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The Stochastic Annuity Method for Supporting Maintenance Costs Planning and Durability in the Construction Sector: A Simulation on a Building Component

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Abstract: Service life estimate is crucial for evaluating the economic and environmental sustainability of projects, by means—adopting a life cycle perspective—of the Life Cycle Cost Analysis (LCCA). Service life, in turn, is strictly correlated to maintenance investment and planning activities, in view of building/building component/system/infrastructure products' durability requirements, and in line with the environmental-energy policies, transposed into EU guidelines and regulations. Focusing on the use-maintenance-adaptation stage in the constructions' life cycle, the aim of this work is to propose a methodology for supporting the "optimal maintenance planning" in function of life cycle costs, assuming the presence of financial constraints. A first research step is proposed for testing the economic sustainability of different project options, at the component scale, which imply different cost items and different maintenance-replacement interventions over time. The methodology is based on the Annuity Method, or Equivalent Annual Cost approach, as defined by the norm EN 15459-1:2017. The method, poorly explored in the literature, is proposed here as an alternative to the Global Cost approach (illustrated in the norm as well). Due to the presence of uncertainty correlated to deterioration processes and market variability, the stochastic Annuity Method is modeled by introducing flexibility in input data. Thus, with the support of Probability Analysis and the Monte Carlo Method (MCM), the stochastic LCCA, solved through the stochastic Equivalent Annual Cost, is used for the economic assessment of different maintenance scenarios. Two different components of an office building project (a timber and an aluminum frame), are assumed as a case for the simulation. The methodology intends to support decisions not only in the design phases, but also in the post-construction ones. Furthermore, it opens to potential applications in reinforced concrete infrastructures' stock, which is approaching, as a considerable portion of the building stock, its end-of-life stage.

Keywords: economic-environmental sustainability; stochastic life cycle cost analysis; risk and uncertainty; optimal maintenance planning; durability; stochastic annuity method; equivalent annual cost; global cost

1. Introduction

In Italy, the residential stock is rather old, in line with the main part of European countries. In general, in Europe, almost half of the residential stock was produced before 1960 and is approaching the end-of-life stage, or have reached the end of its service life [1]. Analogously, a large number of infrastructures built in reinforced concrete have similar conditions. Thus, the issue of intervention for sustainable buildings and, in general, for infrastructure efficiency, at the time being is at the center of the international debate. One of the emerging aspects is the urgent necessity to promote strategic

management of buildings and constructions, firstly through the planning of maintenance activities. Unfortunately, at the same time, maintenance culture is rather weak, both for the strongest market segments, and for the weaker ones. For these last, the service quality is below the acceptable level, including buildings characterized by low energy performance and weak state of conservation.

In a context of growing importance of strategic maintenance activities, life expectancy of buildings/building components/systems, or infrastructures, emerges as a relevant aspect in investment choices. In turn, durability and life expectancy—at the different scales—depend on the different maintenance scenarios and on the (eventual) application of strategic facility management activities [2]. According to this perspective, the "optimal maintenance planning" implies a multidisciplinary approach to the analysis, assuming that the preferable solution is able to guarantee degradation control and performance requirements, at the lowest cost. The cost-optimal maintenance depends on financial investment (maintenance/replacement/repair/adaptation costs), on technological systems/components adopted (materials and assembled components' deterioration levels or durability), and, above all, on the maintenance timing (time intervals for each intervention/replacement).

Focusing on the use-maintenance-adaptation stage in the buildings' life cycle [3], the aim of this work is to propose—according to the economic viewpoint—a methodology for supporting the optimal maintenance scheduling in function of life cycle costs when in presence of financial constraints, and in function of flexible maintenance time intervals when in presence of uncertainty over time. Specifically, in this first research step, an operative modality is proposed for testing the economic sustainability of different project options, at the component scale, which imply different cost items and different maintenance-replacement interventions over time.

The proposed methodology is based on the Annuity Method as defined by the norm EN 15459-1:2017 [4], explored here as an alternative to the Global Cost approach (illustrated in Standard EN 15459-1:2017 as well). The Annuity Method, less explored in literature, seems more suitable than the Global Cost for facing the objective of this work, as will be illustrated in the paper. Furthermore, given the presence of uncertainty over time, the Equivalent Annual Cost is calculated in stochastic terms, as an output of the stochastic LCCA.

In details, the methodology avails of four steps: Firstly, data assumptions are made in relation to the input of the analysis, both in terms of relevant costs and of time intervals for maintenance or repair interventions. Secondly, assuming these relevant input data as stochastic variables and with the support of the Probability Analysis, the probability distribution functions (PDFs) are simulated through the Monte Carlo Method (MCM). Thirdly, assuming the PDFs as input data, the stochastic LCCA is processed by calculating the stochastic Equivalent Annual Cost. Finally, the results are analyzed for selecting the preferable option.

As a case-study for the application, two different frames—an Aluminum Frame and a Timber one—for a glass façade of a hypothetical office building (supposed in Northern Italy) are considered. Notice that the same case study was analyzed in previous works; data and conditions are maintained [5].

It is worth stressing that the methodology intends to support decisions, not only in the design phases (choice among different components, systems, technologies, etc.), but also in the post-construction ones (definition of maintenance strategies). As said, the scope of optimal maintenance planning is to guarantee the components/systems/buildings/infrastructures' durability, at the lowest cost. According to this viewpoint, the cost component (a monetary value) is strategic for identifying the service life of a component/system/building/infrastructure, and, above all, the service life is not assumed (as in the previous applications), but it results from the calculation. In fact, respect to the previous studies, in this case, the time interval distributions are added (repair works and related timespans).

Furthermore, the novelty of the study consists in the fact that for the first time, at least to our knowledge, in the Italian scientific estimative debate and the related literature on topic, the LCC analysis is solved in the form of the Annuity Cost in place of the Global Cost approach. Besides the methodological aspects, this study on a poorly known procedure can be attractive for the economic evaluation of maintenance/replacement scenarios, particularly in view of the application on reinforced

concrete infrastructures (such as roads, bridges, etc.), focusing on post-construction stages. Even if a consistent research is still to be done for shifting from the single component scale to the infrastructure one, the present study can be considered as a first step towards the application of the stochastic LCCA on the construction sector.

The paper is articulated in the following parts: Section 2 presents a literature background on the topic. Section 3 illustrates the methodology. In Section 4, the case study is mentioned. Section 5 presents the results of the application, and Section 6 concludes.

2. Literature and Regulatory Background

The scientific background of the research is twofold. On one side, the European/international regulatory framework in the field of economic-environmental sustainability in a life cycle perspective, and within the framework of energy policies; on the other side, the international literature on topic, which founds on the normative itself. Both areas will be illustrated in the following sub-sections, at least in relation to the most relevant references/documents for the purpose of this study.

2.1. The Regulatory Framework

Regarding the regulatory background, the documents considered are listed in the following bullet point:

- ISO 15686-5:2008, Buildings and Constructed Assets—Service Life planning—Part 5: Life Cycle Costing (revised July 2017—ISO 15686-5:2017) [3];
- ISO 15686-1:2000, Building and constructed assets—Service Life planning—Part 1: General principles (revised by 15686-1:2011) [6];
- ISO 15686-2:2001, Building and constructed assets—Service Life planning—Part 2: Service Life prediction procedures (revised by 15686-2:2012) [7];
- ISO 15686-7:2006, Building and constructed assets—Service Life planning—Part 7: Performance Evaluation for Feed-back of Service Life data from practice (revised by 15686-7:2017) [8];
- ISO 15686-8:2008, Building and constructed assets—Service Life planning—Part 8: Reference Service Life and Service Life estimation [9].
- Furthermore:
- UNI 11156-3: 2006, Valutazione della durabilità dei componenti edilizi. Metodo per la valutazione della durata (vita utile) [10];
- Standard EN 15459-1:2017—Energy performance of buildings—Economic evaluation procedure for energy systems in buildings (repealed by UNI EN 15459-1:2018) [4];
- Guidelines accompanying Commission Delegated Regulation (EU) No 244/2012 [11];
- Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings—recast (revised by Directive 2018/844/EU—EPBD recast) [12].

Consider that the aforementioned norms and directives are transposed, by each single State, into national/regional/local laws.

2.2. The International Literature

From the normative framework, aimed at realizing energy and environmental policies, derives a wide international debate and a substantial literature production covering a multidisciplinary spectrum. For the purpose of this work, the economic evaluation perspective is favored in mentioning the scientific contributions to the project sustainability evaluation, in the construction sector.

From research reports and articles emerges that the LCCA, as normed in [3], is the suggested approach for evaluating the economic sustainability of projects in the building/construction context, being able to support the decision between alternative technological-economic scenarios in a life cycle perspective. LCCA is usually solved through the Global Cost calculation. The Global Cost approach,

illustrated in the aforementioned standard EN 15459-1:2017, is an effective approach for calculating the energy performance of buildings, or building components, and it represents the foundation for identifying the optimal scenarios in terms of energy efficiency and economic sustainability (cost-optimal solutions). Of course, the energy-economic perspective is favored in the calculation, being quantified and modeled only in the environmental components directly related to energy consumptions. The environmental impact assessment in life cycle perspective is usually developed through the Life Cycle Assessment approach (LCA).

In order to implement simultaneously the economic and environmental sustainability of project options, according to a "global performance" viewpoint, the conjoint application of LCCA and LCA is explored. In a recent study, the joint application is proposed by modeling a "synthetic economic-environmental indicator", calculated by means of a hybrid LCCA and LCA approach [5]. In this case, the core of the calculation is the Global Cost as defined in the international standards (energy performance of building and consumptions for HVAC and DHW production), plus environmental components, monetized (environmental impacts, through the monetization of Embodied Energy and Embodied Carbon, disposal/dismantling costs and residual value, by monetizing the level of disassembly of building systems, the recycled materials' quantity and the waste production).

Contextually, studies focus on the decision-making processes in the design phases, assuming the presence of risk and uncertainty in input data [13–15]. Risk analysis, in conjunction with LCCA, is faced through some consolidated approaches, among which is the Probability Analysis [16–19].

Particularly interesting and less explored under the economic viewpoint, is the literature concerning uncertainty into service lives of technological options, and the related impacts in terms of durability. As known, the components' service lives can influence the model results and the residual value's estimates. The residual service life is fundamental for defining the timing of maintenance interventions, for example, for deciding the convenience in intervening with a substitution before or after the end of the service life, to proceed with a component/system replacement or to maintaining it with shorter maintenance intervals (in this case, an analysis of the cost efficiency is necessary). In the meanwhile, life expectancy definition is a complex process, fundamental for maintenance economic planning. The complexity is due to the presence of uncertainty, correlated to the deterioration processes, which, in turn, are correlated to the specific climate conditions, usage, etc.

The expected service lives of components can be affected by uncertainty, both in relation to cost of items (such as cost for maintenance/adaptation/replacement), and in relation to their service life prediction. This last point—service life prediction—is the object of many researches focused on the approaches to predict the life expectancy of building components. For example, Bourke and Davies [20] propose a general framework of (deterministic) approaches for predicting buildings' service lives, focusing on the Factor Method and scenario's analysis. Shohet, Puterman and Gilboa [21] develop a (deterministic) methodology for implementing databases on deterioration patterns of construction components, in order to develop models for predicting their service lives, and to implement instruments for supporting maintenance planning. In details, the proposed methodology is articulated in four steps: Firstly, identification of failure patterns, secondly, determination of component performance, thirdly, determination of life expectancy of deterioration path, and lastly, evaluation of predicted service life. Similarly, Hovde and Moser [22] produce a really consistent review on the methods—both deterministic and probabilistic—for buildings' service life prediction. Preliminarily, a general distinction is made between: Factor method, Probabilistic Prediction Methods, and Engineering Design Methods. Furthermore, Kumar, Setunge and Patnaikuni [23] develop a (deterministic) methodology for optimizing public buildings' management in the City of Greater Geelong municipality in Victoria, Australia. The Factor Method is the core of the methodology, posing a particular attention for information requirements, such as the type of building, replacement costs, expected life of the building, and residual service life. Finally, Flint et al. [24] develop a (probabilistic) methodology for predicting infrastructure durability. The methodology, on the basis of a set of input data on investment costs, environmental impacts, downtimes, and safety costs, is articulated in

the following analyses: Exposure Analysis, Deterioration Analysis, Repair Analysis, Environmental Impact Analysis.

The works mentioned above present strengths and weaknesses. The main limits, according to the aim of the present work, is the scarce number of studies and applications on topic, and, secondly, the fact that among these, only few found on the probabilistic approach.

In response, recent studies propose a probabilistic methodology with flexibility over time: input data are modeled through the "stochastic approach to the Factor Method (FM)" on the basis of the standard Factor Method [25]. This solution is capable of overcoming the limits of the deterministic approaches, or of the hybrid ones. Beside this advantage, the stochastic Factor Method presents the limit to require assumptions which hardly can be validated by effective data (for example, assumptions about the factors' values, supported by experts and potentially affected by subjectivity).

Starting from these premises, in literature, alternatives to the Global Cost method are explored with the aim to overcome the limits. Among these, the Annuity Method [26]. The Annuity Method, or Equivalent Annual Cost method, illustrated in the same norm EN 15459-1:2017, is known as a particularly suitable procedure in the case of building energy retrofit interventions, for testing the balance between investments and savings (for example, energy cost savings). More precisely, the Annuity Method is considered more attractive than the Global Cost being suitable for calibrating the investments in performance improvements in view of the related cost savings.

The Annuity Method is an object of relatively recent studies. For example, Hoff [27] proposes an application of a conjoint LCC and Equivalent Annual Cost method for ranking alternative materials/technologies for roof construction, in the USA. The author proposes a deterministic approach to LCC and Annual Equivalent Cost, assuming point values for comparing the different scenarios. Specifically, the study starts from a set of fundamental questions: How long do roofs last? How much do roofs cost? How do you compare roof systems with different service lives? The solution proposed by the author is the Roof Life Cycle Analysis, using the Estimated Uniform Annual Cost (EUAC), a methodology based on the following passages: 1: Identifying alternatives and timeframes; 2: Identifying and calculating costs; 3: Calculating Life Cycle Cost; 4: Calculating Equivalent Annual Uniform Cost; 5: Analyzing results. The EUAC method of Life Cycle Costing has the merit to represent one of the first studies based on the joint application of the models, but in the meanwhile, it has the limit to propose a deterministic implementation. Schade [28] proposes a general overview of the different calculation models of the LCCA—Net Present Value, Equivalent Annual Cost, Simple/Discounted Payback method—indicating, for each of them, the object of the calculation, advantages, disadvantages, the usability of the model. Marszal and Heiselberg [29] propose an application of LCC solved through Net Present Value and Equivalent Annual Cost (deterministic) to a residential building, NZEB, in Denmark. Three different scenarios with increasing performance levels are analyzed, implementing a deterministic sensitivity analysis on five parameters (component costs, electricity consumption, heating consumption, interest rate, building service life). Then, Plebankiewicz, Zima and Wieczorek [30] in a recent work, propose an application of LCC with Equivalent Annual Cost solved with fuzzy values, for evaluating pneumatic sports halls used for roofing tennis courts, swimming pools, skate parks or football fields in the winter season in Poland. Three scenarios with different increasing service lives are considered, and, among the parameters, lifetime, discount rate, initial costs, annual operating costs, periodical operating costs and withdrawal costs are analyzed.

The contents of the mentioned studies, the knowledge gap existing in the Italian context and, in general, the scarce researches on the Annuity Method, have stimulated the present work, which can contribute in growing the literature on topic.

3. Methodology

According to the standard EN 15459-1:2017, the economic-energy performance of buildings can be calculated through two different modalities: Global Cost approach and the Annuity Method.

Considering the aim of this work, and considering the literature background illustrated in Section 2, in the following sub-section, the Annuity Method approach is synthetically reminded.

3.1. The Annuity Method Approach

The Annuity Method approach founds on the determination of the annual costs of a building/system/component [4], by combining all the costs into a single annualized mean cost. The modality for treating the "time-money" issue is the main difference between the Annuity Cost method and the Global Cost approach. In fact, through the Global Cost, a total cost value referred to the calculation period (τ) discounted at the initial time is calculated. In the schematic example illustrated in Figure 1a, the relevant costs are represented by: C_i, initial investment costs, not discounted being referred to the initial period; C_r, running costs, constantly distributed along the service life of the building/component, discounted at the initial time; and finally, C_{RJ} or periodic replacement/extraordinary maintenance costs, discounted at the initial time. The discounting is operated by means of the discount factor and the related discount rate r value. On the contrary, through the Annuity Cost, all the costs are transformed into annual costs by means of the annuity factor a(n). The annuity factor can be considered as the reciprocal of the discount factor, or the "present value of the discount factor". More precisely, the annuity can be considered as the equivalent of the Net Present Value: this last one is converted into the equivalent annuity, by multiplying it by an annuity factor and by calculating the corresponding yearly amount. In the example (see Figure 1b), the initial investment costs are spread along the lifespan.

(**a**)

(**b**)
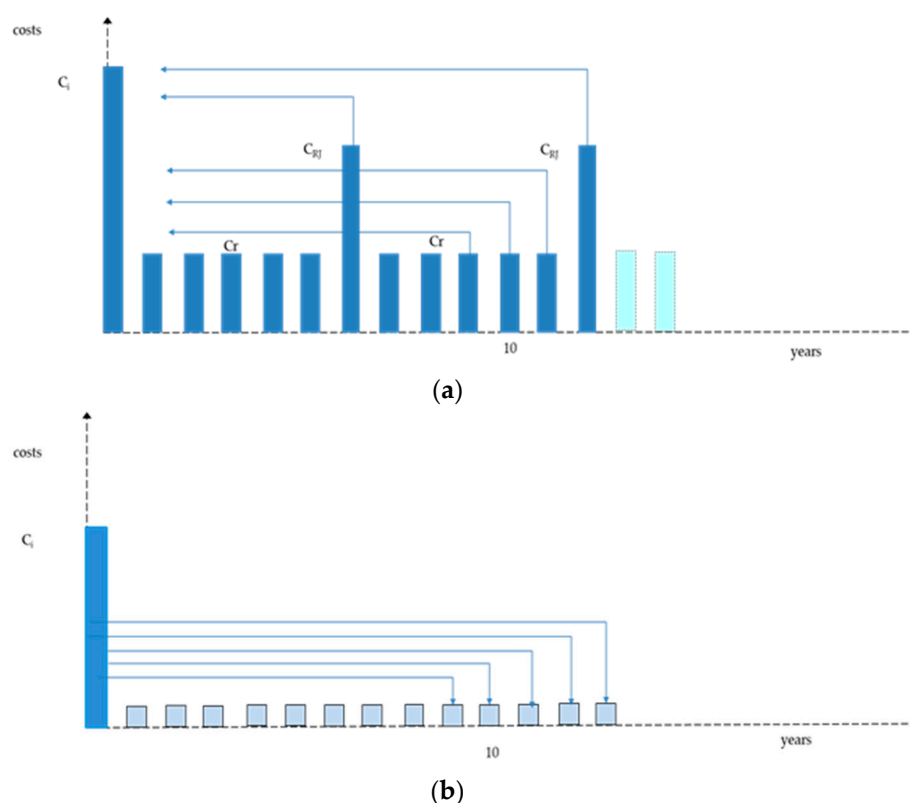
Figure 1. Global Cost discounting schematic example (**a**) and Annuity Cost annualization schematic example (**b**).

Operatively, according to the standard EN 15459-1:2017, the Annuity Cost is the sum of three components. Assuming a calculation period τ, the procedure starts by distinguishing the following relevant cost items:

–   running costs, generally constant over time;

- replacement costs (or extraordinary maintenance costs), periodically distributed, related to components or systems with a service life lower or higher than the building life cycle.

The Annuity Cost calculation can be formalized as in the following Equation (1):

$$AC = Cr + \sum_i (a(i) * \sum_j V_0(j)) + a(\tau\_Building) * \left(\sum_j V_0(j)\right)$$ (1)

for *j*, where τ (*j*) = *i* < τ_Building and for *j*, where τ_n (*j*) ≥ τ_Building. AC stands for Annuity Cost; the first component Cr represents the annual running costs (energy, operation, maintenance, etc.) which are yearly by definition; the second component $\Sigma(a(i) * (\Sigma V_0(j))$ represents the total annualized costs related to *j* components or systems replacement, for which the service life is assumed lower than the building life cycle; the third component $a(\tau\_Building) * (\Sigma V_0(j))$ represents the total annualized costs related to *j* components or systems replacement, for which the service life is assumed unchanged during the building life cycle, having a life cycle longer than that of the building. It must be pointed out that the term $\Sigma(a(i)$ represents the annuity factor when the component service life is lower than the building life cycle, whilst the term $a(\tau\_Building)$ represents the annuity factor when the component service life is longer than the building service life (or than the lifespan of the analysis).

Notice that the three components are summed and not discounted, being related to annual periods. Then, notice that the annual costs are assumed constant.

In Figure 2, the example presented in Figure 1b is implemented by introducing diverse relevant cost items (C_i, initial investment costs; C_{RJ}, periodic replacement or extraordinary maintenance costs; C_r, running costs). The relevant cost items' repartition, in terms of annuity costs, are graphically presented. Their different distribution over time is highlighted.
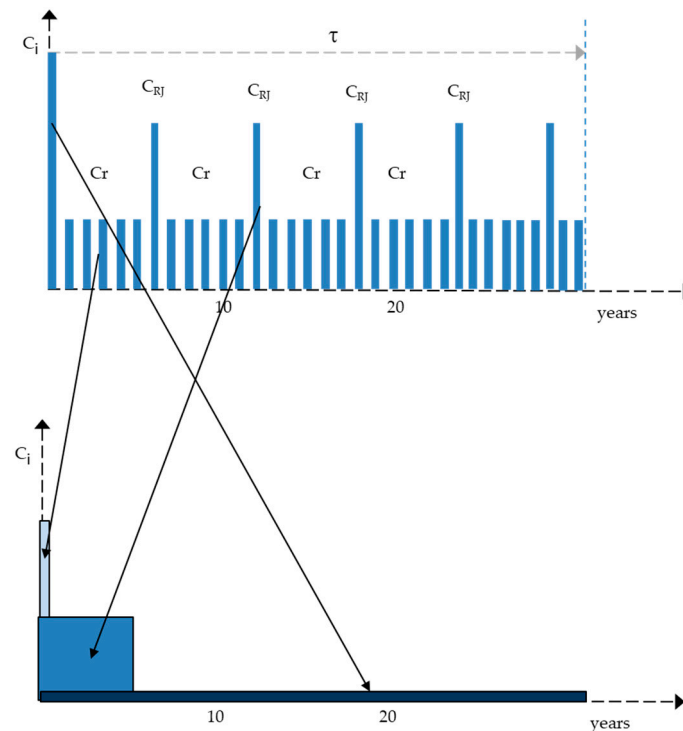
Figure 2. Annuity cost graphic presentation (Source: Elaboration from CEN 15459:2007—Energy performance of buildings—Economic evaluation procedure for energy systems in buildings, Final Draft, p. 17) [4].

When in the presence of different project options, for example, different technological scenarios, the Annuity Cost, or Equivalent Annual Cost, can be considered as a useful indicator for selecting the preferable solution. The lowest Equivalent Annual Cost corresponds to the preferable result, in

that it represents not only the lowest maintenance cost, but also the time span between maintenance interventions able to guarantee the required component/system efficiency in the presence of financial constraints: this time span is named "optimal maintenance interval". Thus, this indicator is fundamental for the strategic planning maintenance, under an energy-environmental-economic viewpoint.

Summing up, the Annuity Method is attracting to being linked to the investment advantages in a more effective way than the Global Cost, even if the calculation is more difficult. For these reasons, the Annuity Method is proposed for the application presented in this work.

3.2. The Stochastic Annuity Method Approach

As known, the construction sector is heavily influenced by economic, financial and technical/technological risk, specifically for long-term projects. In order to strengthen the preventive evaluation, flexibility can be introduced by modeling stochastically the critical (most sensitive) input data. For this reason, in the present research, risk and uncertainty presence is assumed and modeled.

Thus, the Annuity Cost model expressed in Equation (1) is transformed into a full stochastic model, as in the following Equation (2):

$$\text{A}\,\hat{c} \;=\; \hat{c}r + \sum\nolimits_i \Big(a(i) \; * \; \sum\nolimits_j \hat{V}_0(j)\Big) + a(\tau\_Building) \; * \; \Big(\sum\nolimits_j \hat{V}_0\,(j)\Big) \tag{2}$$

for *j*, where $\tau_n(j) = i < \tau\_Building$ and for *j*, where $\tau_n(j) \geq \tau\_Building$. A $\hat{c}$ stands for stochastic Annuity Cost; $\hat{c}r$ represents stochastically the annual running costs (energy, operation, maintenance, etc.); the second component $\Sigma(a(i) * (\Sigma\,\hat{V}_0(j))$ represents stochastically the total annualized costs related to *j* components or systems replacement, for which the service life is assumed lower than the building life cycle; the third component $a(\tau\_Building) * (\Sigma\,\hat{V}_0\,(j))$ represents stochastically the total annualized costs related to *j* components or systems replacement, for which the service life is assumed unchanged during the building life cycle, having a life cycle longer than that of the building; $\Sigma(a(i)$ represents the annuity factor when the component service life is lower than the building life cycle, whilst the term $a(\tau\_Building)$ represents the annuity factor when the component service life is longer than the building service life.

The stochastic Annuity Method formalized in Equation (2) is fundamental for the following steps of the methodology. In fact, the stochastic Annuity Cost, calculated through the stochastic Annuity Method, is used as output data for the LCC application, as illustrated in the coming sub-sections.

3.3. The Life Cycle Costing Approach

The Life Cycle Costing (LCC) approach, or Life Cycle Cost Analysis (LCCA), is normed by ISO 15686-5:2008, revised by July 2017—ISO 15686-5:2017. As known, LCC is used for quantifying costs and benefits in short/long-term alternative projects [31–33]. Coherently, with the Life Cycle Thinking perspective, the entire life cycle of each project option is considered, from "cradle to grave". The peculiarity of the method is the Global Cost concept, defined in the Standard EN 15459:2007 (revised by EN 15459-1:2017). The Global Cost includes all the relevant cost items during the whole life cycle of a construction project, including environmental costs; operatively, it is solved by the Net Present Value calculation. Above all, the Global Cost is the fundamental for the LCC analysis. In facts, it represents the main synthetic quantitative indicator through which the LCC analysis is solved.

Whilst in the recent studies the LCC analysis is frequently proposed in conjunction with the Global Cost calculation, the Annuity Method seems poorly explored. Thus, in this work, we propose the Annuity Cost approach in place of the Global Cost to solve the LCC analysis.

Summing up, the methodology performed can be summarized in the following four steps:

Step 1: Relevant input data assumptions. In this first step, the relevant input data are selected and their values are assumed. For the cost items and the discount rate, the ranges of value are defined (in terms of point estimates, low and high values), whilst for input distributed over time, for example, repair works, the time intervals are defined;

Step 2: Probability distribution functions definition. In this second step, the PDFs for the relevant items selected in step 1 are simulated through the MCM (sampling and iteration process);

Step 3: Stochastic LCCA application. In this third step, the PDFs calculated in step 3 are modeled, as input data, in the LCCA. According to Equation (2), LCCA is solved by calculating the stochastic Equivalent Annual Cost. The Probability Analysis is applied for solving stochastically the LCCA, through the MCM and by processing the following analyses: Multiple Regression Analysis for ranking the input values by their effect on the output mean; Spearman's correlation coefficients, for identifying the correlation between output value (the Equivalent Annual Cost) and the data samples for each input distribution; Sensitivity Analysis, for identifying, graphically, the most critical variables (in terms of perturbation effects on the simulation output);

Step 4: Results and final considerations. In this fourth and final step, the results calculated in Step 3 are analyzed for selecting the preferable option (the lowest Equivalent Annual Cost and the effects of input variables on the output values are considered). Furthermore, the best-fitting distribution function for the output (Equivalent Annual Cost) is calculated.

A graphic presentation of the workflow is presented in the following Figure 3.
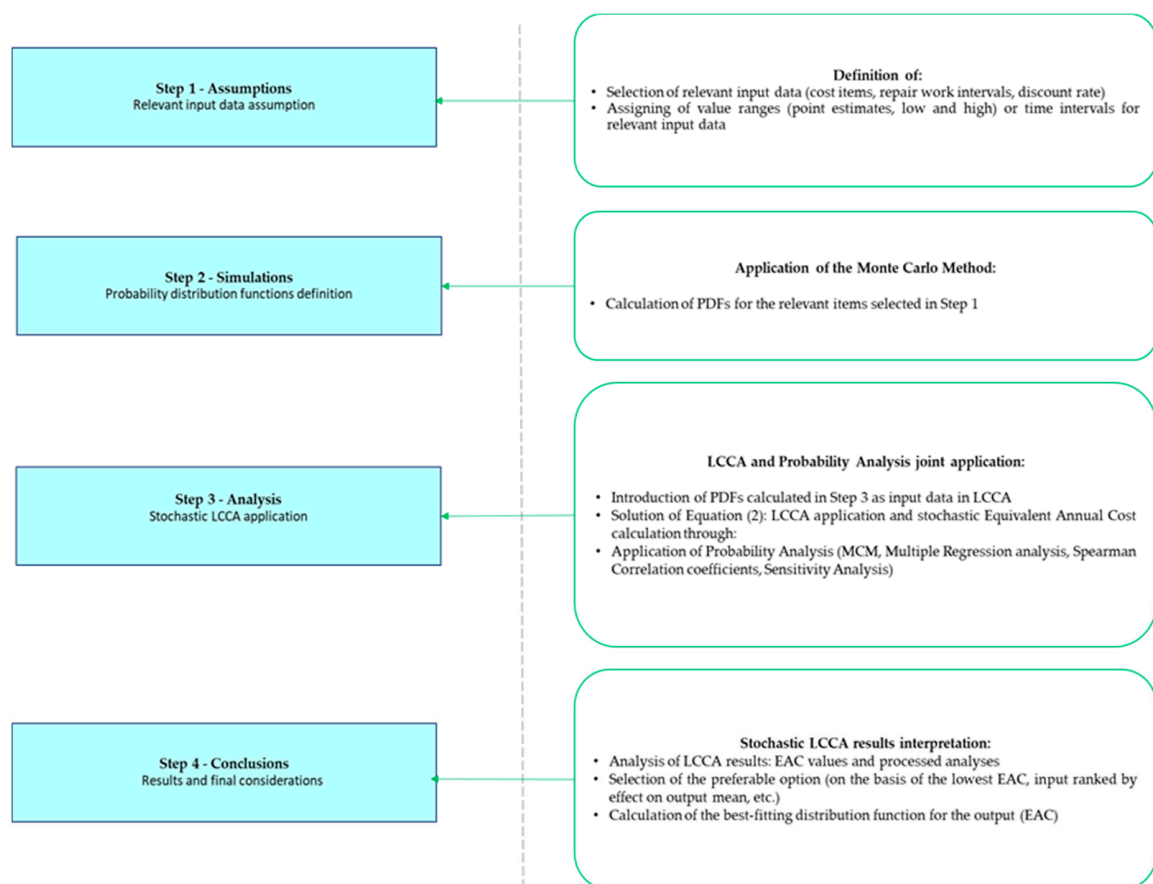

Figure 3. Workflow (left side) and steps of the analysis (right side).

4. Case Study

The case study presented in previous studies is adopted in this work. The analysis is applied on two different window systems, assuming that this specific component can be considered fundamental in the case, for example, of a residential building, a commercial building, or an office building. The glass façade is composed by, alternatively, a timber frame window, and an aluminum frame window (see Figure 4).

(**a**)　　　　　　　　　　　　(**b**)
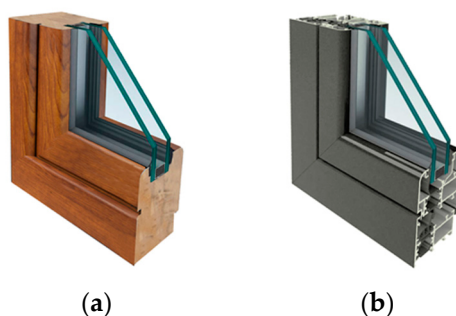
Figure 4. Case study: (**a**) timber window frame; (**b**) aluminum window frame.

The characteristic (initial investment cost, total running and replacement costs, disposal costs, embodied energy and embodied carbon for both options, are summarized in [4].

5. Simulation and Results

The methodology (and related workflow) previously illustrated is applied, assuming the case study reminded in Section 4. The simulations are produced by means of the software @Risk (by Palisade Corporation, Ithaca, NY, USA, release 7.5). The results are illustrated in the coming sub-sections.

5.1. Input Data Assumptions and Probability Distribution Functions Calculation

The first step consists of the definition of the main assumptions about input data, expressed through unit values: point estimates, low and high ranges for relevant cost items, time intervals and discount rate. The specific amounts for each input data are illustrated in Table 1 (coherently with the previous studies).

Table 1. LCCA input data assumptions.

Input Data	Unit	Timber Frame			Aluminum Frame		
		Low Range	Point Estimate	High Range	Low Range	Point Estimate	High Range
Inspection	€ per year	6220	6547	7202	2253	2372	2609
Preemptive maintenance	€ per year	15,550	16,369	18,005	11,267	11,860	13,046
Repair work (light)	€	62,201	65,474	72,022	45,067	47,439	52,183
Repair work (light) interval	years	1.8	3	3.3	3.5	5	5.5
Repair work (main)	€	117,854	130,949	157,138	74,717	83,019	99,622
Repair work (main) interval	years	4.2	7	7.7	7	10	11
Replacement	€	339,561	377,290	452,748	258,404	287,115	344,538
Replacement interval (lifespan)	years	15	25	30	17.5	25	27.5
Dismantling cost	€/m²	29.7	33	39.6	29.7	33	39.6
Disposal cost	€/ton	49.5	55	66	−640	−800	−880
Dismantling/disposal interval	years	15	25	30	17.5	25	27.5
Discount rate	%	1.25	1.39	2.50	1.25	1.39	2.50

Notice that, comparing with the previous studies, in this case, the time interval distributions are added, related to repair works (light and main), and related to lifespans expressed through replacement intervals. Some additional assumptions are related to the time:

– Firstly, a higher probability for repairing/replacement time intervals reduction is considered, and a lower probability for repairing/replacement time intervals lengthening;

– Secondly, a noticeable reduction on the time intervals for Timber Frame, considering a lower durability degree as respect to Aluminum Frame.

As a second step, input data and probability distribution values, processed with MCM, are calculated, as reported in Table 2. In order to simplify the example, triangular type distributions are assigned to input data.

Table 2. Input data and probability distribution values. MCM simulation output.

Input Data	Distribution	Graph	Min	Mean	Max	5%	95%
Disposal cost_glass	Triangular		72.04	82.67	95.96	75.1	91.62
Disposal cost_timber	Triangular		49.52	56.83	65.96	51.63	62.99
Disposal cost_aluminum	Triangular		640.15	773.33	879.75	683.82	849.02
Dismantling cost	Triangular		29.7	34.1	39.57	30.98	37.79
Discount rate	Triangular		1.25%	1.71%	2.5%	1.34%	2.24%
Inspection cost (€):							
Timber	Triangular		6221	6657	7201	6347	7023
Aluminum	Triangular		2254	2411	2608	2299	2544
Preemptive maintenance cost (€):							
Timber	Triangular		15,554	16,641	17,999	15,867	17,557
Aluminum	Triangular		11,268	12,057	13,042	11,496	12,721
Repair work (light) cost (€):							
Timber	Triangular		62,214	66,565	71,998	63,468	70,228
Aluminum	Triangular		45,078	48,230	52,181	45,986	50,884

Table 2. *Cont.*

Input Data	Distribution	Graph	Min	Mean	Max	5%	95%
Repair work (light) interval (years):							
Timber	Triangular		1.8	2.7	3.3	2.1	3.15
Aluminum	Triangular		3.5	4.67	5.5	3.89	5.28
Repair work (main) cost (€):							
Timber	Triangular		117,889	135,313	157,043	122,925	149,965
Aluminum	Triangular		74,759	85,786	99,608	77,932	95,075
Repair work (main) interval (years):							
Timber	Triangular		4.20	6.30	7.70	4.90	7.35
Aluminum	Triangular		7	9.33	11	7.77	10.55
Replacement cost (€):							
Timber	Triangular		339,753	389,866	452,604	354,172	432,083
Aluminum	Triangular		258,506	296,685	344,449	269,523	328,812
Replacement interval (years):							
Timber	Triangular		15.02	23.33	29.98	17.74	28.06
Aluminum	Triangular		17.53	23.33	27.49	19.44	26.38
Old fixture elements disposal interval (years)							
Timber	Triangular		15.01	23.33	29.97	17.74	28.06
Aluminum	Triangular		17.52	23.33	27.49	19.44	26.38

5.2. Stochastic Equivalent Annual Cost Calculation in Life Cycle Cost Analysis

Step 3 of the analysis is devoted to the stochastic Annuity Cost calculation, according to Equation (2). The simulation is developed with the MCM, using the stochastic input variables processed in Step 2. The results, calculated for Timber Frame and Aluminum Frame, are illustrated in Figure 4 in terms of Equivalent Annual Cost distribution function and statistics.

As expected, the distribution function for Timber Frame is slightly more inclined to the left, coherently with the assumption on durability of the Timber Frame in comparison with the Aluminum one. (See Figure 5).

Timber Frame

Statistics	
Minimum	€ 79,869.62
Maximum	€ 123,243.19
Mean	€ 95,836.33
Std Dev	€ 5549.87
Variance	30801109.61
Skewness	0.464672077
Kurtosis	3.136286012
Median	€ 95,334.59
Mode	€ 94,299.05
Left X	€ 87,584.44
Left P	5%
Right X	€ 105,772.50
Right P	95%

Aluminum Frame

Statistics	
Minimum	€ 46,047.71
Maximum	€ 65,703.63
Mean	€ 53,888.75
Std Dev	€ 2359.26
Variance	5566126.426
Skewness	0.338846033
Kurtosis	3.041596407
Median	€ 53,741.76
Mode	€ 53,596.38
Left X	€ 50,262.54
Left P	5%
Right X	€ 57,985.77
Right P	95%

Figure 5. Output probability distribution function, statistics for stochastic Equivalent Annual Cost, Timber/Aluminum frames. MCM simulation output.

Thus, the stochastic input variables are ranked in view of their effect on output mean, for Timber and Aluminum Frames. In Figure 6, the tornado graphs represent graphically the results of the Multiple Regression Analysis produced on simulation data, highlighting the predominance of time intervals/lifespans between repair works/replacements over the other input items.

The input variables "Repair work" (light and main)—time intervals and "Replacement"—lifespan, ranked by the effect on the Equivalent Annual Cost mean, produce the greatest perturbation in the case of Timber Frame. Analogously, for the Aluminum Frame, for which the variables related to maintenance timing are confirmed to be the most impactful on the output mean. This demonstrates that the results of the investments on maintenance can significantly influence the costs' yearly spread over time and, clearly, an effective maintenance strategy is able to influence the durability of the component. This result gives a fundamental support for orienting the maintenance temporal planning in view of the cost amounts, according to an optimality view.
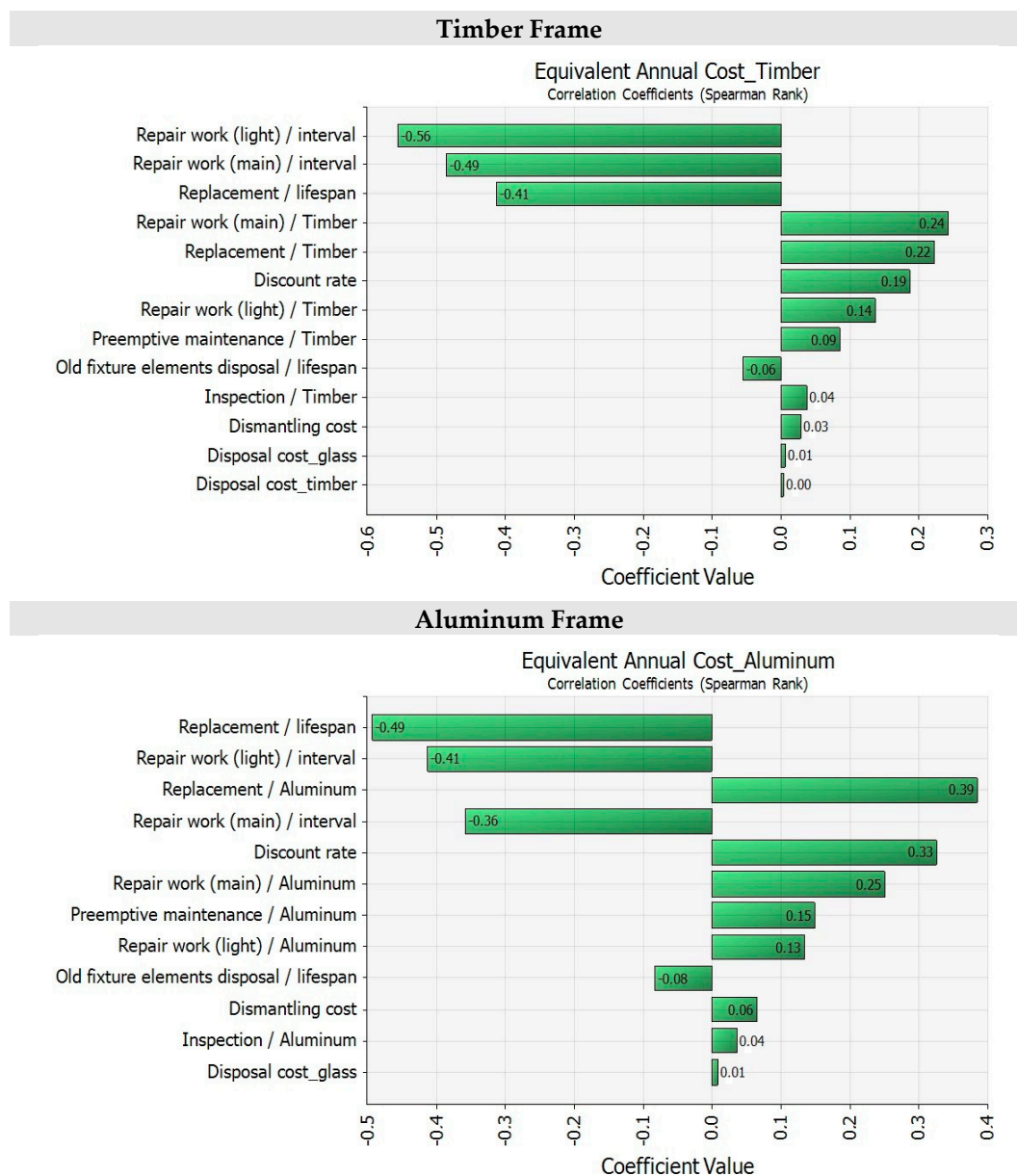
Timber Frame
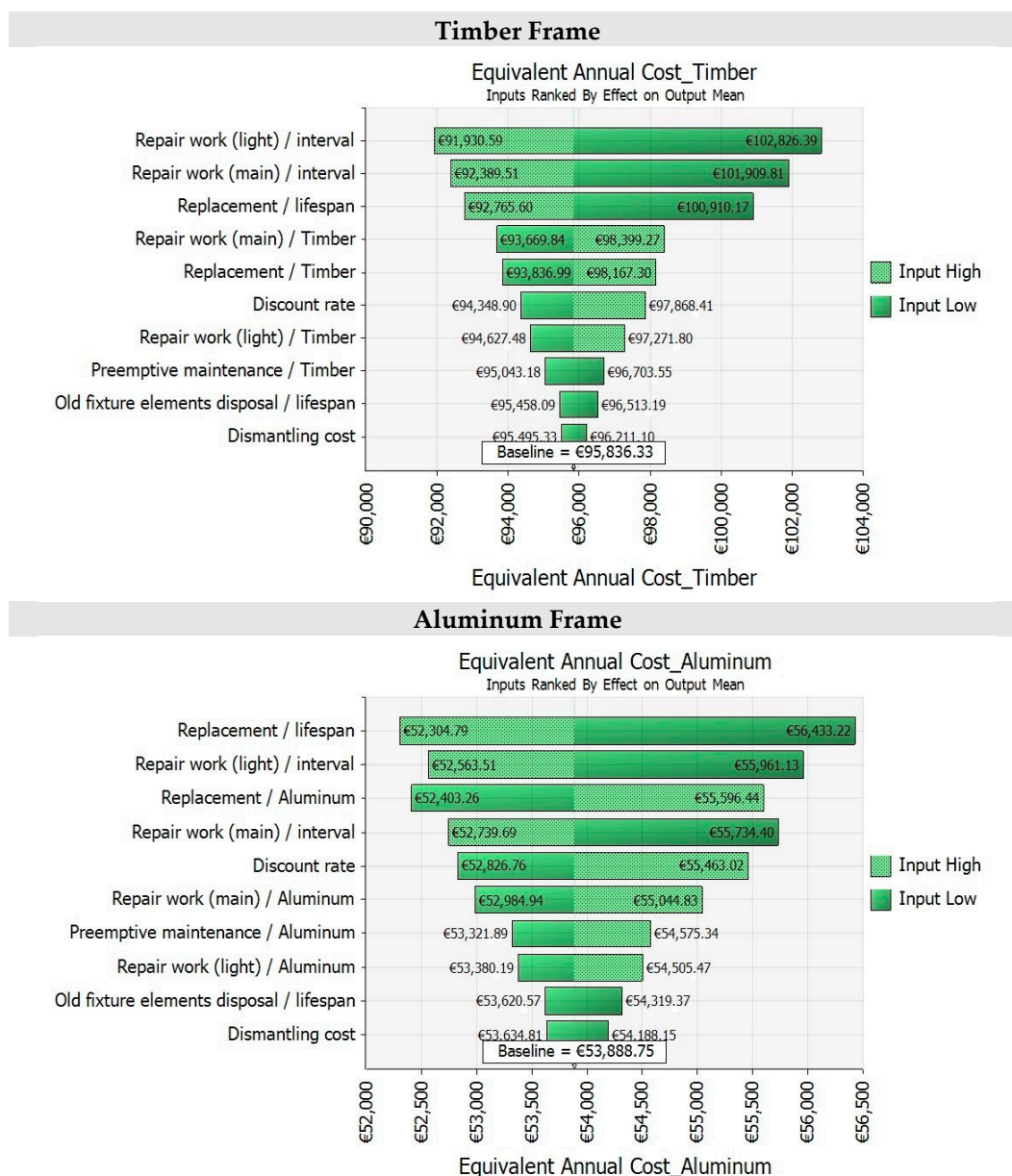
Aluminum Frame

Figure 6. Input ranked by effect on output mean, Timber/Aluminum frames, for stochastic Equivalent Annual Cost. MCM simulation output.

Then, the Spearman correlation coefficients are calculated to identify the correlation between the output value (the Equivalent Annual Cost) and the data samples for each input distribution. In this case, the Spearman correlation coefficients—illustrated in Figure 7—show the high impact of time intervals between repair works and lifespan related to components' replacement on the general results, with the longest bar. Notice that a value between −1 and 1 represents the desired degree of correlation between two variables (Equivalent Annual Cost and each input data) in sampling. Positive values stand for a positive relation between variables; negative coefficient values are the opposite.

Finally, a Sensitivity Analysis is carried out graphically, by means of the spider graph, for assessing the sensitivity of the output to the variability in input variables, for both the alternatives. In Figure 8, the steeper curves in spider graphs represent the more critical variables (for both options, the variation of repair work light and main, and replacement). The relevance of time intervals between repair works and components' lifespan on model output is confirmed: the spider graphs show their most

evident slope. The variable time interval represents the input with the highest influence potentiality on LCCA output.

Figure 7. Spearman correlation coefficients, Timber/Aluminum frames, for stochastic Equivalent Annual Cost. MCM simulation output.

In conclusion, from the analysis, it emerges that the time intervals between repair works and components' lifespan are the most relevant input variables to the LCCA output calculation, assuming unchanged all the other input.

Furthermore, significant differences can be highlighted between Timber Frame and Aluminum Frame: in the case of Aluminum Frame, replacement costs and time are proportionally more significant then Timber Frame. This could be due to the higher incidence of maintenance and repairing costs and to the higher frequency of interventions (time intervals between light repairs) in the case of Timber Frame than Aluminum Frame.
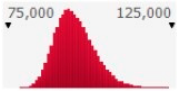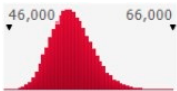
Figure 8. Spider graphs, Timber/Aluminum frames, for stochastic Equivalent Annual Cost. MCM simulation output.

5.3. Stochastic LCCA Results and Final Considerations

The final step 4 of the analysis is devoted to the analysis of the Stochastic LCCA simulation output and the selection of the preferable option. For Timber and Aluminum frames, stochastic Equivalent Annual Cost values are reported in Table 3, through their probability distribution functions and main statistics, in which it is highlighted the preferability of Aluminum frames (lowest stochastic Equivalent Annual Cost values).

Concluding the analysis, the stochastic Equivalent Annual Costs for Timber/Aluminum frames are presented in Figure 9, through their probability density function curve fitting, or, in other words, their best-fit distribution function. In this case, the gamma distribution results the best fit for the stochastic Equivalent Annual Cost values, both for Aluminum and for Timber frames.

Table 3. Stochastic Equivalent Annual Cost output values for Timber/Aluminum frames: PDFs and statistics. MCM simulation output.

Output	Graph	Min	Mean	Max	5%	95%
Equivalent Annual Cost_Timber		€ 79,870	€ 95,836	€ 123,243	€ 87,584	€ 105,772
Equivalent Annual Cost_Aluminum		€ 46,048	€ 53,889	€ 65,704	€ 50,263	€ 57,986
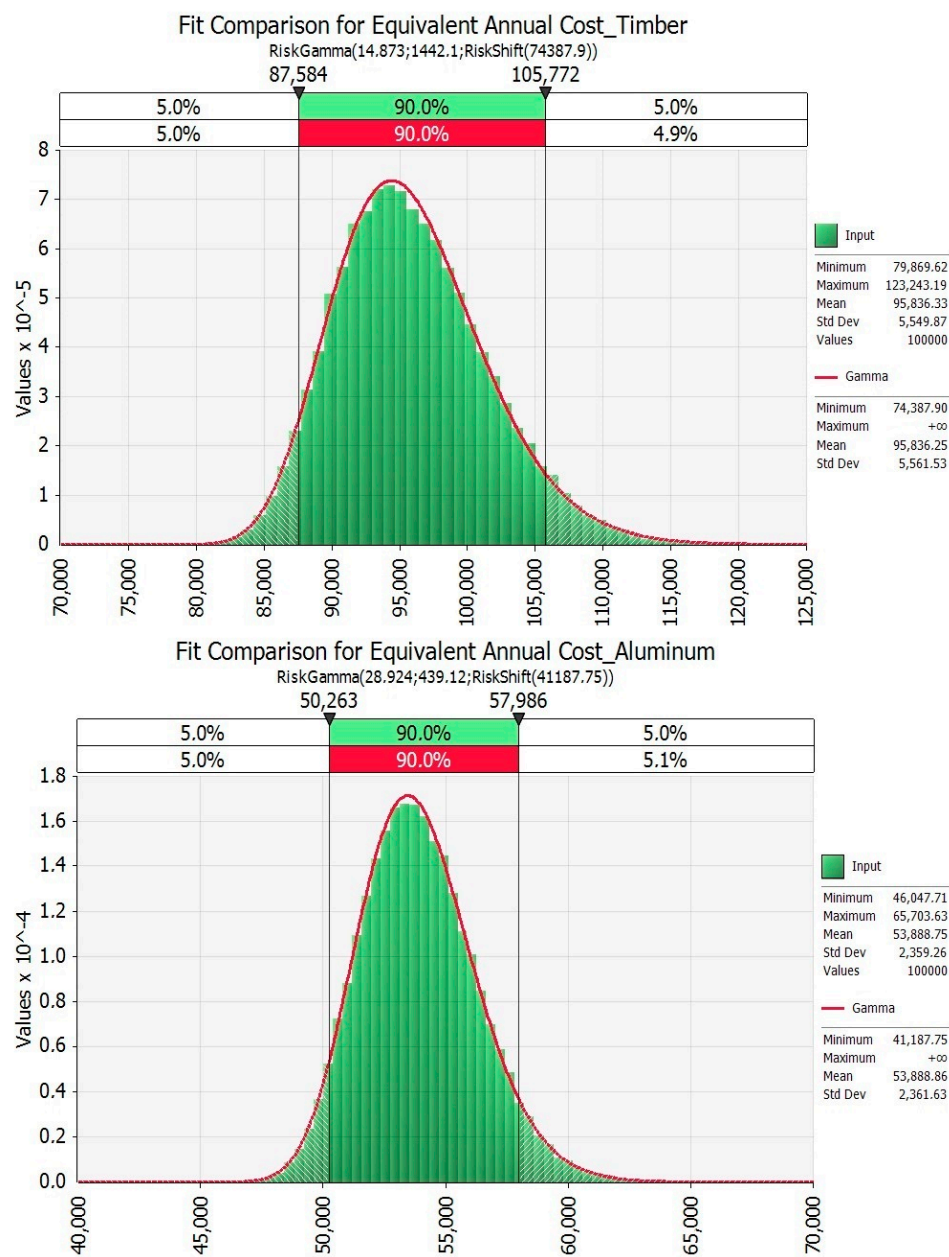
Figure 9. Stochastic Equivalent Annual Cost for Timber/Aluminum frames: probability density function curve fitting.

Notice that, as highlighted in the literature [34] and confirmed in this work, the gamma distribution is particularly suitable for modeling uncertainty in time through stochastic input variables, in the context of building construction processes.

In conclusion, assuming that different maintenance strategies imply different maintenance intervals, and, in turn, different expected service lives, the results show that the Annuity Method is particularly suitable for calculating the performance of a component (or a system/building/infrastructure). Particularly, the Annuity Method is an effective tool for comparing projects with different service lives as in this application, and, potentially, long-term projects. Furthermore, the Global Cost approach developed through the Net Present Value calculation seems to give a greater relevance to the initial investment costs, based on the life cycle costs' discounted sum. At the opposite, the Annuity Method developed through the Equivalent Annual Cost assumes the costs during the life cycle as prevalent, on an annual basis. Focusing on the service life and at the operation phase, the maintenance costs result more significant, as the results of the analysis demonstrate.

Therefore, the final choice between the two alternatives will depend on the facility manager's propensity to invest money and efforts for maintenance planning, according to the optimal-cost and durability principles.

6. Conclusions

In this paper, a methodology based on the Annuity Method was proposed in conjunction with the Life Cycle Cost Analysis, for the purpose of comparing different technological solutions, paying a special attention for costs and timing of maintenance, repair, replacement and dismantling of components in the building sector. The potential effects of risk and uncertainty were introduced into the analysis, by modeling stochastic input data. This methodology was applied on a simulated case study, aimed at selecting the most sustainable solution among two different technologies, for a hypothetical multifunctional building glass façade project in Northern Italy. The same case study was analyzed in previous articles, of which the present work is a methodological development.

Specifically, the Annuity Method was applied through a four-step procedure. In the first step, the main assumptions regarding point estimates, low and high ranges of input data, such as maintenance, repair and replacement costs, and the related time intervals, as well as the discount rate were defined. In the second step, according to the assumptions made in step 1, the probability distributions for each input data were defined and the related PDFs were simulated through the MCM. In the third step, the PDFs were introduced, as input data, in the Life Cycle Cost Analysis, solved through the calculation of the stochastic Equivalent Annual Cost. Finally, in the fourth step, the results obtained in step 3 were analyzed and interpreted in order to identify the best option, both in terms of the lowest Equivalent Annual Cost and in terms of effects of each stochastic input variable on the output.

The results indicate that the time intervals between repair works and components' lifespan are the most relevant variables, maintaining unchanged all the other input elements, able to influence the results of the evaluation. High impact of time intervals between repair works and lifespan related to components' replacement on the general results, confirm the importance to concentrate the efforts for implementing approaches able to calibrate maintenance interventions in view of lifespans (time) and investments (costs), in order to guarantee the durability and the economic efficiency of the construction element. Furthermore, confirming the results of previous analyses, it emerges that the uncertainty in the lifespan input variable, in long-term valuations, has the most relevant influence on the output, contrarily to the usual relevance of financial variables.

The methodology illustrated in this work can be considered a support for buildings/infrastructures' management by considering both technological scenarios and economic impacts of optional interventions. The methodology takes into consideration particularly the effects of maintenance timing. This can support private operators and public authorities involved in decision-making processes, promoting, in the meanwhile, the integration of maintenance, repair, and replacement

in management strategies definition. Furthermore, it can support the selection of investment on technological options, in view of economic and environmental objectives, in a temporal perspective.

As said, this reasoning opens to interesting potentialities of application, shifting from the single component scale to the entire building, to the infrastructure scale, with all the appropriate adaptations. Besides the potentialities of the method, some limits emerge. Given the prevalent interest on methodological aspects considered in the present work, these results were obtained employing input data PDFs defined through general hypotheses based on experts' suggestions. More defined indications could be obtained by modeling input data PDFs starting from experimental evidences, even though these could be available with difficulty for most of the input items involved in the analysis.

Future research developments starting from the proposed methodology could be oriented towards the passage from the single component scale to the entire building system/infrastructure [35]. This could give support also to the elaboration of policies for building districts or other typologically homogeneous parcels of territory, taking into account both building/component performances and market conditions.

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