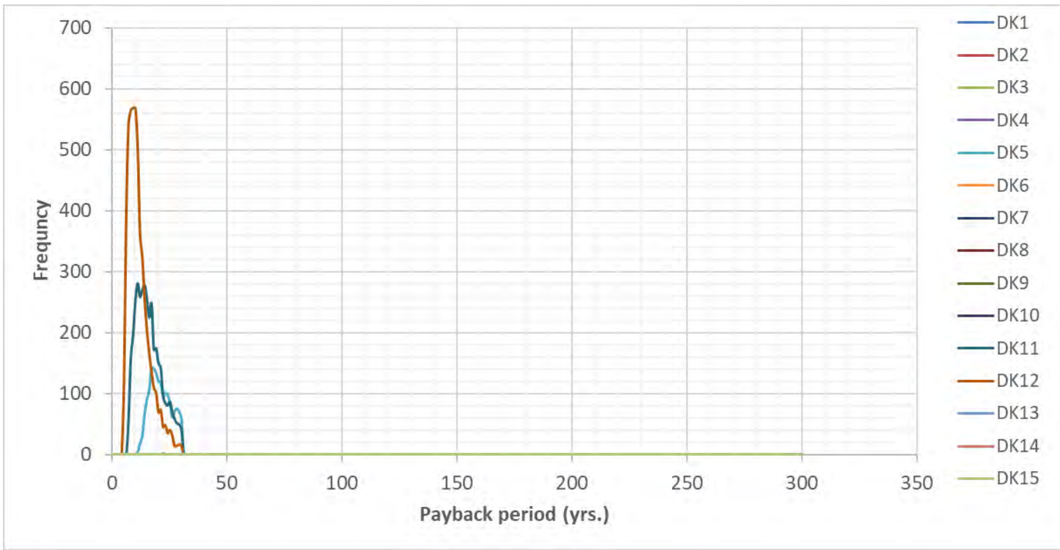


Figure 85 Frequency diagram illustrating the frequency of the payback period for the CS10 insulation system under stagflation for the 15 energy supply systems

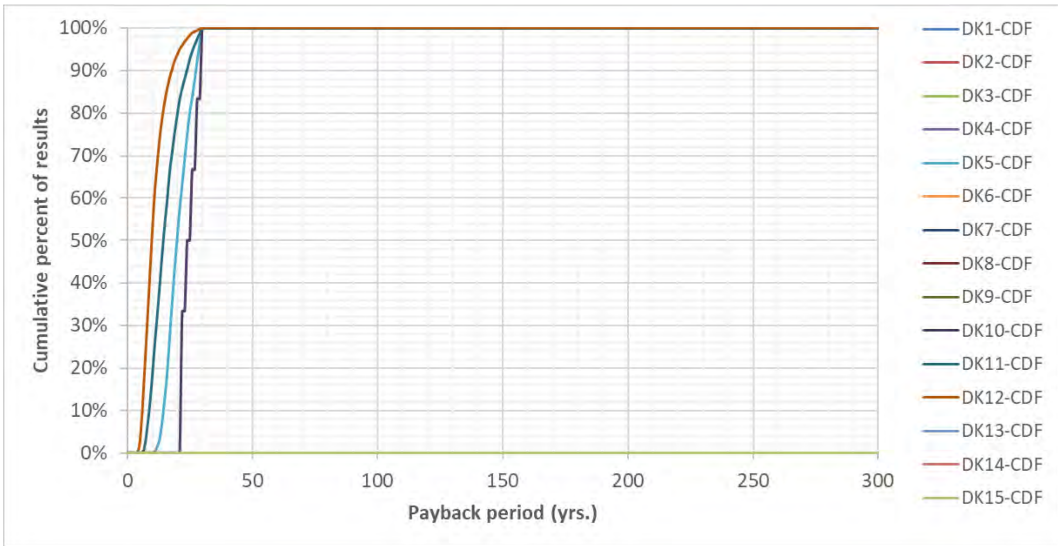


Figure 86 Cumulative frequency distribution diagram illustrating the cumulative frequency of the payback period for the CS10 insulation system under stagflation for the 15 energy supply systems

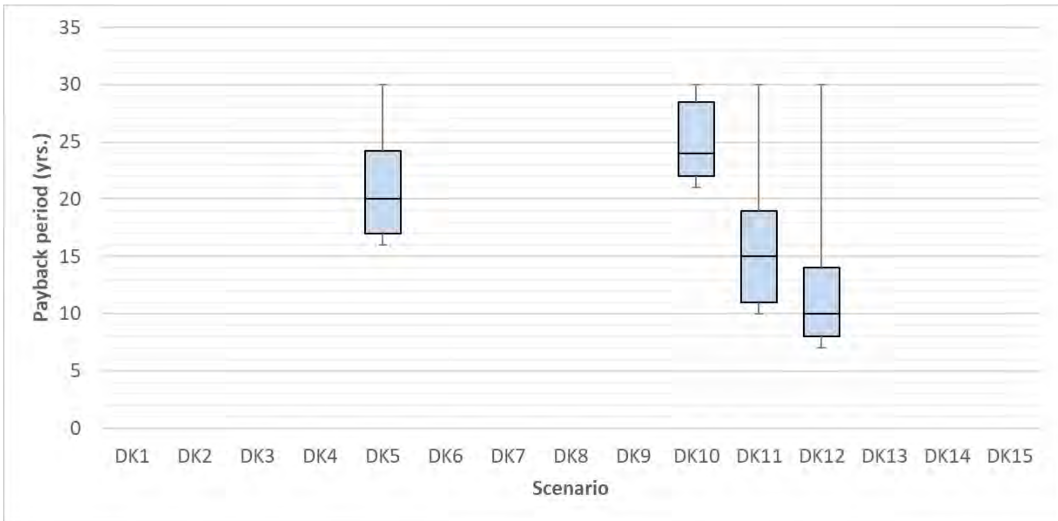


Figure 87 Boxplot depicting the distribution (min, max, 1st quartile, 3rd quartile and median of the payback period for the 15 energy supply systems in combination with insulation system CS10 under stagflation

6.4.3 Economic scenario – deflation

For CS10 under deflation, Figure 88 reveals that some of the energy supply systems yield distinct low payback periods. Disregarding amortization and maintenance the best performing energy system in combination with CS10 under deflation is DK5 with an average payback period of 11 years. Taking into account amortization and maintenance the best performing energy system in combination with CS10 is DK12 with an average payback period of 7 years.

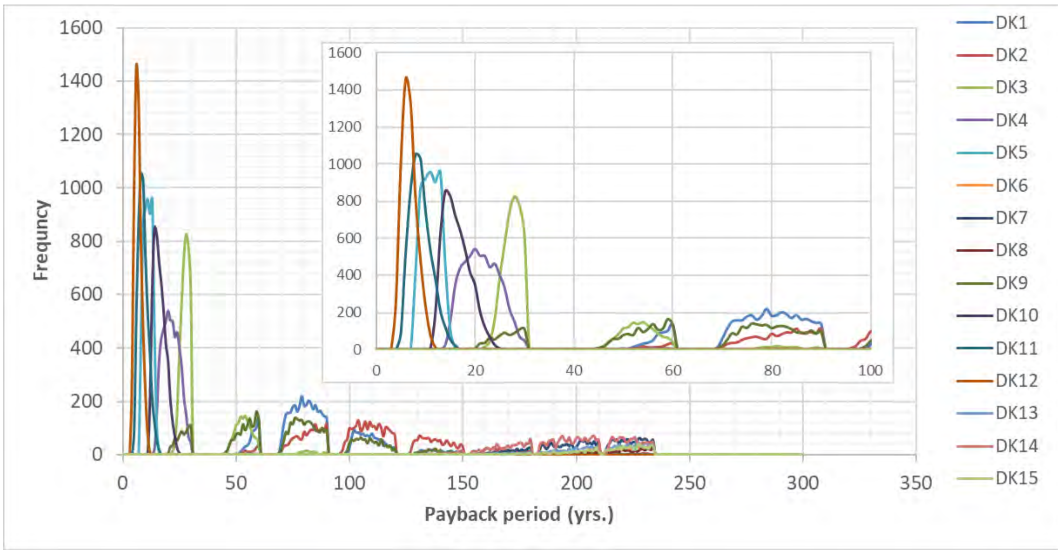


Figure 88 Frequency diagram illustrating the frequency of the payback period for the CS10 insulation system under deflation for the 15 energy supply systems

6.4.4 Economic scenario – regular growth

For CS10 under regular economic growth, Figure 89 reveals that some of the energy supply systems yield distinct low payback periods. Disregarding amortization and maintenance the best performing energy system in combination with CS10 under regular economic growth is DK5 with an average payback period of 13 years. Taking into account amortization and maintenance the best performing energy system in combination with CS10 is DK12 with an average payback period of 7 years.

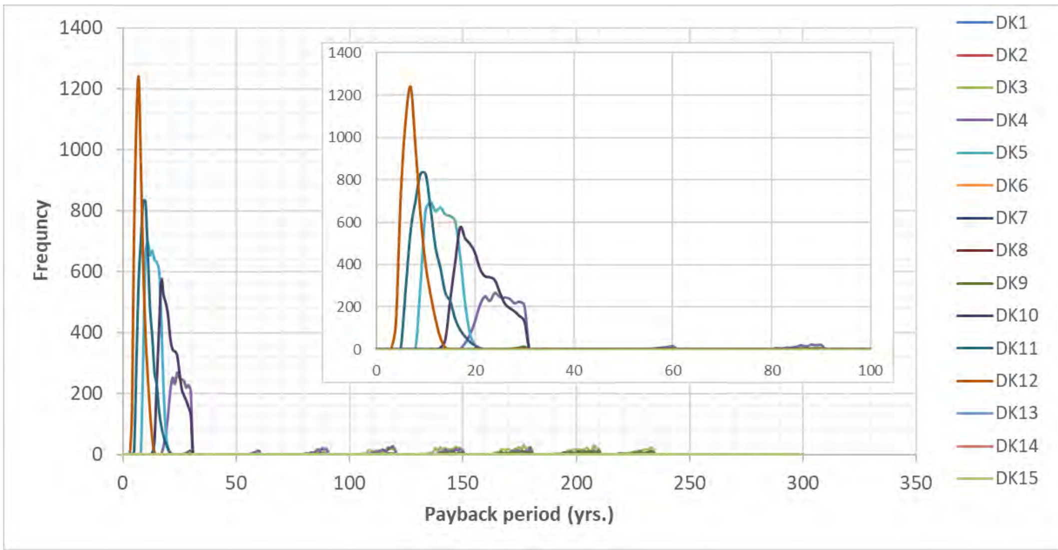


Figure 89 Frequency diagram illustrating the frequency of the payback period for the CS10 insulation system under regular economic growth for the 15 energy supply systems

6.5 Conclusions

The Danish case study investigated the relationship among internal insulation solutions and possible building energy supply scenarios, including or neglecting in the analysis the amortization and maintenance of the heating equipment. The assessment was performed under the 4 different economic scenarios embedded in the WP5 methodology. The results of the 180 scenarios explored in the Danish case study are summarized in Table 38.

The results highlight that for all the insulation systems, the energy supply solution yielding the lowest payback period is DK5 and DK12 which both represent heat pumps (geothermal->water), respectively disregarding or accounting for amortization and maintenance.

The payback time when disregarding amortization and maintenance ranges from 6 to 21 years and 4 to 12 years when accounting for amortization and maintenance, depending on the macroeconomic scenario considered in the assessment. In particular, the highest PB is obtained in the stagflation scenario, while the lowest in the deflation scenario.

It should be noticed that, in the majority of the analysed cases, the Payback Period obtained was longer than the calculation period assumed (30 years) and this is mainly due to: the low difference among the heat transmission loss through the wall before and after renovation; the high maintenance costs assumed.

Table 38 Summary of the 180 scenarios covered in the Danish case study. DAM – best energy supply solution Disregarding Amortization and Maintenance, PBP – Pay Back Period, AAM – Best solution accounting for amortization and maintenance

Economic scenario	CS8				CS9				CS10			
	DAM	PBP (yrs)	AAM	PBP (yrs)	DAM	PBP (yrs)	AAM	PBP (yrs)	DAM	PBP (yrs)	AAM	PBP (yrs)
Deflation	DK5	6	DK12	4	DK5	5	DK12	3	DK5	11	DK12	7
Regular growth	DK5	7	DK12	4	DK5	6	DK12	3	DK5	13	DK12	7
Intense growth	DK5	7	DK12	4	DK5	6	DK12	4	DK5	14	DK12	8
Stagflation	DK5	10	DK12	5	DK5	8	DK12	4	DK5	21	DK12	12

7 Implementation of the probabilistic LCC methodology in a software tool

7.1 Introduction

The LCC probabilistic methodology developed and documented in sections 2 and 3 has been implemented into a software tool using *R*, an open source programming language and software environment for statistical computing and graphics [106], 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 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, macro-economic scenarios and calculation periods). 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[37].

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 and 5.3, that can be edited or enriched at user's choice.

This section mainly addresses the LCC section of the tool[38], describing the calculation assumptions and providing a guide for the implementation of the inputs database and the software use[39].

7.2 Calculation assumptions

The calculation of the economic impacts (global cost and payback period) of the insulation systems embedded into the software code is based on the methodology developed in Task 5.3 and described in section 2.5.2.2. The parameters included in the calculation (section 2.5.2.2 from Eq. 6 to Eq. 17) are summarized in the following Table 39.

Table 39 Input parameters of the LCC included in the software tool

Input Parameter	Symbol	Unit
Year	t	[-]
(Insulation) System	j	[-]
Calculation Period	cp	[year]
Initial investment cost of the system j (at time t_0)	CI_j	€/m^2 or €
Maintenance cost for system j at the year t	$CM_{j,t}$	€/m^2 or €
Energy cost due to the system j at the year t	$CE_{j,t}$	€
Discount Rate (at the year t)	R_t^{disc}	%
Inflation rate (at the year t)	π_t	%

[37] At this aim, the term "insulation system" used in the following sections can be generically intended for "system", thus meaning "renovation measure".
[38] For what concerns the LCA section, refer to RIBuild Deliverable 5.1.
[39] The software tool guide, included in the software installation folder, presents both the LCA and LCC sections of the tool.

Nominal interest rate (at the year t)	i_t^N	%
Price development rate for human operation (labour cost) (at the year t)	R_t^L	%
Price development rate for energy (for the year t)	R_t^E	%
Real discount factor	d_t	%
Nominal growth rate of GDP	g_t^N	%
Nominal growth rate of crude oil price	$oilpg_t^N$	%
Heat transmission losses through the wall during the heating period	Q_h	[kWh/year]
Overall building efficiency for heating	ETA_h	[-]
Energy tariff	$EnT_{(c,e)}$	$\left[\frac{€}{kWh}\right]$
Service Life for the System j	SL_j	[year]
Replacement cost for the System j in the replacement year t_j	CR_{j,t_j}	€/m^2 or €
Replacement year	t_j	[-]
Final value of system *j* at the calculation period *cp*	$Val_{j,cp}$	€/m^2 or €
Residual years of the system j	r_j	[year]
Global Cost (corresponding to the calculation period *cp*)	GC_{cp}	€

As specified in sections 2.5.1 and 2.6.1, 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 7.3.2). Alternatively, if Q_h distributions are not available, 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 7.3.3).

7.3 Software User guide

The following sections provide 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.

7.3.1 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 computer. To install the WP5 tool Web App in a locale computer 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")
install.packages("ggrepel")
```

Packages installation instructions are also provided in the commented (#) code lines in the header of the file named *Global.R* in the installation folder. 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 tens of seconds.

7.3.2 Creation of the software database

Data inputs for the LCC 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 3 data frames (files *.csv*) provided into the folder "WP5 software tool": *Insulation_systems.csv; Case_studies.csv; Energy_sources.csv*[40]. Once data are filled, it is strictly necessary that the files remain included into the tool folder. At the moment, the data frames contain data input provided by RIBuild Task 5.3 partners (reported in Appendix 2).

The data frames must be filled 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. LCC input parameters can be entered as "deterministic" values or "probability distributions", among the available PDFs typologies included in the software, reported in Table 40. Information on input PDFs are reported in 4 columns of the data frame for each input:
    - The first column must be filled with a text (the distribution name in Table 40) 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 40 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 41). 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 41 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*

[40] These 3 excel files are mandatory for the LCC assessment. For the LCA assessment a further file is needed: *Materials.csv*, as documented in RIBuild deliverable 5.1, section 4.

rlnorm	*meanlog*	*sdlog*	*0*
rtriangle	*min*	*max*	*mode*

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

insulation_systems.csv
This file contains 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 written as free text, e.g. Italy, Belgium, Denmark, Germany, Latvia, Sweden, Switzerland, etc.
- **CI** = insulation system investment cost. It can be entered as a deterministic value or a PDF, so it is represented by four columns, as explained: CI_DISTR (distribution name), CI_1, CI_2, CI_3 (deterministic value or distribution parameters expressed by numbers according to the description in Table 41).
- **CM =** insulation system maintenance cost. As for other input parameters, it is represented by four columns, as explained.
- **SL** = the service life of the whole insulation system. As for other input parameters, it is represented by four columns, as explained.
- **DU** = Thermal resistance of the insulation system (m^2K/W), surfaces resistances excluded. It is considered as a single deterministic value.

Columns related to: **n_mater**, **materials, m_mater** and **M_selection** are mandatory for the LCA assessment and related to the other data frame *Materials.csv*[41]. In case of only LCC assessment, the 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 represents the insulation system installed in a specific 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…
- **Qh_{post}** = 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.
- **Qh_{pre}** = 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.

[41] Instructions on these parameters are reported in RIBuild deliverable report 5.1, section 4.

- **CN** = number of insulation systems included in the case study[42].
- **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 façade area[43].

Note that data on Qh_{post} and Qh_{pre} must be filled if the user exploits an external software for their assessment (based on calculation options 1 and 2, see section 2.3.3). 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 LCC 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…
- **EnT** = Energy tariff for the source concerned. As for other input parameters, it is represented by four columns, as explained.
- **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. This parameter is considered only for the LCA assessment. If only the LCC is performed, the user can write 0 (zero) in the parameters' values, but always a text in the distribution type (e.g. rnorm)
- **ETAh** = the overall building efficiency for heating. As for other input parameters, it is represented by four columns, as explained.

Columns related to **EI** (energy impact) are to be filled for the LCA assessment and are documented in RIBuild Deliverable 5.1. In case of only LCC assessment, the user can write 0 (zero) in the parameters' values, but always a text in the distribution type (e.g. rnorm).

7.3.3 Use of the software tool

Once the App is launched, the internet browser opens and the home page in Figure 90 appears[44].

[42] Within RIBuild project, which only addresses the internal insulation, this parameter must be set = 1. 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.
[43] Within RIBuild project this parameter must be set = 1, as the functional unit selected for WP5 LCA and LCC 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 and costs of the systems.
[44] The map in the home page will appear only if the computer is connected to internet.

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*.

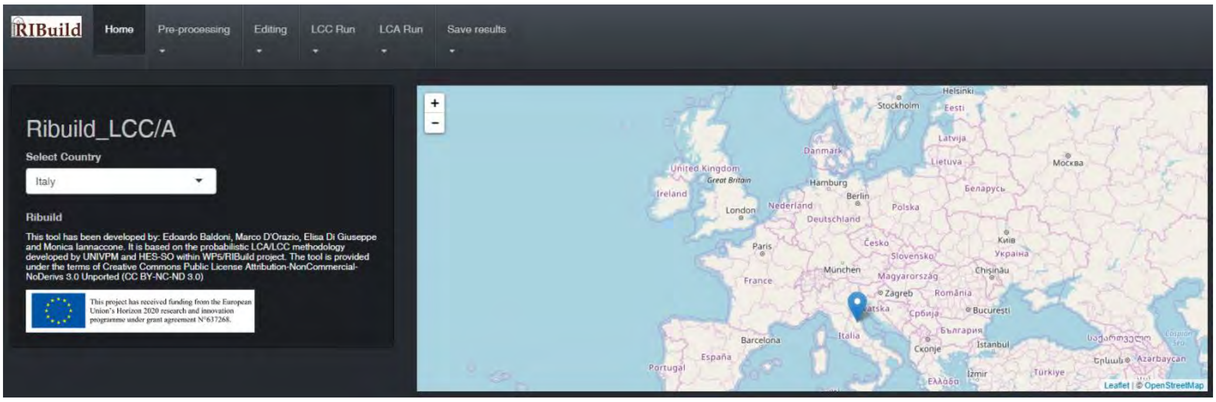


Figure 90 WP5 software tool homepage

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 LCC assessment (Figure 91).

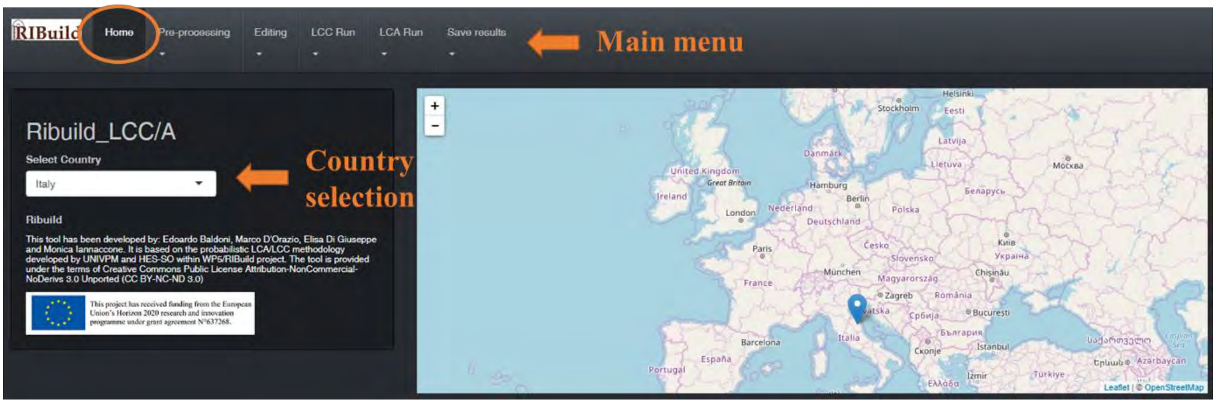


Figure 91 WP5 software tool homepage. Country selection.

Pre-processing

The *Pre-processing* menu contains the following items: *Visualize data*, *New system impact generation* (for the LCA assessment, as documented in RIBuild deliverable D5.1), *Economic Scenario visualization*, *Qh calculation*.

In *Visualize data* (Figure 92), the user selects the insulation systems included into the database (dataframe *insulation_system.csv*) and, by pushing on *visualize* button, he visualizes the PDFs of the related LCC (and LCA) data inputs, as the system CI (investment cost), CM (maintenance cost), SL (service life).

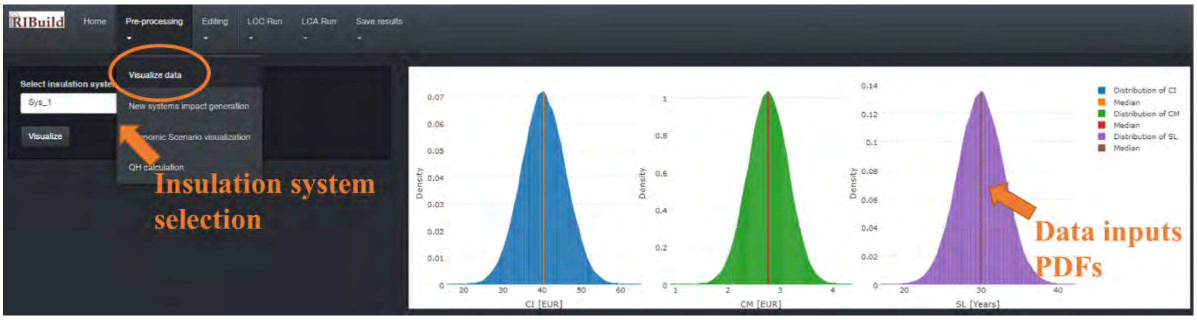


Figure 92 Pre-processing menu → Visualize data, visualization of the PDFs of LCC (and LCA) data inputs

In *Economic Scenario visualization* (Figure 93), the user can visualize the results of the characterisation of the macro-economic scenarios included in the methodology and tool and described in section 3. For each scenario, quarterly and yearly predictions of the 3 economic variables can be visualized, as well as their mean and standard deviation.

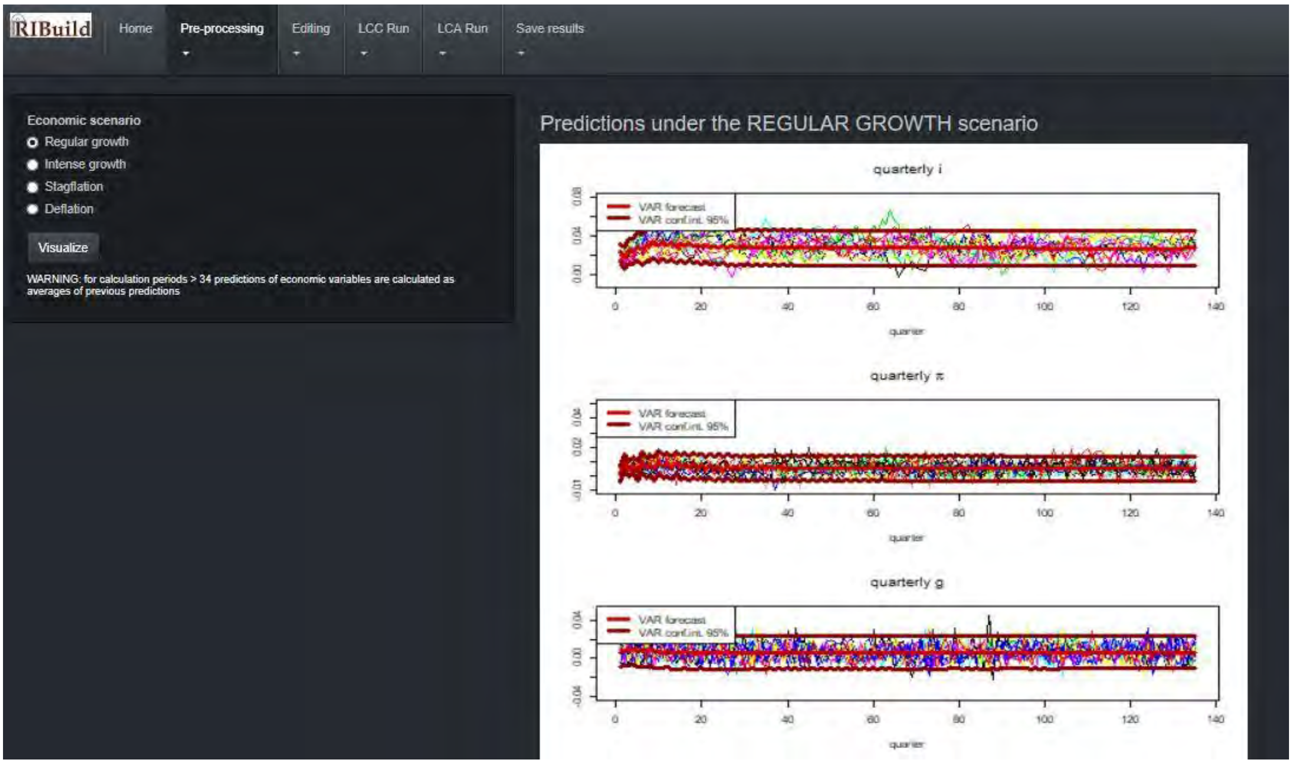


Figure 93 Pre-processing menu → Economic scenario visualization. Visualization of the characterisation results for the macro-economic scenarios

In *QH calculation* (Figure 94), 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 2.5.1 and 2.6.1). 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 1, 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.

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 below.

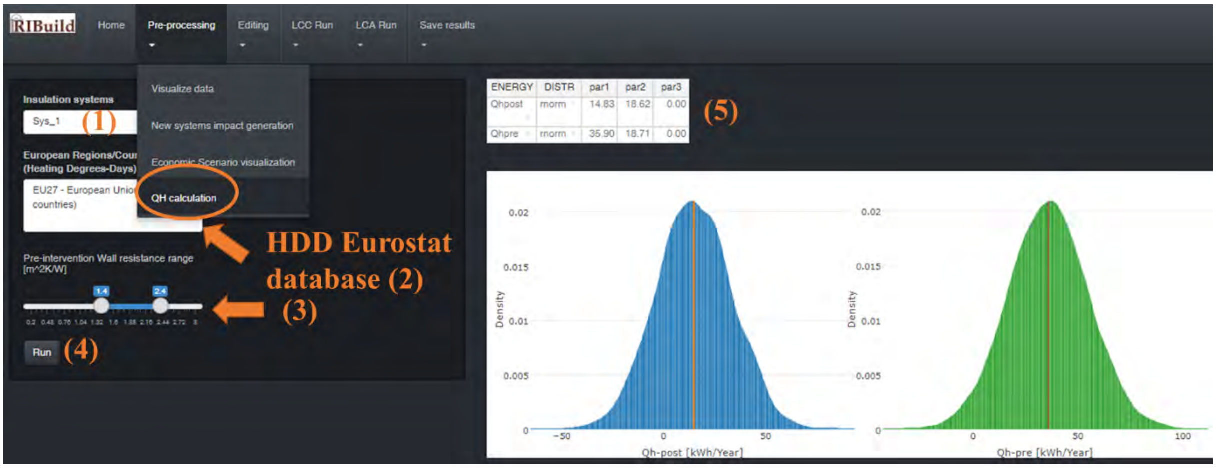


Figure 94 Pre-processing menu → QH calculation. Assessment of the Qh_{post} and Qh_{pre} for a certain case study, based on the simplified HDD methodology (option 3).

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 95), the user (1) selects the case study name, to which an insulation system is associated (2)[45]. After pushing *Confirm* button (3), summary data inputs on tables will appear on the right (4).

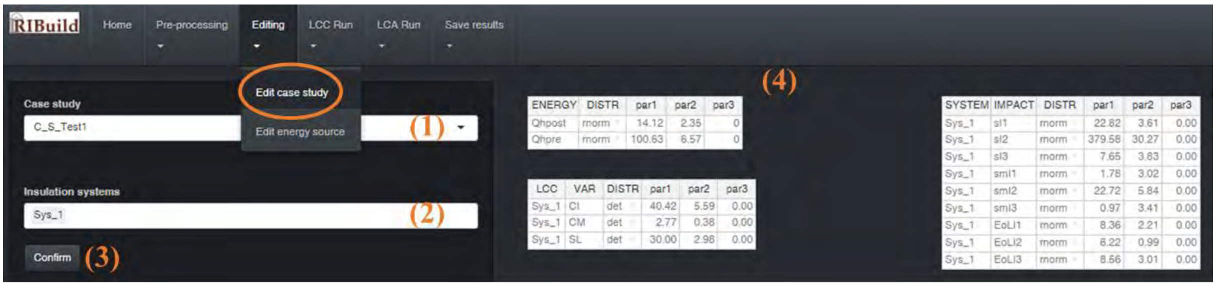


Figure 95 Editing menu → Edit case study. Visualization of the summary data of a case study.

To create a new case study (Figure 96), the user selects the *NEW* option from the bar (1) and writes a name for the case study (2). Then he selects the insulation system included in the case study from the bar (3)[46] 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}, investment cost (CI), maintenance cost (CM) and system service life (SL) must be provided and then *Save changes* button must be pushed to save the new case study. Notice that this procedure must be always applied when the user assesses Qh_{post} and Qh_{pre} through the HDD method included in the tool (as previously described).

[45] More renovation measures can be associated to a case study.
[46] Multiple selection is allowed, if more renovation measures are associated to a case study.

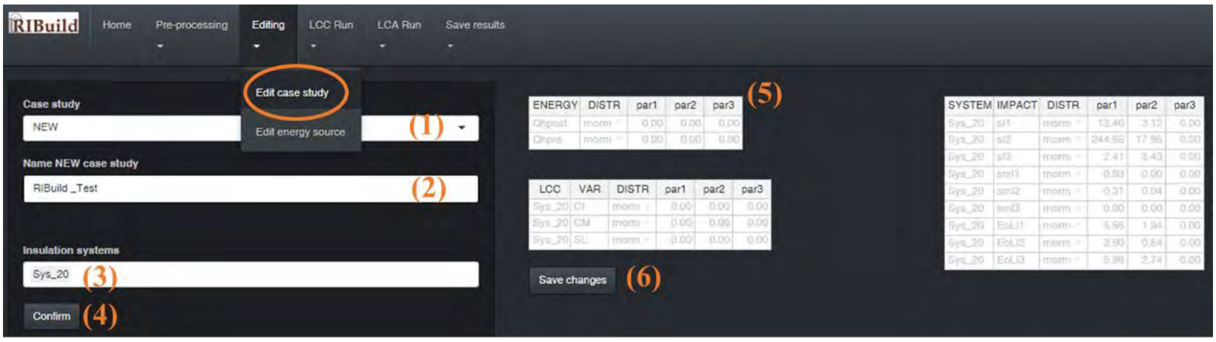


Figure 96 Editing menu → Edit case study. Creation of a new case study.

Similarly, in *Edit energy source* (Figure 97), 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.

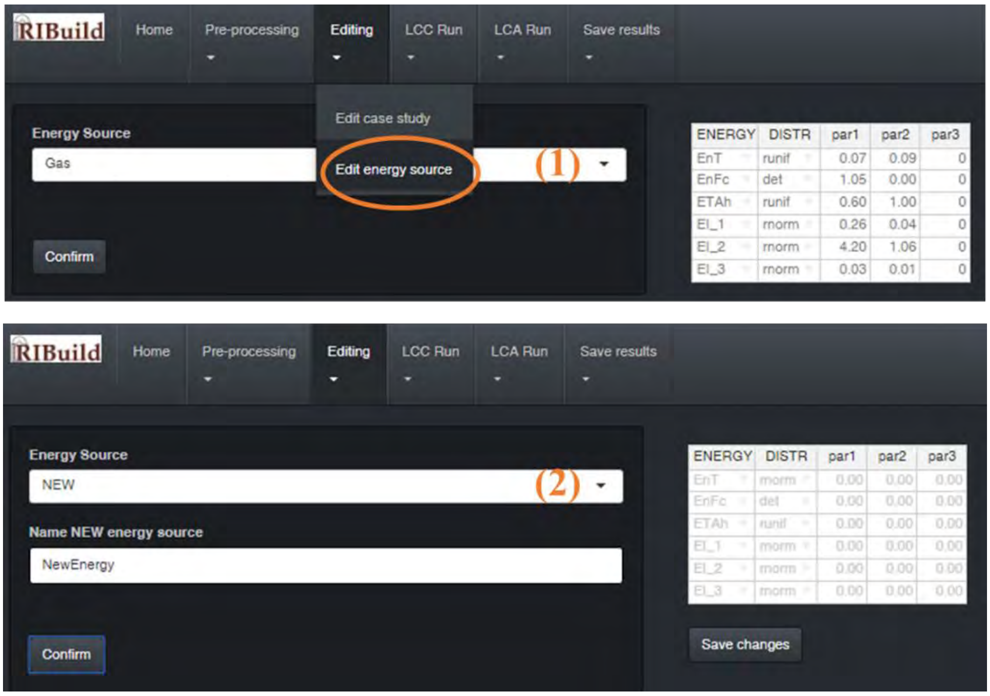


Figure 97 Editing menu → Edit energy source. Visualization of the summary data of an energy source (above) and creation of a new energy source (below).

LCC Run

The *LCC Run* menu contains *LCC analysis*, in order to perform the Monte-Carlo based LCC and *LCC - Sensitivity analysis*, to calculate the sensitivity indices according to the method described in section 2.7.

In *LCC* Analysis (Figure 98), the user (1) selects the case study to be assessed, among those in the tool database or among those created or edited during the work session. The user must also select scenarios for the assessment: energy scenario (2), calculation period (4) -dragging the specific slider-, macro-economic scenario (5). Finally, the user must choose the number of iterations[47] for the Monte Carlo calculation (3) and then push the *Compute* button (6).

The calculation may take a few tens of 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 Global costs and Payback period;
- Tables for each graph summarizing the simulation number, the mean value, the median value and the standard deviation of the PDF obtained.
- A table (down in the page) including an example of the yearly evolution of outputs from a single draw of input data.

Figure 98 *LCC Run* menu → *LCC analysis.* Assessment of the Global Cost and Payback period for a certain case study.

In *LCC – Sensitivity analysis*, after concluding the LCC assessment, the user can evaluate the sensitivity according to the methods 1 and 2 documented in section 3.6.

Concerning the Sensitivity *Method 1* (Figure 99), the user directly gets the first and total order Sobol's indices by selecting the method (2) and pushing on *Run sensitivity analysis* button (3). The graph and table representing the obtained first order and total order indices for LCC inputs will appear on the right.

[47] The software suggests the minimum number of iterations required.

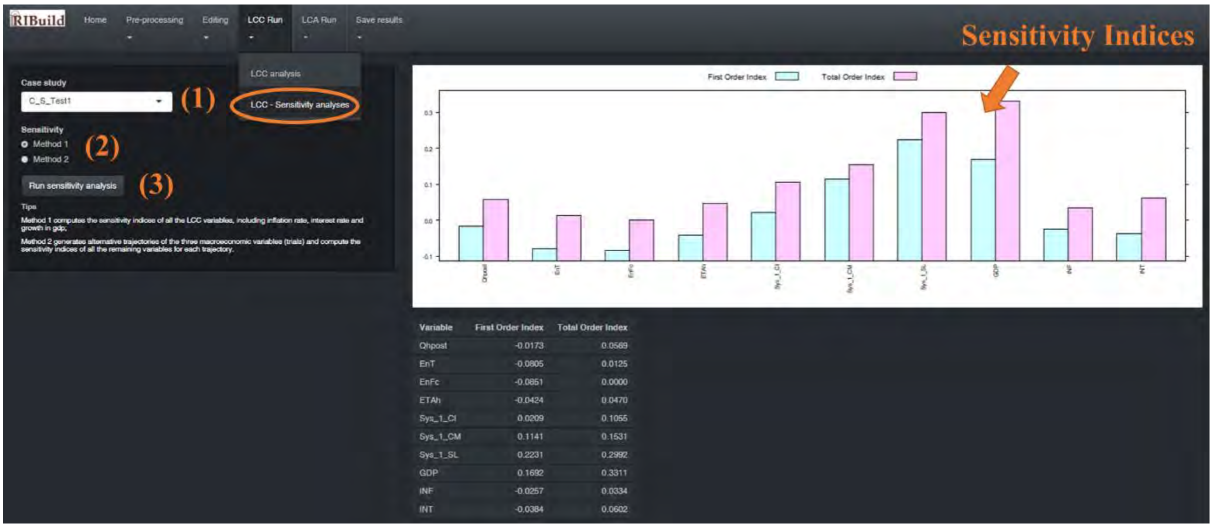


Figure 99 LCC Run menu → LCC – Sensitivity analysis. Calculation of the Sobol's first order and total order indices for LCC inputs with Method 1

Concerning the Sensitivity *Method 2* (Figure 100), the user must also select the number of simulation trajectories of the economic parameters (3) and then obtain the distribution of first and total order Sobol's indices by pushing on *Run sensitivity analysis* button (4). The graph and table representing the first order and total order indices for the LCC inputs obtained will appear on the right.

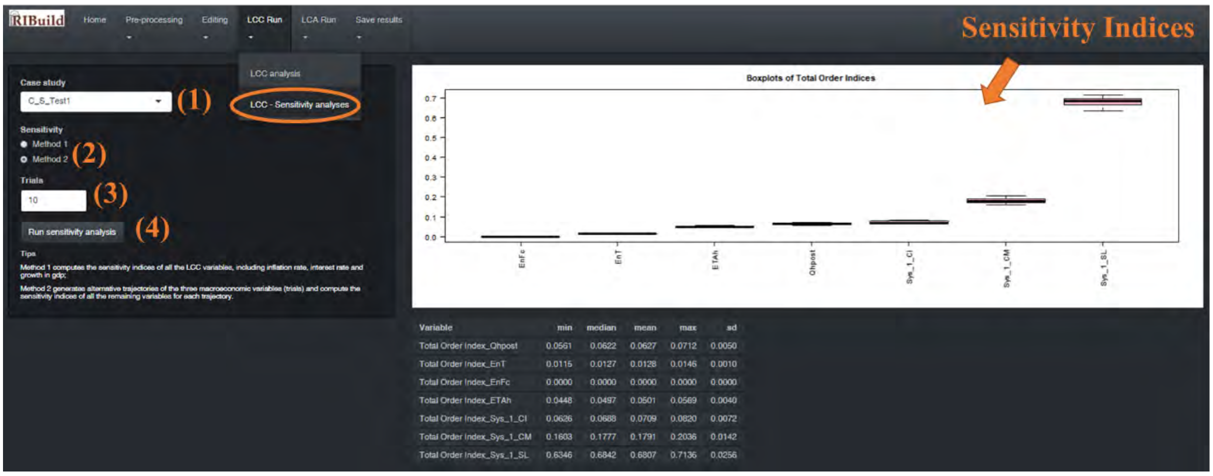


Figure 100 LCC Run menu → LCC – Sensitivity analysis. Calculation of the Sobol's first order and total order indices for LCC inputs with Method 2

Save results

Once the calculation is performed, results can be saved as *.xlsx* file or *.Rdata* workspace (Figure 101). 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 Costs and Payback Period);
- the cost shares defined as:
  SHARE_inv = (investment cost + replacement cost – residual value)/(global cost)
  SHARE_maint = (maintenance cost)/(global cost)

SHARE_energ = (energy cost post renovation)/(global cost);
- the first and total order sensitivity indices related to the Method 1 and 2.

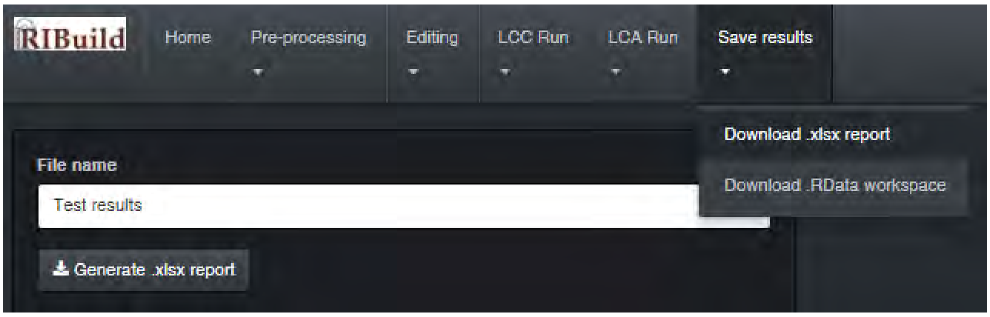


Figure 101 Save results menu.

8 Conclusions

This document reports the main results of the work carried out in RIBuild WP5, Task 5.3 "Probabilistic Life Cycle Cost (LCC) analysis and Cost-Optimal (CO) levels of minimum energy performance of interior insulation solutions". It describes the probabilistic LCC methodology and the software tool developed in the field of internal insulation solutions of historical buildings, also providing exemplary cases of the methodology application and potential.

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

As shown in detail in the report, the work performed is an important contribution in the field of building LCC of renovation solutions - especially internal insulation - for several reasons summarized below.

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

→ *Task 5.3 developed a probabilistic approach to LCC that allows expressing both the economic indicators expected values and their inherent uncertainty and risk, thus considerably improving the reliability of decision making in building renovation and overcoming the current limits of traditional LCC deterministic approaches.*

(2) As documented in *Section 2, 4, 5, 6*, the LCC probabilistic methodology can be applied to assess the economic performance of several design options (internal insulation solutions) in several possible scenarios (original wall applications, climatic contexts, energy sources, macro-economic scenarios, calculation 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 LCC probabilistic methodology can then be effectively applied in further developments of the RIBuild project in WP6, i.e. to assess the economic impact of several insulation solutions, in several existing walls configurations and in different climates, in order to realize the RIBuild guidelines on internal insulation.*

(3) The proposed approach for the characterization of alternative future macro-economic scenarios reported in *Section 3* explicitly takes into account the interdependent stochastic nature of the economic variables included in LCC assessments.

→ *The identification of the macro-economic scenarios reflects the main feature of the proposed methodology and is perhaps one of the major novelties with respect to the existing literature, thus providing a significant research result.*

(4) The methodology has been implemented into the *WP5 software tool* described in *Section 7.*

→ *WP5 software can be effectively used for the realization of the RIBuild guidelines on internal insulation solutions within WP6, to calculate the distributions of global costs and payback periods* *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 5.3 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.*

These achievements constitute an effective starting point for future developments, not only within RIBuild project WP6, but in further projects in the field of LCC of renovation measures.

References

1. ISO - International Organization for Standardization. ISO 15686-5 Buildings and constructed assets — Service life planning — Part5: Life-cycle costing. 2017.

2. ASTM. ASTM E917-17 Standard Practice for Measuring Life-Cycle Costs of Buildings and Building Systems. 2017.

3. ISO - International Organization for Standardization. ISO 12249-1 Particulate air filters for general ventilation -- Part 1: Method of calculation for the life cycle cost for air cleaning devices.

4. ISO - International Organization for Standardization. ISO/TS 21929-2:2015 Sustainability in building construction -- Sustainability indicators -- Part 2: Framework for the development of indicators for civil engineering works. 2015.

5. European Parliament. Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings (recast). Official Journal of the European Union [Internet]. 2010; Available from: http://data.europa.eu/eli/dir/2010/31/oj

6. Commission Delegated Regulation (EU) No 244/2012 of 16 January 2012 supplementing Directive 2010/31/EU of the European Parliament and of the Council. Official Journal of the European Union. 2012;55:18–36.

7. Guidelines accompanying Commission Delegated Regulation (EU) No 244/2012 of 16 January 2012 supplementing Directive 2010/31/EU of the European Parliament and of the Council. Official Journal of the European Union. 2012;55:1–28.

8. CEN European Commitee for Standardization. EN 15459-1:2017. Energy performance of buildings - Economic evaluation procedure for energy systems in buildings - Part 1: Calculation procedures, Module M1-14. 2017.

9. Hauschild MZ, Rosenbaum RK, Olsen SI. Life Cycle Assessment - Theory and Practice. Springer; 2018.

10. Hunkeler DD, Lichtenvort K, Rebitzer G, Ciroth A. Environmental life cycle costing. CRC Press, Pensacola; 2008.

11. White GE, Ostwald PF. Life cycle costing. Management Accounting. 1976;57(7):39–42.

12. Korpi E, Ala-Risku T. Life cycle costing: a review of published case studies. Managerial Auditing Journal. 2008;23(3):240–61.

13. ISO - International Organization for Standardization. ISO 14040:2006. Environmental management -life cycle assessment- principles and framework. 2006.

14. ISO - International Organization for Standardization. ISO 14044, Environmental management — Life cycle assessment — Requirements and guidelines. 2006.

15. Langdon D. Life Cycle Costing (LCC) as a contribution to sustainable construction: a common methodology. Final Report. Brussels; 2007.

16. Moreau V, Weidema BP. The computational structure of environmental life cycle costing. International Journal of Life Cycle Assessment. 2015;(20):1359–63.

17. Park CS. Contemporary Engineering Economics. Pearson Prentice Hall, New Jersey; 2011.

18. Sullivan WG, Wicks EM, Luxhoj J. Engineering Economy. Pearson Education, New Jersey.; 2006.

19. Corgnati SP, Fabrizio E, Filippi M, Monetti V. Reference buildings for cost optimal analysis: Method of definition and application. Applied Energy. 2013 Feb;102:983–93.

20. Hamdy M, Hasan A, Siren K. A multi-stage optimization method for cost-optimal and nearly-zero-energy building solutions in line with the EPBD-recast 2010. Energy and Buildings. 2013 Jan;56:189–203.

21. Ascione F, Bianco N, De Stasio C, Mauro GM, Vanoli GP. A new methodology for cost-optimal analysis by means of the multi-objective optimization of building energy performance. Energy and Buildings. 2015;88:78–90.

22. Ferrara M, Fabrizio E, Virgone J, Filippi M. Energy systems in cost-optimized design of nearly zero-energy buildings. Automation in Construction. 2016;70:109–27.

23. Morrissey J, Horne RE. Life cycle cost implications of energy efficiency measures in new residential buildings. Energy and Buildings. 2011 Apr;43(4):915–24.

24. Mauro GM, Hamdy M, Vanoli GP, Bianco N, Hensen JLM. A new methodology for investigating the cost-optimality of energy retrofitting a building category. Energy and Buildings. 2015 Nov;107:456–78.

25. Han G, Srebric J, Enache-Pommer E. Variability of optimal solutions for building components based on comprehensive life cycle cost analysis. Energy and Buildings. 2014 Aug;79:223–31.

26. Ferreira M, Almeida M, Rodrigues A, Silva SM. Comparing cost-optimal and net-zero energy targets in building retrofit. Building Research & Information. 2016 Feb 17;44(2):188–201.

27. Asadi E, Da Silva MG, Antunes CH, Dias L. Multi-objective optimization for building retrofit strategies: A model and an application. 2012 Jan;44(1):81–7.

28. Oduyemi O, Okoroh M., Fajana OS, Arowosafe O. The need for economic performance measures for life cycle costing of sustainable commercial office buildings. Journal of Facilities Management. 2018;16(1):54–64.

29. Mah CM, Fujiwara T, Ho CS. Life cycle assessment and life cycle costing toward eco-efficiency concrete waste management in Malaysia. Journal of Cleaner Production. 2018;172:3415–27.

30. Lim BTH, Zhang W, Oo BL. Sustainable procurement in Australia: Quantity surveyors' perception on life cycle costing. International Journal of Integrated Engineering. 2018;10(2):1–6.

31. Illankoon IMCS, Tam VWY, Le KN, Wang JY. Life cycle costing for obtaining concrete credits in green star rating system in Australia. Journal of Cleaner Production. 2018;172:4212–9.

32. Milic V, Ekelow K, Moshfegh B. On the performance of LCC optimization software OPERA-MILP by comparison with building energy simulation software IDA ICE. Building and Environment. 2018;128:305–19.

33. Van den Boomen M, Schoenmaker R, Wolfert ARM. A life cycle costing approach for discounting in age and interval replacement optimisation models for civil infrastructure assets. Structure and Infrastructure Engineering. 2018;14(1):1–13.

34. Tighnavard Balasbaneh A, Bin Marsono AK, Kasra Kermanshahi E. Balancing of life cycle carbon and cost appraisal on alternative wall and roof design verification for residential building. Construction Innovation. 2018;

35. Rahman S, Vanier DJ. Life cycle cost analysis as a decision support tool for managing municipal infrastructure. In: CIB 2004 Triennial Congress. Toronto, Ontario; 2004. p. 1–12.

36. Gluch P, Baumann H. The life cycle costing (LCC) approach: a conceptual discussion of its usefulness for environmental decision-making. Building and Environment. 2004;39(5):571–80.

37. Pittenger D, Gransberg DD, Zaman M, Riemer C. Stochastic Life-Cycle Cost Analysis for Pavement Preservation Treatments. Transportation Research Record: Journal of the Transportation Research Board. 2012 Jan 22;2292(1):45–51.

38. Burhenne S, Tsvetkova O, Jacob D, Henze GP, Wagner A. Uncertainty quantification for combined building performance and cost-benefit analyses. Building and Environment. 2013 Apr;62:143–54.

39. Wang N, Chang Y-C, El-Sheikh AA. Monte Carlo simulation approach to life cycle cost management. Structure and Infrastructure Engineering. 2012 Aug;8(8):739–46.

40. Das P, Van Gelder L, Janssen H, Roels S. Designing uncertain optimization schemes for the economic assessment of stock energy-efficiency measures. Journal of Building Performance Simulation. 2017 Jan 2;10(1):3–16.

41. Goh YM, Newnes LB, Mileham AR, McMahon CA, Saravi ME. Uncertainty in through-life costing-review and perspectives. IEEE Transactions on Engineering Management. 2010;57(4):689–701.

42. Menassa CC. Evaluating sustainable retrofits in existing buildings under uncertainty. 2011 Dec;43(12):3576–83.

43. Sesana MM, Salvalai G. Overview on life cycle methodologies and economic feasibility for nZEBs. Building and Environment. 2013 Sep;67:211–6.

44. Moore T, Morrissey J. Lifecycle costing sensitivities for zero energy housing in Melbourne, Australia. Energy and Buildings. 2014 Aug;79:1–11.

45. Ilg P, Scope C, Muench S, Guenther E. Uncertainty in life cycle costing for long-range infrastructure. Part I: leveling the playing field to address uncertainties. The International Journal of Life Cycle Assessment. 2017 Feb 5;22(2):277–92.

46. Burhenne S, Tsvetkova O, Jacob D, Henze GP, Wagner A. Uncertainty quantification for combined building performance and cost-benefit analyses. Building and Environment. 2013;62:143–54.

47. Morrissey J, Meyrick B, Sivaraman D, Horne RE, Berry M. Cost-benefit assessment of energy efficiency investments: Accounting for future resources, savings and risks in the Australian residential sector. Energy Policy. 2013 Mar;54:148–59.

48. Copiello S, Gabrielli L, Bonifaci P. Evaluation of energy retrofit in buildings under conditions of uncertainty: The prominence of the discount rate. Energy. 2017;137:104–17.

49. Almeida RMSF, Ramos NMM, Manuel S. Towards a methodology to include building energy simulation uncertainty in the Life Cycle Cost analysis of rehabilitation alternatives. Journal of Building Engineering. 2015;2:44–51.

50. Van Gelder L, Janssen H, Roels S. Probabilistic design and analysis of building performances: Methodology and application example. Energy and Buildings. 2014 Aug;79:202–11.

51. Di Giuseppe E, Massi A, D’Orazio M. Impacts of Uncertainties in Life Cycle Cost Analysis of Buildings Energy Efficiency Measures: Application to a Case Study. Energy Procedia. 2017;111:442–51.

52. Di Giuseppe E, Iannaccone M, Telloni M, D’Orazio M, Di Perna C. Probabilistic life cycle costing of existing buildings retrofit interventions towards nZE target: Methodology and application example. Energy and Buildings. 2017 Jun 1;144:416–32.

53. (IEA) International Energy Agency. Annex 55 Reliability of Energy Efficient Building Retrofitting - Probability Assessment of Performance & Cost (RAP-RETRO) - Probabilistic Tools. Energy Conservation in Buildings and Community Systems. 2013;

54. Gaterell MR, McEvoy ME. The impact of energy externalities on the cost effectiveness of energy efficiency measures applied to dwellings. Energy and Buildings. 2005 Oct;37(10):1017–27.

55. Plebankiewicz E, Zima K, Wieczorek D. Life Cycle Cost Modelling of Buildings with Consideration of the Risk. Archives of Civil Engineering. 2016 Jun 1;62(2):149–66.

56. Di Giuseppe E, Massi A, D’Orazio M. Probabilistic Life Cycle Cost Analysis of Building Energy Efficiency Measures: Selection and Characterization of the Stochastic Inputs through a Case Study. In: Procedia Engineering. 2017. p. 491–501.

57. IEA. Methodology for Cost-Effective Energy and Carbon Emissions Optimization in Building Renovation (Annex 56). 2014. 210 p.

58. CEN/ISO. EN ISO 6946:2007. Building components and building elements — Thermal resistance and thermal transmittance — Calculation method. 2007.

59. Janssen H, Roels S, Van Gelder L, Das P. IEA Annex 55 Reliability of Energy Efficient Building Retrofitting - Probability Assessment of Performance & Cost (RAP-RETRO) - Probabilistic Tools. 2015.

60. Eurostat. Cooling and heating degree days by NUTS 2 regions - annual data [Internet]. 2017 [cited 2018 Jun 14]. Available from: http://ec.europa.eu/eurostat/web/products-datasets/-/nrg_chddr2_a

61. ISO - International Organization for Standardization. ISO 15686-5:2017 - Buildings and constructed assets -- Service life planning -- Part 5: Life-cycle costing.

62. CEN/ISO. EN ISO 13790 Energy performance of buildings - Calculation of energy use for space heating and cooling. 2008.

63. ISO - International Organization for Standardization. ISO 15686-7:2006. Buildings and constructed assets -- Service life planning -- Part 7: Performance evaluation for feedback of service life data from practice. 2006.

64. Silva A, de Brito J, Gaspar PL. Methodologies for Service Life Prediction of Buildings with a focus on facade cladding. Cham: Springer International Publishing; 2016. 432 p. (Green Energy and Technology).

65. Hovde PJ. Factor methods for service life prediction: state-of-the-art. Draft Report. Trondheim: Norwegian University of Science and Technology; 2000.

66. Hovde PJ. The Factor Method For Service Life Prediction From Theoretical Evaluation To Practical Implementation. In: The 9th International Conference on Durability of Building Materials and Components (9DBMC). 2002. p. 1–10.

67. Hovde PJ. The Factor Method – a simple tool to service life estimation. 10DBMC International Conference on Durability of Building Materials and Components\r. 2005;(TT4-115).

68. Hendriks NA, Van Nunen H, Erkelens P. Application of the improved factor method to the Environmental impact assessment of buildings. In: Central and Eastern European Conference on Sustainable Building (SB04). Warsaw, Poland; 2004. p. 12.

69. Re Cecconi F. Epistemic Uncertainty Propagation in Service Life Prediction Using the Factor Method. In: International Conference on Durability of Building Materials and Components. Porto, Portugal; 2011. p. 1–9.

70. Re Cecconi F. Engineering method for service life planning: the evolved factor method. In: Building for the Future: The 16th CIB World Building Congress 2004. Rotterdam, Netherlands; 2004. p. 1–9.

71. Silva A, de Brito J, Gaspar PL. Application of the factor method to maintenance decision support for stone cladding. Automation in Construction. 2012 Mar;22:165–74.

72. Inukai TNT, Motohashi K. Toward Practical Application Of Factor Method For Estimating Service Life Of Building. 2002;(1944):1–14.

73. Aktas CB, Bilec MM. Impact of lifetime on US residential building LCA results. International Journal of Life Cycle Assessment. 2012;17(3):337–49.

74. Saltelli A, Ratto M, Andres T. Global Sensitivity Analysis: The Primer. Chichester: Wiley, John; 2008.

75. Saltelli A, Annoni P, Azzini I, Campolongo F, Ratto M, Tarantola S. Variance based sensitivity analysis of model output. Design and estimator for the total sensitivity index. Computer Physics Communications. 2010 Feb;181(2):259–70.

76. Sobol IM. Global sensitivity indices for nonlinear mathematical models and their Monte Carlo estimates. Mathematics and Computers in Simulation. 2001;55(1–3):271–80.

77. Nguyen A-T, Reiter S. A performance comparison of sensitivity analysis methods for building energy models. Building Simulation. 2015 Dec 14;8(6):651–64.

78. Janssen H. Monte-Carlo based uncertainty analysis: Sampling efficiency and sampling convergence. Reliability Engineering & System Safety. 2013 Jan;109:123–32.

79. Lee BS. Causal Relations among Stock Returns, Interest Rates, Real Activity, and Inflation. The Journal of Finance. 1992;47(4):1591–603.

80. Ministero del Lavoro e delle Politiche Sociali. D. D. n. 23/2017 del 3 aprile 2017 concernente la determinazione del costo medio orario del lavoro, a livello provinciale, per il personale dipendente da imprese del settore dell'edilizia e attività affini, con decorrenza 2016. [Internet]. 2017. Available from: http://www.lavoro.gov.it/temi-e-priorita/rapporti-di-lavoro-e-relazioni-industriali/focus-on/Analisi-economiche-costo-lavoro/Documents/Operai-maggio-2016.pdf

81. European Parliament. Directive 2009/72/EC of the European Parliament and of the Council of 13 July 2009 concerning common rules for the internal market in electricity and repealing Directive 2003/54/EC. 2009.

82. European Parliament. Directive 2009/73/EC of the European Parliament and of the Council of 13 July 2009 concerning common rules for the internal market in natural gas and repealing Directive 2003/55/EC. 2009.

83. Registre fédéral des bâtiments et logements.

84. SIA 380/1:2016 - Besoins de chaleur pour le chauffage. Société Suisse des Ingénieurs et Architectes; 2016. p. 60.

85. KBOB. Données des écobilans dans la construction 2009/1:2016. 2016.

86. SIA Baustoffkennwerte. 2017.

87. Base de données DUREE v9. 2017.

88. Environmental product declaration Calsitherm Silikatbaustoffe GmbH. 2013.

89. Huijbregts MAJ, Hellweg S, Frischknecht R, Hendriks HWM, Hungerbühler K, Hendriks AJ. Cumulative Energy Demand As Predictor for the Environmental Burden of Commodity Production. Enviromental science and technology. 2010;2189–96.

90. (OFEV) O federal de l'environnement. Taxe sur le CO2 prélevé sur les combustibles. 2016.

91. Programme bâtiment/Das Gebäudeprogramm.

92. (OFS) O fédéral de la statistique. Indices suisses des prix de la construction - Evolution des prix de la construction. 2017.

93. Modèle de prescriptions énergétiques des cantons (MoPEC). 2014.

94. Détermination de la puissance du générateur de chaleur. 2015.

95. SIA 380 : 2015 - Bases pour les calculs énergétiques des bâtiments. Société Suisse des Ingénieurs et Architectes; 2015. p. 64.

96. Office fédérale de la statistique (OFS). Prix moyens de l'énergie, indice des prix à la consommation. 2017.

97. Lasvaux S, Giorgi M, Favre D, Padey P, Périsset B, Farsi M, et al. DUREE: Annual report 2017, Analysis of service lives of building elements for a better understanding of the renovation of the building stock. Swiss Federal Office for Energy (SFOE); 2017.

98. Stolz P, Frischknecht R. Umweltkennwerte und Primärenergiefaktoren von Energiesystemen, KBOB ökobilanzdatenbestand v2.2:2016. 2016.

99. Office fédéral de l'énergie OFEN. Conventions d'objectifs conclues avec la Confédération et visant l'amélioration de l'efficacité énergétique. Bern; 2014.

100. Hoval, prix indicatifs pour systèmes de chauffage.

101. Viessmann, liste de prix.

102. Planair. Thermoréseau de Datom SA, Monthey, Comparaison de prix de chauffage. 2015.

103. Bony J, Citherlet S, Favre D, Hildbrand C, Lasvaux S, Périsset B. Projet ECO-Reno, WP2: Optimum environnemental et financier des isolations pour les rénovations.

104. TOBLER. Résumé et comparaison des coûts des différents systèmes de chauffage. 2009.

105. Elcotherm SA. Comparaison des coûts des différents systèmes de chauffage. 2008.

106. The R Project for Statistical Computing [Internet]. [cited 2018 May 29]. Available from: https://www.r-project.org/

107. Hamilton JD. Time Series Analysis. Princeton University Press; 1994.

Appendix 1: HDD data from Eurostat database and data-fitting results

Table 42 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 43 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 2: LCC inputs for the case studies included in the software tool database

Table 44 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	0.8833	0.1223	0	rnorm	30	2.98	0	6	101 102 101 103 104 105	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	0.8833	0.1223	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	0.8833	0.1223	0	rnorm	30	2.98	0	6	101 109 101 103 104 105	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	0.8833	0.1223	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	0.8833	0.1223	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	0.8833	0.1223	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	0.8833	0.1223	0	rnorm	30	2.98	0	8	119 120 121 122 123 103 104 105	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	Denmark	det	96.85	0	0	det	0	0	0	det	30	0	0	1	101	rnorm	0	0	0	0	2.87
9	Comp_9	Denmark	det	103.5848	0	0	det	0	0	0	det	30	0	0	1	101	rnorm	0	0	0	0	4
10	Comp_10	Denmark	det	191.95	0	0	det	0	0	0	det	30	0	0	1	101	rnorm	0	0	0	0	1.034
11	Comp_11	Switzerland	rtriangle	152	269	198	det	0	0	0	rnorm	33.82	14	0	1	101	rnorm	0	0	0	0	0
12	Comp_12	Switzerland	rtriangle	128	265	190	det	0	0	0	rnorm	33.82	14	0	1	101	rnorm	0	0	0	0	0
13	Comp_13	Switzerland	rtriangle	199	330	259	det	0	0	0	rnorm	33.82	14	0	1	101	rnorm	0	0	0	0	0
14	Comp_14	Switzerland	rtriangle	98	276	176	det	0	0	0	rnorm	33.82	14	0	1	101	rnorm	0	0	0	0	0
15	Comp_15	Switzerland	rtriangle	731	893	812	det	0	0	0	rnorm	33.82	14	0	1	101	rnorm	0	0	0	0	0
16	Comp_16	Switzerland	rtriangle	1001	1224	1112	det	0	0	0	rnorm	33.82	14	0	1	101	rnorm	0	0	0	0	0
17	Comp_17	Switzerland	rtriangle	334	408	371	det	0	0	0	rnorm	33.82	14	0	1	101	rnorm	0	0	0	0	0
18	Comp_18	Switzerland	rtriangle	82	199	128	det	0	0	0	rnorm	33.82	14	0	1	101	rnorm	0	0	0	0	0
19	Comp_19	Switzerland	rtriangle	58	195	120	det	0	0	0	rnorm	33.82	14	0	1	101	rnorm	0	0	0	0	0
20	Comp_20	Switzerland	rtriangle	129	260	189	det	0	0	0	rnorm	33.82	14	0	1	101	rnorm	0	0	0	0	0
21	Comp_21	Switzerland	rtriangle	28	206	106	det	0	0	0	rnorm	33.82	14	0	1	101	rnorm	0	0	0	0	0
22	Comp_22	Switzerland	rtriangle	562	686	624	det	0	0	0	rnorm	33.82	14	0	1	101	rnorm	0	0	0	0	0
23	Comp_23	Switzerland	rtriangle	146	258	190	det	0	0	0	rnorm	33.82	14	0	1	101	rnorm	0	0	0	0	0
24	Comp_24	Switzerland	rtriangle	122	254	182	det	0	0	0	rnorm	33.82	14	0	1	101	rnorm	0	0	0	0	0
25	Comp_25	Switzerland	rtriangle	191	317	248	det	0	0	0	rnorm	33.82	14	0	1	101	rnorm	0	0	0	0	0
26	Comp_26	Switzerland	rtriangle	94	265	169	det	0	0	0	rnorm	33.82	14	0	1	101	rnorm	0	0	0	0	0

Table 45 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	Denmark	det	116.8	0	0	det	138.6	0	0	1	8	1
9	C_S_Test9	Denmark	det	110.7	0	0	det	138.6	0	0	1	9	1
10	C_S_Test10	Denmark	det	108.7	0	0	det	129.5	0	0	1	10	1
11	C_S_Test11	Switzerland	rnorm	26.45	6.87	0	rnorm	239.7	67.79	0	1	11	1
12	C_S_Test12	Switzerland	rnorm	26.53	6.97	0	rnorm	240.8	67.68	0	1	12	1
13	C_S_Test13	Switzerland	rnorm	26.32	6.55	0	rnorm	238.73	64.47	0	1	13	1
14	C_S_Test14	Switzerland	rnorm	26.46	7.07	0	rnorm	240.24	69.49	0	1	14	1
15	C_S_Test15	Switzerland	rnorm	26.62	6.78	0	rnorm	239.78	66.07	0	1	15	1
16	C_S_Test16	Switzerland	rnorm	21.24	5.72	0	rnorm	241.51	68.01	0	1	16	1
17	C_S_Test17	Switzerland	rnorm	21.16	5.53	0	rnorm	240.19	69.62	0	1	19	1
18	C_S_Test18	Switzerland	rnorm	21.19	5.66	0	rnorm	241.23	69.77	0	1	20	1
19	C_S_Test19	Switzerland	rnorm	21.1	5.5	0	rnorm	239.6	68.05	0	1	21	1
20	C_S_Test20	Switzerland	rnorm	21.28	5.53	0	rnorm	239.75	69.28	0	1	16	1
21	C_S_Test21	Switzerland	rnorm	32.39	8.56	0	rnorm	239.78	69.68	0	1	23	1
22	C_S_Test22	Switzerland	rnorm	28.85	7.61	0	rnorm	239.46	67.84	0	1	24	1
23	C_S_Test23	Switzerland	rnorm	40.38	10.54	0	rnorm	239.67	67.99	0	1	25	1
24	C_S_Test24	Switzerland	rnorm	34.49	9.11	0	rnorm	239.39	68.69	0	1	26	1
25	C_S_Test25	Switzerland	rnorm	54.05	14.25	0	rnorm	239.73	68.7	0	1	17	1
26	C_S_Test26	Switzerland	rnorm	40.15	10.56	0	rnorm	239.13	67.35	0	1	22	1

Table 46 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	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	1	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	0	0	runif	0.4	0.8	0	rnorm	0.3183	0.0577	0	rnorm	4.923	1.448	0	rnorm	0.0152	0.0084	0

																									8		
4	Tar_4	Denmark	DK1_Wood_pellet_excl_amort	det	0.056375839	0	0	det	1	0	0	runif	0.7	0.83	0	rnorm	0	0	0	rnorm	0	0	0	rnorm	0	0	0
5	Tar_5	Denmark	DK2_District_heating_excl_amort	det	0.102684564	0	0	det	0.8	0	0	runif	0.9	3	0	rnorm	0	0	0	rnorm	0	0	0	rnorm	0	0	0
6	Tar_6	Denmark	DK3_Heat_pump_air_air_excl_amort	det	0.208053691	0	0	det	2.5	0	0	runif	3	3.5	0	rnorm	0	0	0	rnorm	0	0	0	rnorm	0	0	0
7	Tar_7	Denmark	DK4_Heat_pump_air_water_excl_amort	det	0.208053691	0	0	det	2.5	0	0	runif	1.5	3	0	rnorm	0	0	0	rnorm	0	0	0	rnorm	0	0	0
8	Tar_8	Denmark	DK5_heat_pump_geo_water_excl_amort	det	0.93557047	0	0	det	2.5	0	0	runif	3	6	0	rnorm	0	0	0	rnorm	0	0	0	rnorm	0	0	0
9	Tar_9	Denmark	DK6_new_natural_gas_furnace_excl_amort	det	0.038926175	0	0	det	1	0	0	det	93	0	0	rnorm	0	0	0	rnorm	0	0	0	rnorm	0	0	0
10	Tar_10	Denmark	DK7_new_oil_furnace_excl_amort	det	0.134228188	0	0	det	1	0	0	det	84	0	0	rnorm	0	0	0	rnorm	0	0	0	rnorm	0	0	0
11	Tar_11	Denmark	DK8_old_oil_furnace_excl_amort	det	0.020805369	0	0	det	1	0	0	det	78	0	0	rnorm	0	0	0	rnorm	0	0	0	rnorm	0	0	0
12	Tar_12	Denmark	DK9_District_heating_excl_amort	runif	0.134105825	0.285668731	0	det	0.8	0	0	runif	0.9	3	0	rnorm	0	0	0	rnorm	0	0	0	rnorm	0	0	0
13	Tar_13	Denmark	DK10_Heat_pump_air_air_excl_amort	runif	0.301420149	0.569691127	0	det	2.5	0	0	runif	3	3.5	0	rnorm	0	0	0	rnorm	0	0	0	rnorm	0	0	0
14	Tar_14	Denmark	DK11_Heat_pump_air_water_excl_amort	runif	0.410304675	0.85025898	0	det	2.5	0	0	runif	1.5	3	0	rnorm	0	0	0	rnorm	0	0	0	rnorm	0	0	0
15	Tar_15	Denmark	DK12_heat_pump_geo_water_excl_amort	runif	1.201060477	2.410367459	0	det	2.5	0	0	runif	3	6	0	rnorm	0	0	0	rnorm	0	0	0	rnorm	0	0	0
16	Tar_16	Denmark	DK13_new_natural_gas_furnace_excl_amort	runif	0.049044592	0.095841973	0	det	1	0	0	det	93	0	0	rnorm	0	0	0	rnorm	0	0	0	rnorm	0	0	0
17	Tar_17	Denmark	DK14_oil_furnace_excl_amort	runif	0.159267457	0.317028416	0	det	1	0	0	det	84	0	0	rnorm	0	0	0	rnorm	0	0	0	rnorm	0	0	0
18	Tar_18	Denmark	DK15_old_oil_furnace_excl_amort	runif	0.027461312	0.048266681	0	det	1	0	0	det	78	0	0	rnorm	0	0	0	rnorm	0	0	0	rnorm	0	0	0
19	Tar_19	Switzerland	SW1_Gas	rtriangle	0.101	0.1269	0.11116	det	1	0	0	rlnorm	0.02	0.04	0	rnorm	0	0	0	rnorm	0	0	0	rnorm	0	0	0
20	Tar_20	Switzerland	SW2_Oil	rtriangle	0.0932	0.1275	0.11112	det	1	0	0	rlnorm	0.003	0.09	0	rnorm	0	0	0	rnorm	0	0	0	rnorm	0	0	0

21	Tar_21	Switzerland	SW3_Electricity	rtriangle	0.1919	0.2595	0.2223	det	1	0	0	rtriangle	0.95	1	0.975	rnorm	0	0	0	rnorm	0	0	0	rnorm	0	0	0
22	Tar_22	Switzerland	SW4_Wood pellet	rtriangle	0.0946	0.13	0.1073	det	1	0	0	rlnorm	-0.16	0.028	0	rnorm	0	0	0	rnorm	0	0	0	rnorm	0	0	0
23	Tar_23	Switzerland	SW5_PAC	rtriangle	0.064	0.118	0.0855	det	1	0	0	rlnorm	1.03	0.04	0	rnorm	0	0	0	rnorm	0	0	0	rnorm	0	0	0
24	Tar_24	Switzerland	SW6_Oil	rtriangle	0.1107	0.1441	0.1291	det	1	0	0	rlnorm	0.00326835	0.09128251	0	rnorm	0	0	0	rnorm	0	0	0	rnorm	0	0	0
25	Tar_25	Switzerland	SW7_Gas	rtriangle	0.2248	0.2653	0.2423	det	1	0	0	rlnorm	0.020444464	0.047327727	0	rnorm	0	0	0	rnorm	0	0	0	rnorm	0	0	0
26	Tar_26	Switzerland	SW8_Oil	rtriangle	0.2633	0.3176	0.2907	det	1	0	0	rlnorm	0.00326835	0.09128251	0	rnorm	0	0	0	rnorm	0	0	0	rnorm	0	0	0
27	Tar_27	Switzerland	SW9_Electricity	rtriangle	0.1979	0.2662	0.2287	det	1	0	0	rtriangle	0.95	1	0.975	rnorm	0	0	0	rnorm	0	0	0	rnorm	0	0	0
28	Tar_28	Switzerland	SW10_Wood pellet	rtriangle	0.2997	0.3595	0.3243	det	1	0	0	rlnorm	-0.16513159	0.0285995	0	rnorm	0	0	0	rnorm	0	0	0	rnorm	0	0	0
29	Tar_29	Switzerland	SW11_PAC	rtriangle	0.1964	0.2659	0.2253	det	1	0	0	rlnorm	1.030044326	0.046597109	0	rnorm	0	0	0	rnorm	0	0	0	rnorm	0	0	0