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Decision Support for existing buildings: an LCC-based proposal for facade retrofitting technological choices

Decision Support for existing buildings: an LCC-based proposal for facade retrofitting technological choices

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Abstract. The goal of this paper is to present a usable and effective tool to evaluate residential façade retrofitting solutions in early stages of design, keeping into account envelope features and installation issues. Decarbonisation goals set for 2050 impose existing building stock renovation and energy retrofit. Several drivers are available in EU Countries to trigger these operations. Nonetheless, the renovation rate in EU Member States remains low: barriers to building retrofit are identified, and a main issue in this sense is the lack of use of Decision Support Systems. DSS exist but are often neglected by building designers or owners, due to different reasons. Existing methodologies do not take into account the quantity and quality of information available at the various stages of building life cycle; furthermore, they mainly focus on energy related aspects, neglecting technological and installation related factors. This paper aims at providing an LCC-based decision framework to help decision makers in early stages of design to choose the most suitable technology for building façade retrofitting. A Utility Function expressing LCC for residential building renovation is provided, focusing on façades renovation and on installation and morphology related aspects. Information and data flow through the phases is presented and discussed, showing how the proposed method can be adapted to different stages, and testing its robustness through sensitivity and uncertainty analyses. Three main categories of renovation technologies are analysed (ventilated façade, ETICS, and prefabricated solutions). The proposed method is applied to a residential case study building. The adaptability of the tool to different stages of design is discussed, and further potential applications are presented.

1. Introduction

Building retrofit is a crucial aspect and a primary concern in European agenda [1], as a reflection of the relevant role played by existing buildings in terms of energy consumption [2] [3] [4]. European regulations regarding building retrofit in Member States are therefore aiming to an improvement of energy performance of existing building stock [5] [6]. EU goals for 2050 include a reduction of 80% in GHG emissions target, and an increase up to 97% in the use of renewable energy sources [7].

To reach these goals, several efforts have been made, in terms of legislation, best practices application, and research projects carried out.

Deep renovations are in fact fully recognized as a priority, mainly in legislative and tax-related sense. On the other hand, there is currently a need of concrete support to deep renovation, with the use of cost-optimality as a procedure to evaluate alternative scenarios.

Considering calculation and assessments of cost optimal strategies, it is to be noticed that there is no common and uniform approach to performance requirements in the EU. On the other hand, and for this reason, major improvements can be carried out in the sense to guarantee more effective and complete strategies.

Current practices in building retrofit mainly address isolated building components, such as roofs or building services; this strategy shows limits as it does not involve a long-term energy reduction, and often results in expensive solutions [7]. Most of the existing approaches are meant to be used in advanced stages of design, when complete information and data about the building are available. Nonetheless, in many cases, technology related choices are carried out in early stages of design, as they strongly affect following activities and developments [8][9][10]. Retrofit related decisions are mainly carried out based on previous experience, without a proper scientific base that could justify those choices.

2. Decision Support Systems for building retrofit: available approaches

The lack of knowledge, experience and awareness underlined make refurbishment related decisions particularly hard to make[11]. Depending on the actor in charge of these decisions, different criteria could play a more relevant role; building owners could not have enough expertise to evaluate technical related aspects, focusing mainly on economic investment [12]. Several tools, methods and models have been developed to provide help to different actors in this sense. Decision support approach to building retrofit is mainly carried out in terms of evaluation of alternatives, by means of some tools or some guidelines. Some common approaches can be explained as:

- Evaluation of magnitude of the intervention: full retrofit, partial renovation, building services update [13] [14] [15];
- Evaluation of the use of different elements: different building insulation materials (material and size), different windows, and different building services [16] [17] [18] [19].

Those methods are primarily focusing on the retrofit effect in terms of energy savings, therefore the most part of their development is related to energy simulation [8]. The focus is kept on the energy update related to the renovation process. In some cases, such as MCDM (multi-criteria decisions methods), other factors are considered: social sustainability, in terms of users comfort, and in a larger scale in terms of effect on the local community [8] [20] [21]. In general, these approaches include the setting of a goal, and the evaluation of different alternatives in terms of compliance with the goal or the goals set. This evaluation is generally carried out by means of comparison of parameters. In case of cost-optimality, the "cost-optimal" level means the energy performance level which leads to the lowest cost during the estimated economic lifecycle [22] [23] [24]. The cost-benefit ratio of alternative solutions is therefore calculated based on economic parameters. In case of multi-criteria approaches, the quantity of parameters is wider, and includes social, economic, and environmental factors. Some commonly used factors include primary energy, GHG emissions, water consumption, materials used and waste produced (environmental factors); Life Cycle Cost (economic factor); indoor air quality, lighting, thermal and acoustic comfort, process quality (social factors). Besides representing valuable and relevant aspects for building assessment, it is possible to underline a general lack of consideration towards installation-related and technological aspects. However, when considering renovation or retrofit operation, especially in case of building façades, those factors have proven to be crucial for a successful intervention [25]. An integrated approach, that could keep into account, but not limited to, energy related, and cost factors would be useful to properly develop an innovative DSS for existing buildings. A further relevant aspect is related to the investigation of the impact that morphology and technology have on these decisions and in general on the total cost of a building intervention.

The aim of this research work is providing a DSS framework for façade renovations, combining Life Cycle Cost with an evaluation of sensitivity and uncertainty.

3. Methodology and workflow

Morphological and technological factors play a relevant role in the definition of value of a retrofit intervention. It is important to (i) define this value, (ii) find a relation between these factors and cost, and (iii) measure their relevance and impact.

The definition of value is provided in terms of a Utility Function, defined in mathematical terms: the technology related data are made explicit in the function and its sub-functions. The framework is set as calculation sheets, including building and building site data, evaluating cost-related aspects during the whole Life Cycle of the intervention. Life Cycle Cost is chosen as the Utility Function as it provides an effective expression of value of an intervention: economic related factors play a relevant role for many stakeholders involved in the process [26] [27] [28]. The system set is useful to keep track of information and data during the decision related process.

The proposed method allows distinct levels of definition in the calculation: some computation can only be properly developed in specific stages in building lifecycle, as they require a quantity and a quality of information that could be unavailable in pre-design phases, or during feasibility [29]. For this reason, simplification have been carried out in order not to overburden the model. Once the model has been set and tested on case study buildings, sensitivity and uncertainty analysis have been performed to verify its robustness, and to provide relevance and impact of morphological factors.

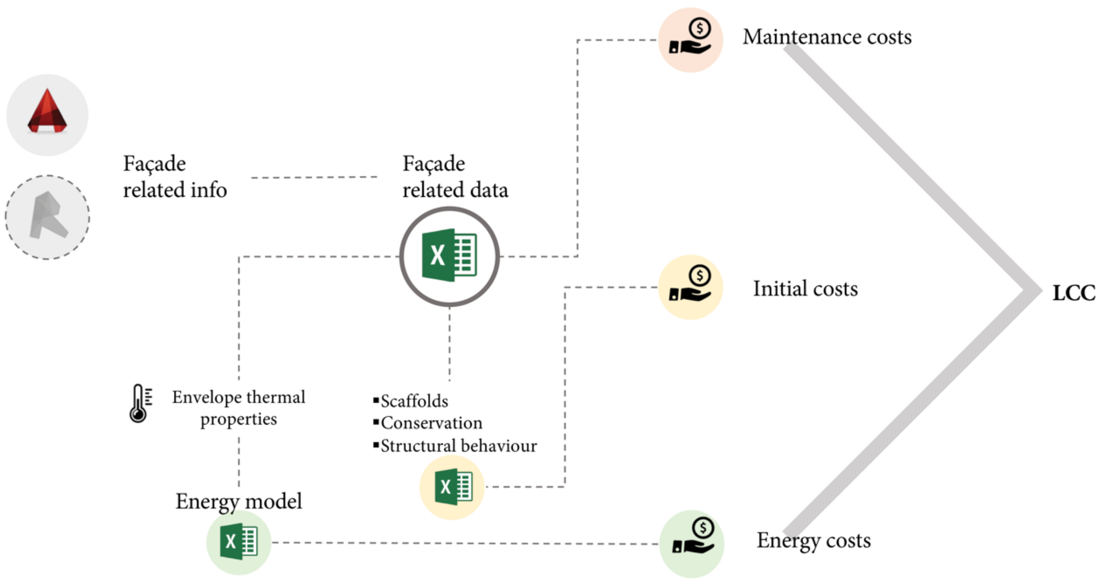

Figure 1. Structure of the proposed model.

The evaluation of the interventions on the façade is based on the proposed model (see figure 1). Information related to the existing building could be retrieved from CAD drawings of the building; few information related to plans are necessary, as visible in following sections of this paper. This information is expressed as data to be manually filled in the proposed data sheet. The building data sheet is linked to two main categories of further sheets: one is related to energy and the other one is related to installation and mechanical properties. The thickness of the insulation layer is automatically calculated to fulfil legal requirements in terms of heat losses. This value is then implemented in the other sheets. Energy evaluation is entirely carried out in an excel sheet that provides heating demand and primary energy demand.

Installation related sheets regard scaffolds, conservation (in terms of degradation of the claddings), and structural behavior. As previously explained, part of these data is used to provide a preliminary evaluation of the compatibility between the proposed solution and the existing building; these data are also useful to evaluate the cost of potential preliminary activities on façades, such as structural reinforcements, and cleanings or removal of degradation. Maintenance related sheets include the maintenance plans for proposed solutions, together with their evaluation in the life cycle of the buildings. The output provided by the model is the Life Cycle Cost of a retrofit intervention on building façades.

Sensitivity analysis related to morphology and technology are then performed, to provide an evaluation of the relevance and the impact of those factors on the cost of the intervention. Uncertainty analysis, based on Monte Carlo simulations, is also provided, to test the reliability of the method and to verify the impact of uncertain factors on the calculation.

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4. Model workflow

The workflow of the model use can be summarized as following:

4.1. Preliminary activity

From the first meeting with the client, it is necessary to collect available documents and information, and to understand the needs of the client in terms of aesthetics, as well as cost and time constraints [30] [31] [32] [33]. Further specification related to particular needs and issues should also be included in this phase.

4.2. Data filling: inputs

4.2.1. Main data sheet. This part of the model is related to façade generic geometric data (façade length, height, area, together with areas of balconies, loggias, windows) and building site related data (building site area, operating space, minimum width).

4.2.2. Preliminary checks and preliminary activities costs. This part provides a preliminary evaluation of feasibility of the three main solutions (ETICS, rain-screen façades, prefabricated panels) in terms of (i) structural feasibility, based on the features of the existing wall and the weight of the proposed solution, (ii) coating compatibility (that could imply an increase in costs related to coating removal), and (iii) building site compatibility, in terms of manoeuvre margins, access to the site and operating space. Preliminary activities include removal and substitution of gutter and sprouts, potential coating removal, degradation removal or structural improvement. This part provides therefore the cost of these activities, based on price lists for public works.

4.2.3. Energy data. This sheet is necessary to calculate the amount of insulation that is required to satisfy legislative requirements, both in terms of thermal transmittance and heat transfer coefficient. The model is set to automatically optimize the thickness, based on the type of insulation wanted, keeping into account legislative requirements in the calculation and choosing the minimum thickness required to satisfy those limits. In the base case, both for ETICS and ventilated facades, EPS insulation for is proposed due to its diffusion and use [34] [35]. It is possible anyway to evaluate different insulation materials, by changing thermal properties in this data sheet.

4.2.4. Construction costs. The construction costs section is thus automatically filled based on data. These costs are evaluated as materials, labour and scaffolding, or machinery depending on the proposed solution, based on thickness of insulation and façade features.

4.2.5. Energy costs (not to be confused with energy data). The first sheet provides an evaluation of energy demand (for heating and cooling), based on a simplified lumped parameter model. This sheet automatically takes relevant data from the main data sheet, in terms of geometry of façade and building, materials and thermal properties. It is possible to change parameters related to building system functioning (such as air change rate, mechanical ventilation and heat recovery schedule) and to internal gains (related to artificial lighting, people occupancy, appliances). This data sheet provides as main outputs the heating energy demand; the heating energy demand is used to calculate the cost related to heating requirements of the building. This number is implemented in an energy system related sheet, that provides the efficiency of the heating system (related to emission, setting, distribution and production efficiency), to obtain the heating consumption of the building. In this same sheet, this quantity is multiplied for the energy cost. Primary energy required is also evaluated in this sheet, as this quantity is necessary as performance indicator of the building.

4.2.6. Maintenance costs This sheet takes relevant data from the main sheet and use them to evaluate the costs of maintenance activities throughout the life of the building. The maintenance activities included in this sheet are only related to the opaque parts of the façade (the one interested in the analyzed interventions). The maintenance plans, based on different strategies (inspections and predictive

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maintenance), are implemented in the sheet and depend on the technological solution proposed; maintenance plans have been set in accordance to guidelines, standards, and literature reviews. Costs derive from price lists.

4.3. Costs actualization
This phase is required to compare cash flows that are incurred at different times during the life cycle of a project; LCC of alternatives must in fact be calculated uniformly in present-value. The chosen discount rate allows to actualize to present value all the recurring costs of the life cycle, that are purchased energy and maintenance interventions. Discount rate depends on inflation and interest rates, evaluated on historical records.

4.4. Outputs – make final decision
All the costs are summed to obtain the Life Cycle Cost of different solutions, providing a comparison of their impact, together with amounts of singular parts. This is the structure of the evaluation model, based on an LCC approach, that is then applied and used to measure the actual impact of variations in the input data. The dual usefulness of this model lies in (i) its capability of providing a comparison of building interventions and (ii) providing a basis for evaluation of morphological relevance in terms of costs.

5. Case study application
The proposed model has been applied on two case study buildings: the application, in terms of inputs and outputs is here presented on the first building, as a reference. The first building is a multi-story and multi-family building located in Cinisello Balsamo, near Milan, and was chosen as it is representative of a wide part of public building stock. Data are provided in a calculation sheet, as presented in the following image, regarding general data about the façade and the building site, window-related data, conditions and conservation of the existing walls, coating and materials used. The provided image regards north façade of the case study building. The model follows the pattern described in the previous section: a preliminary check is performed, and costs are calculated.

BUILDING and FACADE DATA				PRELIMINARY STAGE PRELIMINARY CHECK		
FACADE 1 - N				ETICS	Ventilated façade	Prefabricated panels
1. General	*Façade area [m²]*	313,65				
	Net façade area [m²]		255,29			
	Façade length [m]	25,1				
	Balconies [m²]	0				
	Loggias [n]	2				
	Balconies lines [n]					
	Occupied area [m²]					
	Length/depth [m]					
	Building site area [m²]	0				
2. Windows	*Window area [m²]*	2,16				
	Window number [adm]	21				
	Total area [m²]	58,36				
3. Wall age and conditions	*Wall typology*	e. Concrete blocks (45 holes)				
	Level of knowledge of the wall	LK1 - Limited on site survey and limited on site tests				
	Wall age	Non-historical				
				VERIFIED	*VERIFIED*	*VERIFIED*
	Degradation	g.Sediments	5,4			
		l.Efflorescence	12,3			
		...				
4. Coating and materials	*Thickness of the existing coating [mm]*	10		*VERIFIED*	*VERIFIED*	*VERIFIED*
	Material	a.Concrete				
5. Building site features	*Operating space [m]*	13,1		*VERIFIED*	*VERIFIED*	*VERIFIED*
	Minimum Available width [m]	12		*VERIFIED*	*VERIFIED*	*VERIFIED*
				✔ *0*	✔ *0*	✔ *0*

Figure 2. Building data related to north façade

Based on this data, the model provides the calculation of Life Cycle costs, as presented in the previous section. The results of the calculation are the following:

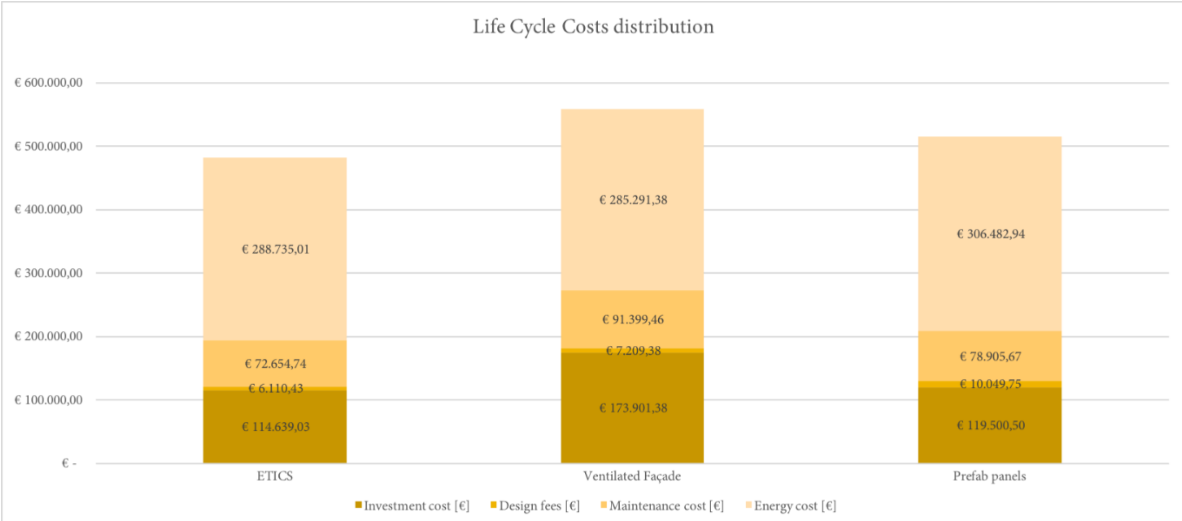

Figure 3. LCC distribution

The calculation has undergone modifications during the development, in order to fit the features of the building, avoiding overburdening of the process. The features of the proposed case study building, as previously stated, represent typical characteristics of residential multi-storey building. The proposed approach is a useful method to calculate Life Cycle Cost of residential buildings,
underlining the relevance of facade features and geometry and providing a robust base for further evaluations related to sensitivity and uncertainty, that will be presented in following chapters. Three retrofit solutions are evaluated, but further potential retrofit strategies can be added following the proposed process. Energy costs represent a major voice in a Life Cycle perspective, and together with maintenance cover the most part of total cost. For this reason, factors related to these aspects are investigated in uncertainty analysis.

6. Sensitivity analyses

The impact of morphology related parameters is tested by means of a sensitivity analysis on the input factors. Sensitivity analysis provides an evaluation of how the uncertainty in the output of a system can be related to uncertainty in its inputs [36]. Several sensitivity analysis methodologies could be used for this purpose [37]. In this case, a One at a time analysis is provided. OAT is a common and known approach that consists in changing one input variable while the others are kept fixed, and to see how this influence the results (outputs) of the model [38]. This operation is carried out on chosen parameters, monitoring the changes in the output. This approach is valuable as it allows to see without ambiguities how the variation in the input is affecting the output.

The usefulness of OAT is also related to the testing of a model: if the model fails at some point, it is possible to relate unambiguously the failure to a single input, and therefore clearly modify or adapt the model. In this sense, sensitivity analysis also provides a test of the effective- ness and robustness of the proposed model. The chosen input parameters to be varied in this case are the following:

- Transparent area (windows);
- Geometry (balconies and loggias);
- Insulation amount.

Geometry and transparency provide an evaluation of the relevance of morphology on LCC of façade retrofitting. Considering the model structure, the sensitivity analysis proposed can be applied to other parameters, depending on the building features of the case study. The setting of the analysis is in fact based on explained approach and does not change in relation to the chosen parameter. Each of the proposed parameters has been analysed singularly to identify possible ambiguities or fails in the model; a general discussion is then provided, considering the mutual relevance of the parameters on the final output of the model. For each parameter, two scenarios are provided in terms of increase or decrease; variations in energy, maintenance, installation, and scaffold costs are provided to better understand the effects of input changes on the final outcomes.

6.1. Transparency: windows

As a reference, sensitivity analysis related to windows is presented. The presence of windows affects multiple aspects of the LCC of the intervention: windows play a crucial role in energy behaviour of the building, and their presence acts on the construction costs. The thermal effect is particularly relevant and should therefore be evaluated accurately, as the increase in number of transparent parts acts both on the improvement of winter behaviour (increase in solar gains), and in increase of losses due to the type of frame considered, as well as increase in thermal bridges. In this case, the sensitivity analysis does not involve a change in the frame features; with this approach the evaluation provided is only related to the presence and geometrical features of the windows and their role in the behaviour of the façade.

Results related to a change in window percentage on façades are evaluated in relation to the base case, that is the present status of the building. Two cases are presented; the first involves an increase in window surface on façade of 20%. The second case involves an increase of 50%. This percentages were chosen in accordance to analysed building morphologies of residential buildings. The increase in window surface has been evaluated as an increase in number of single windows, involving an increase in frame amount of the façade. This choice acts on thermal bridges evaluation, and therefore on energy behaviour of the building.

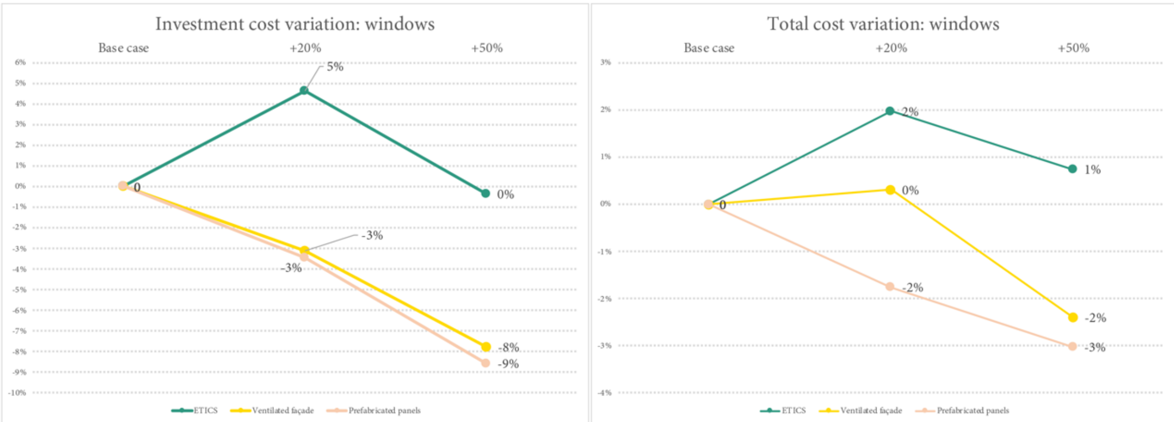

Figure 4. Results of variations in windows on investment and total cost

As previously underlined, energy costs do change for all the proposed solutions. In the case of ETICS, an increase for both case 1 and case 2 is visible in spite of the change in insulation thickness. The slight increase is related to the increase in transparent area, that has poor thermal performance. As explained in previous chapter, the thermal transmittance of existing windows is 5.70 W/m^{2}K. This change is not visible in the case of prefabricated panels, that do have in general worse thermal performance; even in base case, that means not considering changes in the quantity of windows, the heating requirements of retrofit with prefabricated panel are higher than with ETICS and ventilated façades. Considering total cost, windows increase provides an increase in cost that is especially visible for ETICS, when changing a small quantity the total number of windows. If the increase in windows is higher, a decrease in cost is visible, related to both the decrease in opaque area to be retrofitted, and the change in thermal behaviour.

7. Uncertainty evaluation

As stated, Life Cycle Cost is a recognized and robust approach to decision support in building interventions; nonetheless, a deterministic calculation does not provide a complete evaluation of data uncertainty, that can be taken into account using probabilistic methodologies [39]. The application of a probabilistic approach allows a statistical description of phenomena, that can help in supporting decisions, as well as in testing robustness and efficiency of proposed decision support models. Probabilistic approaches are clearly valuable as they keep into account the uncertainty related to certain evaluations [40] [41]. For this reason, the setting of Monte Carlo simulations as part of the proposed approach could help in providing robustness and completeness to the model. A sensitivity analysis on the uncertain factors is also provided, to identify the most relevant among them. Different levels and typologies of uncertainty can be identified in the proposed model; main categories can be divided in economic uncertainty, energy uncertainty and maintenance (or operational uncertainty). The analysis of variations in construction costs has not been carried out but has been set and can be added to model. Macroeconomic factors (such as interest and inflation rate) could strongly influence the output and therefore the effectiveness of the model.

The model has been set in Italian context and is therefore linked to its macroeconomic conditions; nonetheless it could be possible to provide different values for interest and inflation to fit the model to different backgrounds. Interest rate and inflation rate are linked to macroeconomic future trends, and influence the calculation of discount rate, that has been proven to strongly influence the global cost of the intervention [42]. Uncertainty is also related to construction prices and their variation in time and place: in this case, building elements can be evaluated based on available price lists. It has been demonstrated that price lists could vary in up to the 10% depending on the Region or City where the building is set [43].

Considering energy related uncertainty, it is known that buildings consume two to five times more energy than predicted at design stage, and this discrepancy can have a strong effect on the robustness of decision support strategies for retrofit interventions [43]. For these reasons, an evaluation of the uncertainty impacting on the Life Cycle Costs of alternatives building retrofit proposals is provided, helping in increasing the effectiveness and robustness of this approach.

7.1. Monte Carlo simulations

Evaluation of uncertainty has been carried out by means of Monte Carlo simulations performed on underlined uncertainty factors. Monte Carlo simulations help in overcoming issues related to traditional sensitivity analysis, associating probability distribution to each risk factor [42].

The probabilistic approach provided by MC simulations implies the use of variable input data, expressed in a probability distribution function (PDF); the variation of input data has therefore an effect on output data in this sense. Every input parameter subject to uncertainty is represented by a probability distribution function; the parameters representation is randomized for a number of times, providing a quantity of possible outcomes [39]. Uncertainty assessment helps in identifying the significance on uncertain input parameters on the final outputs, and therefore their impact on results, providing additional information on selected parameters and leading to possible simplification of the models. The "what-if" analyses deriving from uncertainty assessment plays a role as decision support.

Monte Carlo methods are developed following these steps:

- Definition of domain of the inputs (shifting from deterministic to probabilistic assessment);
- Generation of randomized inputs in terms of probability over the domain;
- Deterministic computation of the inputs;
- Aggregation of the results.

The output of MCC is a probabilistic distribution that represents the proper phenomenon. A statistical description is also provided, in terms of mean value and standard deviation.

Uncertainty has been evaluated by means of a number of 4000 simulations, performed with the simultaneous randomization of the presented input parameters, following PDF in table 1.

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Table 1. Chosen PDF for uncertain factors.

Input	Statistical distribution
Maintenance frequency	Gaussian distribution
Inflation rate	Gaussian distribution
Interest rate	Triangular distribution
Energy need	Triangular distribution
Energy price	Logarithmic distribution

Based on this data, the resulting effect of uncertainty on Life Cycle Costs can be retrieved from the following graph, showing the probability distribution. As a reference, probability distribution of LCC in the case of ETCS is here provided.

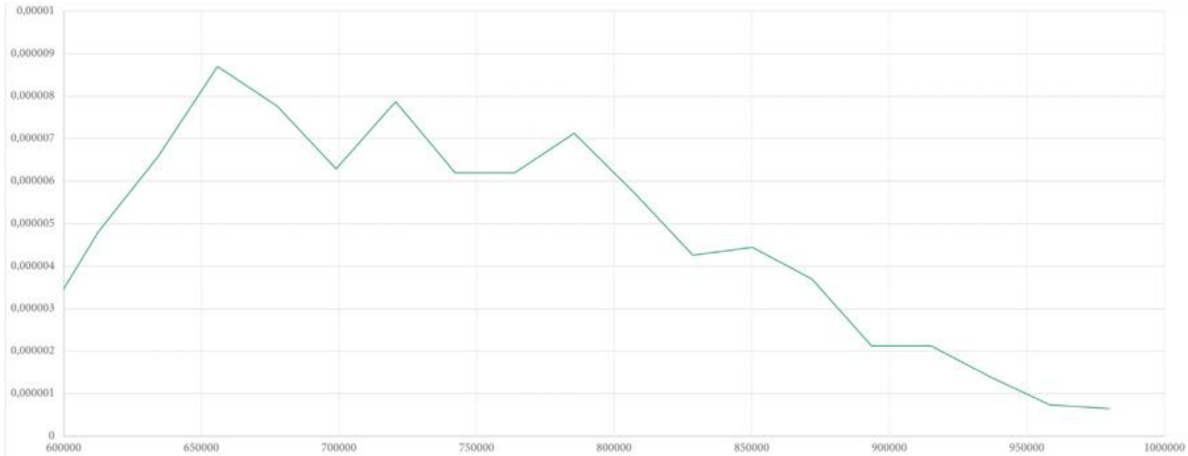

Figure 5. Probability distribution ETICS; x-axis shows the LCC, y-axis the probability density.

Probabilistic LCC expected value is higher than its deterministic value; this effect is due to the statistic uncertainty related to chosen input parameters, that prove therefore to play a crucial role in the calculation of costs over the Life Cycle of the building. This is due to a conservative approach in the choice of PDF, that resulted in an over-estimation of uncertainty when causing an increase in costs and in an under-estimation when generating savings. This approach reflects risk propension of the Client guiding the analysis. It is hard to provide solid scenarios, especially considering economic factors such as inflation, interest and prices; discount rate and energy prices play in fact a strongly more relevant role over variations in LCC rather than other aspects. Uncertainty quantification is therefore a valuable approach to consider those aspects and should be implemented in decision-making operations regarding building retrofit activities.

8. Conclusions

The proposed model and approach have two categories of outcomes: case specific and general outcomes, related to the model and to the workflow provided. This model allows in fact the designer to evaluate different technological solutions on a Life Cycle Cost basis, including investment and operational costs and can be used both for single buildings and for building assets. Furthermore, this approach provides an evaluation of the effects of morphology on selected options, allowing the decision-maker to compare different solutions keeping trace of their effects.

The use of a structured process following building retrofit interventions projects, that allows a higher level of transparency, facilitates the management of information and data, and makes it possible to compare different solutions on a scientific and mathematical basis, including both qualitative and quantitative factors. The proposed approach is repeatable and therefore applicable to other case study

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buildings with different morphologies and different dimensions. This could result in positive outcomes in terms of decision support: a scientific model allows to keep trace of decisions in the process, increasing the use of knowledge-based approaches rather than experience-based ones.

The comparison of different case study can help in defining recurrent building models, with a morphology that is representative of similar buildings. These models can be used as case-base in early stages of design of retrofit interventions, to provide a preliminary cost evaluation of different alternatives. understanding relevance and impact of morphology related aspects can also help in defining digital models requirements, providing a balance between usability and speed of creation of the models, and robustness and reliability. Modeling complete morphologies of building could result in a high computational effort, especially in previous stages of design when the amount of data and information related to the building can be limited or inadequate.

The methodological approach applied in this research is repeatable, flexible and implementable. The repeatability is due to the fact that the model is not case-specific but could be applied to other residential buildings with different features and different morphologies. The flexibility is related to the chosen workflow: input information and data can in fact be varied, depending on the case, and potentially some inputs can be removed. As visible in the previous chap- ter, some minor changes are related to some factors: for this reason, it could be possible to remove non-relevant inputs and avoid overburdening of the approach. This aspect is also related to the stage of the building process in which the model is used and the available information.

The implementability is related to the possibility of increasing the number of inputs or refining the type of data used in the model depending on the availability of information (and the process stage).

The proposed workflow also facilitates transparency through the process: information and data can be traced trough the model, that acts as a grey box. The shift from input data to outcomes is clearly described and accessible in the model and can be modified at any time depending on special requirements related to the case, or different goals.

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