A probabilistic tool for evaluating the effectiveness of financial measures to support the energy improvements of existing buildings

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Abstract

LCC procedures are commonly used in building retrofit interventions for the evaluation of the costs and benefits of different solutions. LCC methods are also commonly applied to energy retrofit interventions according to UNI-EN 15459. However, these procedures can give significantly different results in relation to the methods used to define the economic and technical parameters used in the calculation. Several authors have highlighted how the uncertainties related to the quantification of the costs of initial investment and maintenance, the economic scenarios (inflation and interest rates), the costs of energy and labor and the “service life” of the components strongly influence the results and the assumption of different data sets can result in significantly different results. Several authors pointed out that it is necessary, prior to these procedures, to perform sensitivity analyzes, useful for understanding if and how each of these parameters can influence the results, which leads to the need to use probabilistic methods. The study reported here analyses the influence that different assumptions about the service life of building components have on the economic benefits brought by interventions of energy requalification. Specifically, through a specially developed probabilistic procedure, the influence on the global costs of different assumptions about the probability distributions and the specific parameters characterizing each of them related to the service life of components useful to realize the thermal insulation was evaluated. the envelope of existing buildings. In particular, four different probability distributions (normal, uniform, left triangular, right triangular), different values of the median have been taken into consideration for the same distribution amplitude and the global costs and the return time values have been evaluated. investment considering different alternative economic scenarios for inflation and interest rate.

1. Introduction

Buildings are responsible for the largest share of European final energy consumption (about 40%) and they represent the greatest potential to save energy, as 75% of buildings standing in the EU were built during periods with no, or minimal, energy-related building codes. However, aggregated projections of EU-27 for 2020¹ show that, even if the additional measures currently planned by Member States are adopted and fully implemented, greenhouse gas emissions will reach a level approximately 2% higher than in 2005, and only 6% below their 1990 level. This is a significantly higher level than the unilateral commitment of a 20% reduction, compared to 1990 levels, decided by the European Council in December 2008. Without a public intervention and the strong commitment of all actors, these
ambitious objectives cannot be reached. EU commission has increasingly favored economic or market-based instruments ("MBI"), such as indirect taxation and targeted subsidies, for such policy purposes.

Direct fiscal incentives are, or have been, used in a number of EU Member States as tool to improve energy reduction, specially of existing buildings. Effectiveness of direct fiscal incentives have been analyzed by several authors\(^1\)\(^-\)\(^3\), showing the necessity to improve costs and benefits tools to evaluate in a systematic way impacts and efforts for each policy instrument.

Life Cycle Costing (LCC) calculations, based on EN 15459:2007\(^4\), have been implemented in Europe at national level in compliance with the Directive 2010/31/EU. However, LCC procedures based on EN 15459 have some limitations, mainly related to a deterministic approach in the cost items selection and the quantification and forecast of the macroeconomic variables\(^5\). It is necessary instead taking into account the uncertainties\(^6\)-\(^14\) associated with the initial and periodic costs related to the energy efficiency measures under future economic scenarios and to assess in a probabilistic way the benefits deriving from the adoption of direct tax incentives policies.

The present paper proposes a LCC probabilistic methodology and a related software tool able to evaluate cost and benefits of direct fiscal measures on building energy efficiency measures (EEM), considering alternative macro-economic scenarios. The methodology is based on an uncertainty analysis via Monte Carlo (MC) approach. After a preliminary description of the methodological approach, the application is illustrated through a case study, comparing the impact of specific direct fiscal measures under different macro-economic scenarios.

2. Methodological approach and calculation tool

The LCC tool is based on the Global Cost method described in the European Standard EN 15459\(^4\) with some modifications to take into account, in probabilistic terms, the initial and periodical costs (investments, replacements, energy costs) and possible alternative evolutions of the macro-economic scenario (how the scenario affects the inflation rate, the discount rate and the price escalation rate). The Global Costs \(C_g(cp)\) at the end of the calculation period (cp), referred to the starting year, are calculated through the following equation:

\[
C_{g,cp} = \sum_{j=1}^{N} \left\{ C_{Ij} + \sum_{t=1}^{CP} \left[ (CM_{j,t} \times R_{disc} \times R_t) + (CE_{j,t} \times R_{disc} \times R_t) \right] + CR_{j,i_j} - Val_{f,j,cp} \right\} \tag{1}
\]

Where: \(C_I\) are the initial investment costs of the EEM \(j\); \(CM_{(i)}\) are the annual maintenance costs of the EEM \(j\); \(CE_j\) is the annual energy cost due to the EEM \(j\); \(R_{disc(i)}\) is the discount rate; \(R_{(i)}\) is the prices escalation rate; \(CR_{j}\) are the replacement costs with a frequency depending on the service life \(SL_{(j)}\) of the EEM concerned; \(Val_f\) is the residual value of the EEM at the end of the calculation period.

The discount rate \(R_{disc(i)}\) depends on the inflation rate \(\pi_{(i)}\) and interest rate \(i_{(i)}\). Since a dynamic calculation according to EN 15459\(^4\) is taken into account, we consider annual variations of the discount rate as well as annual variations of the rate of development of prices for any of the costs considered in the annual costs (i.e. energy costs, periodic or replacement costs, maintenance costs).

The Global Cost assessment of the energy efficiency measures proposed in this work includes uncertainty propagation via Monte Carlo (MC) methods. While a deterministic LCC analysis approach requires input variables that are fixed in their “deterministic” value, in Monte Carlo approach variables are modelled using a Probability Density Function (PDF) and the quantification of the uncertainty of the outputs is a result of possible variance of the input parameters. MC method consists in randomly selecting input variables (or using sampling schemes) and inserting them into the output-equation a proper number of times, depending on the envisaged accuracy level, to predict the corresponding output distributions.

In order to introduce a MC based approach to Life Cycle Costing, we quantified the PDFs of the model’s input parameters to lead the Monte Carlo simulation. Model input included in the assessment are listed in Table 1.
The calculation of the Global Costs is performed under three alternative macro-economic scenarios: Regular Growth (RG), Intense Growth (IG) and Deflation (DE). For each scenario, the economic variables necessary to carry out the LCC calculation have been forecasted over the calculation period of the renovation project. These variables are the nominal interest rate ($i$), the inflation rate ($\pi$) and the rate of growth of the GDP expressed in real terms ($g$). From historical data, multivariate statistical distributions for these scenarios are estimated using the VAR methodology. Consistently with the simulation-based LCC calculation procedure, a MC approach has been used to generate an array of alternative prediction of the variables for each scenario. Thus, projections are generated as draws from appropriate probability distributions. The MC forecast approach and the multi-scenario approach have been used to address the uncertainty inherent in the behaviour of economic variables.

**Table 1. LCC input parameters included in the probabilistic assessment**

| LCC Stage               | LCC Parameter description                                      |
|-------------------------|----------------------------------------------------------------|
| Financial data          | Duration of the calculation Duration of the calculation [years]|
|                         | Financial rates Inflation rate [%] Market interest rate [%]     |
|                         | Rate of development of prices Rate of development of prices [%]|
| System characteristics  | Component Investment cost Design option investment cost [€]    |
|                         | Periodic costs for replacements Design option Service Life [years]|
|                         | Running Costs Design option replacement costs [€]               |
|                         | Design option annual Maintenance cost [€]                       |
| Energy Costs            | Energy consumption Building overall efficiency for heating [-]  |
|                         | Energy Costs Energy source national tariff [€/kWh/y]            |

While the RG scenario represents the dynamics of an economic system with a balanced growth path, i.e., with moderate growth in inflation and in GDP and moderate nominal interest rate, the IG and DE scenarios account for more extreme cases in which relationships between economic variables deviate remarkably from the RG case.

As expected, the RG scenario presents a more balanced evolution of the economic variables with respect to the other two scenarios. This scenario is characterized by a real GDP growth around the 2.5% (sd 1.6%) and an inflation rate around the 2.2% (sd 0.9%). Interest rate, in nominal terms, is around the 5% (sd 1.5%).

The IG scenario is characterized by a more robust growth with an annual average rate of real GDP growth over the 3.3% (sd 1.2%). Inflation rate (mean 2.6%; sd 0.6%) and nominal interest rate (mean 6%; sd 0.7%) are both higher than that in the RG scenario.

The DE scenario is instead characterized by a near-zero annual inflation rate. This is the result of many periods of negative annual inflation rates. In such scenario, interest rate and the growth of the economy are expected to be low. Consistently, the average nominal interest rate is around the 1.9% (sd 1.5%) and the average annual real GDP growth is around 1.3% (1.6%).

As a consequence of the procedure, the resulting Global Costs in the probabilistic analysis is to be evaluated based on its probability distribution. Since the quality of the outcome (the PDF of Global Cost) is dependent on the number of simulations carried out and the sampling scheme used, in this
work, we use Sobol’s sequences as quasi-random sampling technique, in order to generate samples as uniformly as possible.

Data fitting for the input uncertainty characterization, sample generation, uncertainty propagation, and sensitivity analysis are performed through a developed web tool based on the data analysis software “R”, a free software environment for statistical computing and related Shiny web libraries.

3. Application to a case study: comparison of direct fiscal measures

3.1 Case study description

In order to show the potential of the methodology and tool, we evaluate the effectiveness of the financial measures in use in Italy to support the energy improvement of single family houses built during the first part of last century. A large part of the Italian building stock is characterized by the presence of single-family houses of beginning XX Century Figure 1. They are typically two floor masonry buildings of about 60-90 m$^2$/floor, with uninsulated brick masonries of different thickness - about 20-35 cm (U value = 1.5-2.3 W/m2K) - wooden slabs and roofs (U=1.2-1.5 W/m2K) with clay tiles, single glazing windows with timber frames (U=5-6 W/m2K), combined heating and DHW with traditional gas non-condensing boiler. The typical whole energy consumption could range from 110 to 170 kWh/m$^2$ depending on the Italian climate zone, on the geometry and on specific constructive features. Actually in Italy about 7 millions of buildings with these characteristics are in use, with at least 200-250 millions of m$^2$ of uninsulated external wall.

![Figure 1. A typical Italian single-family house of beginning XX Century. (a) Plans; (b) View of the north facade.](image)

Energy consumption of this building typology is largely due to the poor performance of the exterior wall. Thus, a typical energy retrofit measure is the internal insulation of the exterior wall, in order to preserve the architectonic features of the façade, considering that these buildings are often locally listed-buildings. This energy measure may benefit of a specific contribute from the Italian government in terms of tax deduction. The percentage of the deduction varied over the time from 36% to 65% and is actually equal to 50% of the initial cost.

To evaluate the effectiveness, from a user perspective, of the financial measures adopted by the Italian Government in a life cycle perspective, we defined a set of data able to describe the energy performance of this “building class” after and before an internal insulation intervention (10 cm EPS board).

The LCC assessment requires input data on operational energy use before and after the renovation measure in order to take into account the “use phase” (energy costs) and determine the costs savings. The energy cost (CE) is the annual cost for the delivered energy, including national taxes. It is obtained multiplying the annual energy consumption by the tariff (EnT) for the energy carrier.
The delivered energy depends on the energy need (Q) and the building global efficiency for heating (ETAh). As the LCC is performed considering only the envelope intervention, the operational energy use is considered due to the only heat transmission losses through the wall. Heat losses through the wall were calculated using a HDD (annual heating degree-days) method. HDD data were extracted from Eurostat database for Italy for years from 2000 to 2016, considering their variability during time and space. For the original wall thermal resistance, normal distributions are implemented in the software tool, based on the variable thickness range. Thermal resistance of the insulation system was considered as deterministic. PDFs of initial and maintenance costs and environmental impact of the proposed intervention were estimated using Italian market data. Table 2 reports the LCC data inputs distributions.

Table 2. Class data and energy source data. Par1 and Par2 characterise the distributions: they are respectively the mean and standard deviation for the normal distribution and the minimum and maximum values for the uniform distribution.

| Distribution type | Par1 | Par2 | Unit |
|-------------------|------|------|------|
| Qh pre            | Normal | 100.63 | 6.57 | kWh/m² |
| Qh post           | Normal | 14.12 | 2.35 | kWh/m² |
| CI                | Normal | 40.42 | 5.59 | €/m² |
| CM                | Normal | 0.88  | 0.12 | €/m² |
| SL                | Normal | 30.00 | 2.98 | Years |
| Gas EnT           | Uniform | 0.065 | 0.085 | € |
| Gas ETAh          | Uniform | 0.6 | 1 | - |
| Ele EnT           | Uniform | 0.1584 | 0.2143 | € |
| Ele ETAh          | Uniform | 2.5 | 4 | - |
| Oil EnT           | Uniform | 0.115 | 0.1354 | € |
| Oil ETAh          | Uniform | 0.4 | 0.8 | - |

Three different heating equipment and related energy sources (gas, oil, electricity) were selected to evaluate the influence of the overall efficiency of alternative equipment (gas boilers, oil furnaces, electric heat pumps). Three different economic scenarios were considered, including alternative trends of inflation rates, discount rates, prices escalation rates. Finally, three Tax deduction measures were considered (36-50-65%).

3.2 Impact of direct fiscal measures on global cost

Figure 2 and 3 show the box-plots of the expected net global cost (subtracted by the tax deduction) for each wall sqm, respectively during 30 and 10 years. Each graph reports the results obtained in the different economic scenarios (RE, IG, DE) and with the alternative energy sources, identified by colors. These graphs allow to identify the uncertainty ranges and the median values of the economic indicators for the insulation systems considered. As shown, these results are associated with considerable uncertainty, if we consider that the outcome is included within the ranges of the blue box plots only with a 50% probability. What in general emerges in all economic scenarios and time periods is that the wall renovation coupled to the electricity energy scenario is the one able to guarantee minor Global Costs, followed by the natural gas scenario.

Comparing the global costs median values in a “regular growth” economic scenario and gas energy scenario (cases 1 to 4), results show that, from the user perspective, as expected, the increase of the tax deduction level has a positive impact on the global costs. For these cases, 30-years net global costs range, as mean value, from about 122 €/m² (no tax deduction) to 112 €/m² (36%) to 108 €/m² (50% tax deduction) to 104 €/m² (65% tax deduction). The standard deviation for all these cases is about 13 €/m².
The different macro-economic scenarios affect the results, by increasing the Global Cost on average by 12% (deflation scenario) or decreasing it by 5% (intense-growth scenario).

**Figure 2.** Boxplot of cases studies characterized by a calculation period of 30 years

**Figure 3.** Boxplot of cases studies characterized by a calculation period of 10 years
The PDFs of the cases with and without deductions (from 1 to 4) are reported in Figure 4. They are almost overlapped, showing that tax deduction are always positive for the user, but if results variances due to data input uncertainties are taken into account, deduction policies may produce few differences on the results.

Different energy sources, and the related tariffs and energy efficiency, have the effect of increasing the difference between the cases with and without deduction fees. Figure 5 shows the CDFs of the cases characterized by 65% tax fee deduction with different energy sources. In case of electricity as energy source, deduction allows to cover more than 100% of the investment cost in all economic scenarios. The median values of global costs range for these cases from about 104 €/m² (gas) to 47 €/m² (electricity) to 127 €/m² (oil). This depends on the low electricity tariffs in Italy and the high equipment efficiency set as data input.

![Figure 4. Global Costs PDFs for cases 1 (no deduction), 2 (36%), 3 (50%), 4 (65%).](image1)

![Figure 5. Global Costs CDFs for cases 4 (gas), 8 (electricity), 12 (oil) - “normal growth” scenario](image2)

4. Conclusions
This work presents the development and the application of a probabilistic LCC method to a case study of historic building retrofitting through internal insulation. Through a Monte-Carlo based LCC methodology for uncertainty analysis, this paper particularly focuses on the impact of fiscal measures. We compared under different economic scenario the economic impact of tax deduction actions actually in use in Italy, but potentially valuable in other UE countries. Results demonstrate the great potential of probabilistic assessment methodologies in providing more realistic information about results uncertainties. Applying the developed methodology, we obtained more realistic information about the opportunity to introduce very high tax deduction fees as in Italy. Results show that high deduction fees have a little impact on the increase of the probability to spend less money in the LCC, in a user perspective and that is better to maintain for longer period lower deduction fees, in a policy maker perspective. The developed methodology comprised the characterization of several UE potential economic scenarios (regular growth, inflation, deflation, stagflation), hence it is applicable to any UE country to evaluate alternative fiscal measures.

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References

[1] Katri Kosonen, G. N. Taxation papers. The role of fiscal instruments in environmental policy. (2009).

[2] Keay, M. & Hammes, K. Fiscal policy for decarbonisation of energy in Europe. (2017).

[3] Lindkvist, C., Karlsson, A., Sørnes, K. & Wyckmans, A. Barriers and Challenges in nZEB Projects in Sweden and Norway. Energy Procedia 58, 199–206 (2014).

[4] EN 15459:2007 Energy performance of buildings - Economic evaluation procedure for energy systems in buildings.

[5] 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. Int. J. Life Cycle Assess. 1–16 (2016). doi:10.1007/s11367-016-1154-1

[6] Rahman, S. & Vanier, D. J. Life cycle cost analysis as a decision support tool for managing municipal infrastructure. in CIB 2004 Triennial Congress 1–12 (2004).

[7] Pittenger, D., Gransberg, D., Zaman, M. & Riemer, C. Stochastic Life-Cycle Cost Analysis for Pavement Preservation Treatments. Transp. Res. Rec. J. Transp. Res. Board 2292, 45–51 (2012).

[8] Wang, N., Chang, Y.-C. & El-Sheikh, A. Monte Carlo simulation approach to life cycle cost management. Struct. Infrastruct. Eng. 8, 739–746 (2012).

[9] Das, P., Van Gelder, L., Janssen, H. & Roels, S. Designing uncertain optimization schemes for the economic assessment of stock energy-efficiency measures. J. Build. Perform. Simul. 1493, 1–14 (2015).

[10] Goh, Y. M., Newnes, L. B., Mileham, A. R., McMahon, C. A. & Saravi, M. E. Uncertainty in through-life costing-review and perspectives. IEEE Trans. Eng. Manag. 57, 689–701 (2010).

[11] Menassa, C. C. Evaluating sustainable retrofits in existing buildings under uncertainty. 43, 3576–3583 (2011).

[12] Sesana, M. M. & Salvalai, G. Overview on life cycle methodologies and economic feasibility for nZEBs. Build. Environ. 67, 211–216 (2013).

[13] Gluch, P. & Baumann, H. The life cycle costing (LCC) approach: a conceptual discussion of its usefulness for environmental decision-making. Build. Environ. 39, 571–580 (2004).

[14] Burhenne, S., Tsvetkova, O., Jacob, D., Henze, G. P. & Wagner, A. Uncertainty quantification for combined building performance and cost-benefit analyses. Build. Environ. 62, 143–154 (2013).

[15] TABULA Project. Typology Approach for Building Stock Energy Assessment. 16 (2012).