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## Abstract

The application of internal insulation is a widespread and effective solution for energy renovation of historic buildings. However, it entails quite high installation costs and a certain risk of failure due to moisture-related problems. A probabilistic risk assessment of both hygrothermal performance and life cycle costs can be used to address internal insulation issue, in order to support risk management and decision making. This paper presents the application of a probabilistic approach to Life Cycle Costing developed within the EU project RIBuild (Robust Internal Thermal Insulation of Historic Buildings), to five internal insulations solutions widely used in Italy. The method provides estimates of the range and likelihood of global costs and payback periods, also considering alternative energy and future economic scenarios. The impact of insulation systems service life on global costs is also addressed, in order to highlight the possible connection of the method to a stochastic estimation of insulation systems durability based on hygrothermal and damage assessments.


## 1 Introduction

Considering that in today's Europe 30% of all buildings are historic[1] buildings that are expected to last for decades, there is great potential for energy savings, and consequently emission reductions, by their deep renovation. Given the architectural features of the façade of these buildings, the energy retrofit should be properly evaluated considering the need to preserve the cultural value. In this context, the application of internal insulation to the facades is one of the most exploited solutions, given its significant potential for energy savings without compromising the building appearance [1, 2].

However, the implementation of internal thermal insulation is subject to a certain risk of failure, due to the modification of the hygrothermal performance of the building envelope [3–5], and to high installation costs. The EU project *RIBuild* (Robust Internal Thermal Insulation of Historic Buildings) investigates in depth how and under what conditions internal insulation can be employed [6]. Next to the hygrothermal performance, life cycle costs and environmental impacts are important factors to be considered during the decision-making process before installing internal insulation [7, 8].

In the last two decades, Life Cycle Costing (LCC) has become an important decision tool in the building context, both for the development of specific policies and for the single design process. Directive 2010/31/EU introduced the concept of "cost-optimality" of building design solutions [9], and recent Directive 2018/844 encourages *"[...] in relation to buildings undergoing a major renovation, high-efficiency alternative systems, in so far as this is technically, functionally and economically feasible*" [10]. As reported in a comprehensive review of Ferrara et al., a considerable amount of research recently addressed the cost analysis of building design options in Europe [11], mainly referring to standardized LCC methods as those reported in the international standards ISO 15686–5:2008 [12] and EN 15459-1:2017 [13]. However, standard LCC does not fully capture the risk associated to the investment and the calculation is often achieved with notable simplifications related to the cost items and macro-economic scenarios quantification. In reality, accurate cost analysis relies on quality of data and long-term forecasts,

[1] Buildings built prior to 1945. They include heritage buildings and other buildings not protected by legislation.

and data uncertainty is a well-recognized issue associated with LCC methods [14–19]. Ignoring these uncertainties may lead to improper decisions [17].

In this context, as part of *RIBuild* project – work package 5, a "probabilistic" methodology to assess internal insulation affordability, based on an LCC, has been developed, in order to take into account the inherent uncertainties related to the long-term perspective of the building interventions [20]. The method includes a Monte Carlo-based approach to LCC of internal insulation measures and a model to characterize the future macro-economic scenario for the assessment. Furthermore, the probabilistic approach allows to explicitly consider the inputs uncertainty related to the insulation hygrothermal performance, i.e. the heat transmission losses, the service life and their maintenance needs. Indeed, a probabilistic analysis of the hygrothermal performance of interior insulation is also developed within *RIBuild* project – work package 4 [21].

In this paper, the stochastic LCC method is used to assess five internal insulations solutions, among those investigated in *RIBuild* project, usually applied for the renovation of historic buildings in Italy. Special attention is given to their economic performance under alternative macro-economic and building energy scenarios and to the role played by the system service life. Section 2 presents the insulation systems under investigation and summarizes the stochastic LCC methodology. Section 3 and 4 respectively report and discuss the main results, while conclusions and future developments within *RIBuild* and in the general field of historic building renovation are finally drawn in section 5.

## 2 Methodology

### 2.1 The insulation systems

Five internal thermal insulation systems typically used in Italy for historic building renovation have been considered in this study, i.e. Expanded Polystyrene (EPS), Calcium Silicate (CaSi), Autoclaved Aerated Concrete (AAC), Cork and Rockwool (RW). They are applied to an exemplary historic building in Italy in plastered solid bricks masonry, with an overall thickness of about 30 cm and an air-to-air heat transfer coefficient (U-value) of 1.76 W/m$^2$K. The building is supposed to be located in the region Lombardia, belonging to the largest climatic zone of Italy. In Table 1, the thermophysical properties of the five insulation systems are reported. The thicknesses of the different internal insulation layers have been computed in order to reach a U-value lower than 0.36 W/m$^2$K, according to the actual Italian law requirements [22], with slight differences due to the commercial insulation thicknesses available in the market.

**Table 1.** Thermophysical properties of the analyzed internal insulation systems.

| Layer | Standard thickness [m] | Density [kg/m³] | Thermal conductivity [W/mK] |
|---|---|---|---|
| | *"EPS" insulation system* (U-value = 0.36 W/m²K) | | |
| Adhesive mortar | 0.006 | 1400.00 | 0.540 |
| **EPS** | 0.080 | 25.00 | 0.035 |
| Adhesive mortar | 0.006 | 1400.00 | 0.540 |
| Plasterboard | 0.0125 | 680.00 | 0.200 |
| Surface rendering | 0.004 | 1200.00 | 0.47 |
| Primer + paint | 0.0002 | 1670.00 | - |
| | *"CaSi" insulation system* (U-value = 0.36 W/m²K) | | |
| Adhesive mortar | 0.006 | 1800.00 | 0.63 |
| **Calcium Silicate** | 0.125 | 290.00 | 0.053 |
| Surface rendering | 0.006 | 1800.00 | 0.63 |
| Primer + paint | 0.0002 | 1670.00 | - |
| | *"AAC" insulation system* (U-value = 0.35 W/m²K) | | |
| Adhesive mortar | 0.006 | 800.00 | 0.18 |
| **AAC** | 0.100 | 90.00 | 0.042 |
| Surface rendering | 0.006 | 800.00 | 0.18 |
| Primer + paint | 0.0002 | 1670.00 | - |
| | *"Cork" insulation system* (U-value = 0.35 W/m²K) | | |
| Adhesive mortar | 0.006 | 1800.00 | 0.60 |
| **Cork** | 0.100 | 150.00 | 0.041 |
| Surface rendering | 0.006 | 1800.00 | 0.60 |
| Primer + paint | 0.0002 | 1670.00 | - |
| | *"RW" insulation system* (U-value = 0.33 W/m²K) | | |
| **Rockwool*** | 0.080 | 110.00 | 0.035 |
| Vapor barrier | 0.0002 | 2700.00 | - |
| Plasterboard | 0.025 | 680.00 | 0.200 |
| Surface rendering | 0.004 | 1200.00 | 0.47 |
| Primer + paint | 0.0002 | 1670.00 | - |

* Fixed to the wall through a metallic frame.

## 2.2 The stochastic approach to LCC

**LCC model.** The LCC analysis of the internal insulation systems is based on the procedure described in the European Standard EN 15459-1 [13] that allows computing the Global Costs ($GC_{j,0}$), referred to the starting year (*t*=0), of a specific building design option (*j*) at the end of a determined calculation period (*CP*). The $GC_{j,0}$ formula is adapted in this study by including annual variations of the discount factor and specific price developments rates for human operation and for energy, as follows:

$$GC_{j,0} = CI_j + \sum_{t=1}^{CP} \left[ \left( CM_j + CS_{j,t} \right) R_t^{disc} \; R_t^L + CE_j \; R_t^{disc} \; R_t^E \right] - Val_{j,CP} \quad (1)$$

where $CI_j$ is the initial investment cost, $CM_j$ the annual maintenance cost, $CS_{j,t}$ the replacement cost, $CE_j$ the annual energy cost, $R_t^{disc}$ the discount factor (based on inflation rate and market interest rate), $R_t^L$ and $R_t^E$ the price development rates (respectively for human operation and for energy), and $Val_{j,CP}$ the residual value of the design option at the end of the CP. In this study, the CP is assumed to be equal to 30 years. Based on the same data inputs, the Payback Period (PP) of each solution is also calculated as the minimum number of years making the cumulative energy saving equalizing the total investment costs.

**Uncertainty propagation.** The stochastic approach to LCC, developed by the authors and described in depth in [20], couples Monte-Carlo (MC) simulations to the model eq. (1), thus requires defining the Probability Density Functions (PDFs) of all LCC variables and parameters.

MC method selects values from the input PDFs and inserts them into the output eq. (1) for a proper number of times depending on the envisaged accuracy level. The output parameters distributions are then quantified as a result of the possible variance of the input parameters. In this work, Sobol's sequences have been used as a quasi-random sampling technique in order to generate samples as uniformly as possible from inputs PDFs. Data analysis software "R" has been used for both sample generation and uncertainty propagation [23]. The assessment has been performed in several scenarios to evaluate results robustness. These include:

- 2 building heating scenarios, including natural gas and electricity as energy sources (the most widespread in Italy);
- 4 macro-economic scenarios [24], i.e.:
  - *Regular Growth (RG)*, representing an economic situation with a balanced growth path, i.e. a moderate growth of Gross Domestic Product (GDP) and inflation rate, and a moderate nominal interest rate;
  - *Intense Growth (IG)*, characterized by more robust growth in terms of GDP, and inflation and interest rates higher than in the RG scenario;
  - *Stagflation (St)*, where the inflation rate is very high;
  - *Deflation (De)*, where the inflation rate is the lowest (near-zero).
- 3 replacement scenarios, due to hygrothermal damages (i.e. internal insulation service life assumed to be equal to 10, 20 or 30 years). Replacement costs (*CSs*) are assumed to be equal to investment costs. Periodic maintenance on the system is not foreseen, then maintenance costs (*CM*s) have been always considered equal to zero.

As a result, 120 simulation cases have been obtained from the combination of all the insulation systems, economic and energy scenarios (5 insulation systems x 2 energy scenarios x 4 economic scenarios x 3 replacement scenarios).

**Data inputs characterization.** LCC data inputs are grouped into three main categories: design option characteristics (i.e. investment and maintenance costs, service life); building energy performance (energy need and overall efficiency for heating) and energy carrier (national tariffs); macro-economic scenario (i.e. inflation rate, interest rate, price development rates). The PDFs of inputs related to the first two categories, obtained as described in [20], are summarized in **Table 2**.

**Table 2.** Input parameters PDFs. The variability on the PDF mean values corresponds to the 5% and 95% percentile for the normal distribution (Coefficient of Variability, CoV=7.5%) and to the min/max values for the uniform distribution.

| LCC parameters | PDF | Insulation system (mean values) | | | | | Variability [%] |
|---|---|---|---|---|---|---|---|
| | | ***EPS*** | ***CaSi*** | ***AAC*** | ***Cork*** | ***RW*** | |
| $Q_H^{pre}$ [kWh/y] | Normal | | | 96.19 | | | ±12 |
| $Q_H^{post}$ [kWh/y] | | 18.64 | 18.10 | 18.60 | 18.17 | 17.32 | ±12 |
| $CI$ [€] | | 44.40 | 220.62 | 90.59 | 103.78 | 62.57 | ±12 |
| $EnT_{gas}$ [€/kWh] | Uniform | | | 0.075 (taxes included) | | | ±15 |
| $EnT_{electricity}$ [€/kWh] | | | | 0.186 (taxes included) | | | ±15 |
| $\eta_{H,gas}$ [-] | | | | 0.80 | | | ±25 |
| $\eta_{H,electricity}$ [-] | | | | 3.25 | | | ±23 |

In brief, the normal distributions of pre-renovation and post-renovation energy needs ($Q_H^{pre}$ and $Q_H^{post}$, respectively) have been computed through the annual Heating Degree-Days (HDD) method, considering variable HDD data from 2000 to 2016 of the region Lombardia extracted from the Eurostat database. The statistical distributions of the investment costs are assumed normal and based on producers pricing lists. The wall is assumed clean and ready for the internal insulation installation. Uniform distributions have been associated to both the overall building heating efficiency $\eta_H$ and energy tariffs $EnT$ [20].

Finally, concerning the last group of inputs, impacting on the discount factor and the price developments rates of eq. (1), for each macro-economic scenario, the nominal interest rate (*INT*), the inflation rate (*INF*) and the rate of *GDP*, expressed in real terms, have been forecasted (see [20] and [24] for further details).

## 3 Results

**Fig. 1**a and b show the Cumulative Density Function (CDF) of Global Costs (*GC*) and of Payback Periods (*PP*) of the five insulation systems related to: regular growth macroeconomic scenario; natural gas scenario; a service life equal to 30 years. As can be seen, from a merely economic point of view, under these conditions, the *EPS* insulation system is the best performing solution, followed by the *RW* one, while the *CaSi* option is the worst. Concerning the *GC*s, median values for *EPS* and *RW* options are about 107 and 121 €/m², respectively (**Fig. 1**a). *CaSi* option, instead, is characterized by the highest *GC* mean value, i.e. about 277 €/m². *AAC* and *Cork* options have intermediate median values, equal to 152 and 164 €/m², respectively. Concerning the *PP*s, as expected, a similar ranking is obtained (**Fig. 1**b). The lowest *PP* median value is obtained by *EPS* (about 5 years) followed by *RW* (about 7 years). The highest value is reached by *CaSi* (about 23 years), while intermediate values are obtained for *AAC* (about 10 years) and *Cork* (about 11 years) solutions.

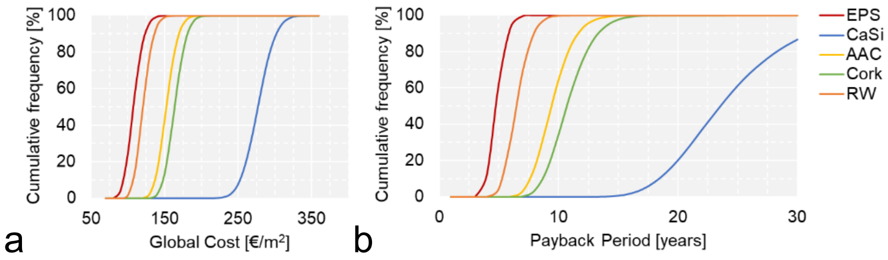


**Fig. 1.** CDF of the Global Cost (a) and Payback Period (b) for the different insulation systems, assuming natural gas as the building energy source and regular growth macroeconomic scenario (insulation systems service life = 30 years, calculation period = 30 years).

Since running costs, such as maintenance and energy costs, are almost the same for all the insulation solutions (the first assumed equal to 0 for all the cases, and the second almost the same due to the similar U-values), the differences between the insulation options obtained in this comparison can be mainly attributed to the different initial investment costs (*CI*s) (see **Table 2**).

In order to evaluate the robustness of the results, and then support designers in the selection of the best performing solution (from a merely economic point of view) under several conditions, **Fig. 2**a compares the *GC*s obtained under different assessment scenarios (different energy sources and macro-economic scenarios). Despite all 40 cases show considerable *GC*s uncertainty, the ranking of the solutions previously obtained is still confirmed for all the economic and energy source scenarios. However, some considerations on the impact of the scenarios on the *GC* results can be highlighted.

Concerning energy sources, electricity scenario entails lower costs than natural gas. This is due to the high equipment efficiency, together with the lower electricity tariffs.

Concerning the macroeconomic scenarios, Regular Growth and Intense Growth give rise to similar *GC* values. Highest and lowest *GC*s are instead obtained in the deflation and stagflation scenarios, respectively. In fact, in the stagflation scenario, lower running costs are obtained due to price development rates lower than 1, and a discount factor higher than that of all other macro-economic scenarios (due to the high inflation rate). In contrast, in the deflation scenario, inflation is the lowest of all scenarios, while discount rates and escalation factors are the highest. This generates higher running costs. This can be clearly gathered from the analysis of the energy costs share on the global costs (**Fig. 2**b). However, the electricity energy source seems to entail lower variations in terms of *GC*s between economic scenarios, than those obtained in the gas energy scenario.

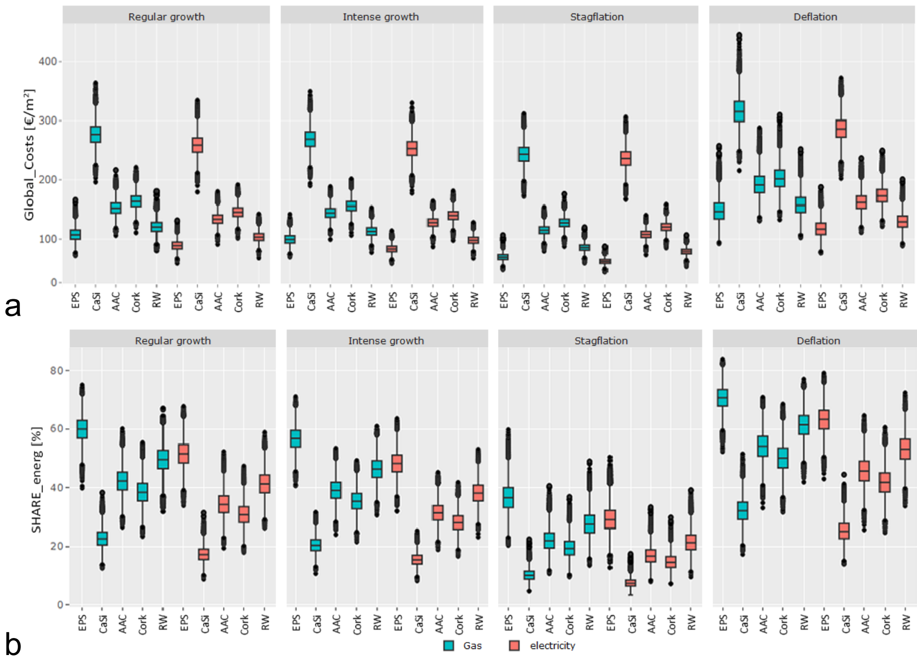


**Fig. 2.** Box-whiskers plots of the Global Cost (*a*) and cost share of the energy cost (*b*) for each insulation system under different economic scenario and by considering different energy sources (insulation systems service life = 30 years, calculation period = 30 years).

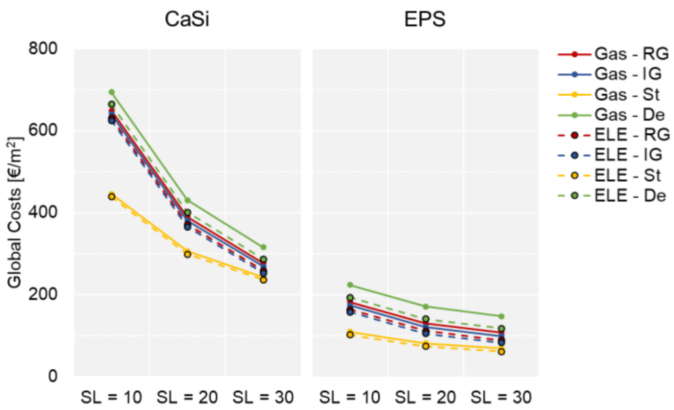


**Fig. 3.** Mean values of GCs for "*CaSi*" and "*EPS*" design option under different economic and energy scenarios by considering different *SL* values.

Finally, according to the different "replacement" scenarios, the impact of different Service Life values (SL) on the *GC*s is evaluated. For the sake of brevity, in **Fig. 3** the mean values obtained for different SLs and related to the best and worst performing solutions, i.e. *EPS* and *CaSi*, have been reported.

As expected, the lower the SL the higher the GC due to the additional replacement costs. A lower impact on global cost due to SL variation is observed in the stagflation scenario. This is mainly due to the lower price development rates and the higher discount factor that are both applied to the additional replacement costs. A nonlinear trend is also observed going from SL=30 to SL=10. In fact, for all the economic and energy scenarios, a higher cost increment is obtained going from SL=20 to SL=10 than that obtained going from SL=30 to SL=10. This is mainly due to the different residual value (Val) of the design option at the end of the CP, which is about 50% of the CI in the SL=20 case and about 0 for the other two "replacement" scenarios.

## 4 Discussion

In the example shown, from a merely economic point of view, EPS insulation solution ranks firsts, followed by Rockwool, AAC, Cork and Calcium Silicate, in all assessment scenarios. This is justified by the lower purchase and installation costs for this system, considering similar running costs for all insulation solutions during the calculation period, due to the same assumed energy and durability performance. This assumption constitutes a limitation of the specific case study, which does not take into account possible factors that could affect the life cycle costs of the renovation measure, such as the systems' repair needs and their real in-situ hygrothermal performance, depending on possible moisture-related problems.

Indeed, the stochastic LCC could be coupled to a probabilistic risk assessment of hygrothermal performance, in order to fully capture the risk associated to the investment, effectively supporting decision making. This means that outputs related to hygrothermal simulations and risk damage assessments (i.e. the probability distribution of the wall heat transmission losses, of the insulation system service life and of maintenance frequency) can be used in the stochastic LCC in order to provide more outstanding and substantial results. Taking into account these factors could even overturn the ranking among the insulation systems obtained in the specific case study, in favor of more expensive solutions, but safer from a hygrothermal point of view. Future applications of the stochastic LCC are foreseen in this direction.

## 5 Conclusion

This paper presented a probabilistic life-cycle costing assessment of five internal insulations solutions for historic buildings renovation in Italy, based on Monte-Carlo simulations and a stochastic characterization of the macro-economic scenario. During a calculation period of 30 years, the following costs items have been taken into account: the investment costs, the energy costs, the replacement costs; while maintenance costs were disregarded. The assessment was performed in 2 alternative building energy scenarios (gas, electricity), 4 alternative macro-economic scenarios and 3 replacement scenarios (considering insulation systems service life alternatively equal to 10, 20, 30 years).

Results (global costs and payback periods) for the design options are expressed as probability distributions, rather than a single point estimate, and their robustness assessed in several scenarios. Even if in the specific case study some simplifications have been applied for input data characterization, the stochastic LCC method constitutes an advance over traditional methods, based on deterministic calculations and static economic scenarios.

When coupled to detailed hygrothermal simulations and risk damage assessments to refine related input data, the method constitutes an even more useful decision-making support tool in the field of building renovation.

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