A life cycle perspective for infrastructure management.

Original
A life cycle perspective for infrastructure management / Fregonara, Elena. - In: AESTIMUM. - ISSN 1724-2118. - ELETTRONICO. - Special Issue "Sustainable development and circular economy":(2021), pp. 5-25. [10.13128/aestim-8449]

Publisher:
FUP

Published
DOI:10.13128/aestim-8449

AESTIMUM 2020 Special Issue: 5-25

Elena Fregonara

Politecnico di Torino, Dipartimento Architettura e Design, Italy

E-mail: elena.fregonara@polito.it

Keywords: *Life Cycle Cost Benefit Analysis, Maintenance Costs Planning, Infrastructures Durability*

Parole chiave: *Analisi Costi Benefici nel Ciclo di Vita, Pianificazione dei Costi di Manutenzione, Durabilità delle Infrastrutture*

JEL codes: *D61, D81, P43, R42*

A life cycle perspective for infrastructure management [§]

Circular Economy, founded on the self-generative economic system concept, can be traced back to the Life Cycle Thinking, that conceives the project as a process along its whole life cycle, at the different scales: material, component, system, building, urban district and territorial area, infrastructure. In Italy, as in the main part of European Countries, a great portion of infrastructures was built in reinforced concrete before 1960 and is approaching the end-of-life stage. Thus, aim of this article is to propose an operative modality for supporting the preventive maintenance investments planning in function of life cycle costs and benefits, assuming the presence of uncertainty over time. Firstly, a recalling of the Cost Benefit Analysis (CBA) approach is presented. Secondly, the Life Cycle Cost Benefit Analysis (LCCBA) approach is proposed, as a tool for supporting long-term investments, management of public services and maintenance planning activities in the infrastructure sector. Thirdly, by integrating CBA and LCCBA, an operative modality is proposed. On the background, life cycle management, optimal maintenance planning and durability concepts are assumed.

1. Introduction

The Circular Economy principles can produce relevant impacts on production and consumption processes, not only in terms of raw materials and energy use in the construction sector, but also in terms of consumers' and producers' behaviour. This is in line with the aim to ensure sustainable behaviours in the construction processes, both in the private contexts and in the public ones, since the early design stages. In fact, as known, Circular Economy is founded on the self-generative economic system concept (the waste generated in a process, becomes a resource for another one), and it assumes the decoupling of economic development of a Country from the uncontrolled exploitation of natural resources. Thus, Circular Economy concept can be traced back to the theoretical approach of Life Cycle Thinking, that conceives the project as a process which develops along its whole life cycle, at the different scales: materials, components, systems, buildings, urban districts and territorial areas, infrastructures (European Commission, 2015).

In the international context several associations are promoting the transition to the "from cradle to cradle" economic model. In Europe, companies such as the British Ellen MacArthur Foundation (Ellen MacArthur Foundation, 2012; 2015), allowed European Commission to promote the Circular Economy in its Commu-

---

[§] The author wish to thank the two anonymous Referees for their suggestions.

DOI: 10.13128/aestim-8449

www.fupress.com/ceset

nity policies (European Commission, 2020). In Italy, acknowledging the principles of Circular Economy, the “real estate appraisal and project evaluation” discipline plays a fundamental role in the scientific debate, by providing economic evaluation methodologies which are rapidly evolving towards the international policies on sustainable development. In fact, at the time being the economic evaluation of projects covers a broad spectrum of procedures recently opened to the life-cycle approaches. This spectrum results from the scientific research evolution process, by incorporating the external changes in economy, society, and environment, and it is constantly related to the international regulatory/policies framework which involves the construction sector.

Recently, the estimative research opened up to the energy and environmental impacts assessment beside the economic ones, as decision criteria for selecting project technological alternative scenarios and for supporting the economic management in construction processes, with a view to the Life Cycle Thinking principles (König et al., 2010). Despite the considerable efforts in growing the literature and the empirical studies, a prevailing attention seems to be posed at exploring the life-cycle models for economic-energy-environmental evaluation in the private context. The focus of the disciplinary debate is posed on the implementation of methodologies for evaluating energy retrofit projects of existing buildings or high performance new built construction projects, opening to the use of economic and environmental life cycle approaches, such as Life Cycle Cost Analysis (LCCA) (ISO 15686-5:2008; ISO 15686-5:2017) and Life Cycle Assessment (LCA) (ISO 14040:2006), also through joint applications (see the literature review in Fregonara and Pattono, 2018).

Life-cycle methods in public projects evaluation seem less explored, exception for specific LCCA application contexts as the “green procurement” one (this last is illustrated in Langdon, 2007).

Thus, there are still several research opportunities for developing long-terms evaluative methods able to model costs and benefits in economic, financial, environmental and social terms, according to the recent holistic view of “global sustainability”.

With these premises, among the topics highlighted for this Special Issue of *Aestimum*, the evaluation of social and environmental benefits and costs of production systems, according to the Circular Economy perspective and in relation to their economic sustainability, seems an interesting challenge under the evaluative-estimative viewpoint. This implies the rethinking of consolidated socio-economic evaluation tools, by introducing life cycle principles.

Among the contexts of analysis, in this work focus is posed on the infrastructural sector, for some relevant motivations. In fact, in Europe, a great portion of infrastructures was built in reinforced concrete before 1960 and is approaching the end-of-life stage, or has reached the end of its service life; in some cases, the service quality is below the acceptable level, and the state of conservation is highly weak (Farhani et al., 2018). The issue of infrastructure maintenance deserves great attention from the scientific communities involved, even if – as highlighted by (Farhani et al., 2018) – at the time being the maintenance culture is rather weak.

In Italy, analogously with the main part of European countries, a large number of infrastructures has similar conditions. For these reasons, there is an urgent necessity to promote strategic management, also through the planning of maintenance activities, calibrating different degrees of intervention in view of the work conditions (light ordinary maintenance intervention, main maintenance intervention, repair, replacement, or demolition and reconstruction).

From these premises, the aim of this article is to propose a methodology for supporting infrastructure management and investment decisions in maintenance planning, assuming a consolidated approach for public projects evaluation – the Cost Benefit Analysis (CBA) – and a recent implementation of LCCA approach – the Life Cycle Cost Benefit Analysis (LCCBA) – and integrating them in a life cycle perspective.

The work develops in three parts: firstly, a synthetic recalling of the "classic" CBA approach is presented (Eckstein, 1957, Marglin, 1963; Mishan, 1974; Pearce, 1971; Pearce and Nash, 1981). Originally applied for evaluating (among the others) infrastructural projects, and, successively, widely explored in public resource investment and in cultural heritage enhancement projects, the approach represents one of the most consolidated models for the socio-economic evaluation of public projects. Secondly, a brief introduction to the LCCBA approach (Thoft-Christensen, 2004, 2006, 2008, 2009, 2012) is proposed, as a tool for supporting long-term investments, management of public services and maintenance planning activities in the infrastructure sector (bridges, roads or highways). The approach, relatively recent, is poorly explored despite its potentialities as a tool for testing the economic sustainability of public projects in a life-cycle perspective, as an alternative to the standard CBA. Thirdly, on the basis of the CBA and LCCBA formalization, an operative modality is illustrated, specifically on the use-maintenance-adaptation phase in the infrastructures' life cycle.

Concluding the work, some open issues are highlighted to address future researches: the possible shift from the Global Cost calculation to the Annuity Method, as a tool to resolve the LCCBA; the service life estimate and maintenance time intervals definition, to guarantee the construction durability; the control of uncertainty components in model input/output data and over time. On the background, "life cycle management", "optimal planning maintenance" and "durability" concepts are assumed.

The paper is articulated as follows. In the section 2 the fundamentals of the Cost Benefit Analysis approach are recalled, according to the standard model. In the section 3 the life-cycle perspective in the evaluation of project sustainability is mentioned, through LCCA method and Life Cycle Cost/Whole Life Cost concepts. The LCCBA approach is synthetically presented, making reference to benefit and cost items detection in a social perspective. In the section 4 an operative modality is presented, for supporting investment decisions in infrastructure maintenance in a social, environmental, financial viewpoint. Finally, the section 5 concludes the article.

2. Cost Benefit Analysis: the socio-economic perspective

To frame methodologically the CBA, it would be necessary to retrace the literature on topic. Considering the vastness of the contributions produced in the decades by the scientific communities, and considering the aim of this paper, a synthesis of the approach is traced, as a tool for supporting the evaluation of public projects economic feasibility (Eckstein, 1957, Marglin, 1963; Mishan, 1974; Pearce, 1971; Pearce and Nash, 1981).

In the evaluative context, the set of the commonly used procedures at the various scales is articulated upon their methodological nature. As known, the approaches are related, alternatively, to the asset/property/resource/project subject to evaluation and differenced according to their public/private nature. CBA is one of the evaluation techniques for testing the feasibility of intervention projects on public assets/resources (architectural, cultural and environmental). It is based on economic-quantitative criteria expressed through a monetary unit, and on synthetic indices of economic profitability, which are capable to measure the "economic value of a project" according to which to accept/exclude alternative project options. Furthermore, CBA is one of the decision-aiding tools for dealing with scarce resources issues.

Recalling well-known aspects, the aim of the technique is verifying the economic feasibility of a project, and, according to the estimative viewpoint, it is included within the scope of the "economic convenience judgments". Synthesizing, the fundamental aspects of CBA are: the transition from financial to economic analysis, the costs and benefit classifying modality, the pricing system, the financial discounting, and the calculation of (financial and economic) profitability indicators. The fundamental difference between financial and economic analyses is that any investment of capital represents a different convenience according to the project promoter. In fact, costs and benefits value is variable in view of the stakeholders that receive benefits/pay costs. Notice that the financial analysis is aimed at evaluating the effects of the project from a financial viewpoint, considering into the model only the input directly quantifiable in monetary terms; therefore, it is carried out from the investor's viewpoint. On the opposite, the economic analysis considers also the effects non directly quantifiable in monetary terms, such as effects on environment, or effects on society and economic activities indirectly involved by the project. In this second case, the analysis is carried out from the collectivity viewpoint.

Operatively, the analyses differ according to the costs and benefit considered. In the financial analysis, financial costs and financial incomes are modelled. Otherwise, the economic analysis considers: financial costs calculated through shadow prices, plus opportunity costs calculated through lost revenues obtainable from the best alternative investments; environmental costs quantified as environment damages or negative externalities; then, financial incomes plus social benefits or positive externalities. Furthermore, they differ according to the prices system adopted: market prices for financial analysis and shadow prices for the economic one. Notice that shadow prices should represent the fair appreciation from society expressed in terms of willingness-to-pay (or, better, capability-to-pay) for a good or a service (Pearce, 1971). In fact, market prices are not always capable to reflect the actual consumers' willingness-to-pay. Furthermore, and, above all, some market prices do not reflect the system of social priorities in place at the time to which the project refers. The divergence between market and shadow prices founds on the divergence between economic and political judgment, and their different evaluation perspectives: all these issues are extensively dealt with through the Welfare Economics.

According to the Welfare Economics theories, costs and benefits of a public project are defined in terms of "social costs" and "social benefits". Respectively, social costs and benefits are defined by summing two components.

The social costs are the sum of financial costs (in other terms, a component related to costs directly quantifiable in monetary terms, for example construction costs necessary for the execution of the work), and externalities (a second eventual component, represented by costs not directly quantifiable in monetary terms, such as environmental damages due to execution of the work, or the goods and services which must be renounced for the project realization). The social benefits, similarly, are calculated by summing a first financial component named financial revenues (directly quantifiable in monetary terms) obtainable by the project, and a second component named positive externalities eventually present (not directly quantifiable in monetary terms, for example, goods and services provided by the project which increase the well-being of the community). Thus, the differences between social costs and benefits are mainly represented by the presence of, respectively, negative/positive externalities, and more precisely the positive or negative alterations of the utility without the payment of money.

Social costs components are deeply treated in literature (see for example Pigou, 1932; Coase, 1960, Pearce and Nash, 1981).

Operatively, for defining costs the concept of opportunity-cost is used, whilst for defining benefits the concept of willingness-to-pay is adopted (which in turn is resolved through the shadow prices system, or through the consumer's surplus calculation, or other methods), since, as said before, market prices do not reflect the actual willingness-to-pay. Notice that all this applies if costs and benefits are detectable, otherwise the closest to them are used.

It is still worth reminding that the benefit determination can be reinforced by the Total Economic Value, which components –Vicarious Value, Option Value, Bequest Value, Existence Value- can be calculated through appropriate techniques and thus modelled as benefits into the economic analysis of the CBA (among the founding contribution on the Total Economic Value theory, see Boyle and Bishop, 1985; Krutilla, 1967; Weisbrod, 1964). These appropriate techniques consist mainly in approaches explored for public assets assessment, such as the direct methods founded on hypothetical markets (e.g. Contingent Valuation Method and its variants), or indirect methods founded on substitute markets (e.g. Travel Cost Method, and Hedonic Prices Method). Thus, for CBA environmental and health impacts are internalized into the model.

Furthermore, a line of research develops towards the conjunction of CBA with Impact Analysis for evaluating the costs/benefits streaming from the project to the stakeholders and social groups involved, on the basis of the Lichfield's Community Impact Evaluation methodology (Coscia et al., 2015; Torre et al., 2017).

Coherently with the generality of models, input data detection and quantification is a crucial step in CBA: the robustness of the analysis results is in view of input data quality. In literature, attention is given firstly to the possible classification of CBA input items (costs and benefits). For example, a common classification distinguishes cost items between primary costs (construction or reconstruction cost, use and maintenance of the whole project), secondary costs (cost for product transformation and marketing), indirect costs (costs for other investments feasible or necessary due to project realization), intangible costs (not directly quantifiable in monetary terms). As concerns benefit items, a distinction is made between principal benefits (e.g. increase in surplus value, reduction in costs for the project implementation), and secondary (e.g. increases in surplus value, lower costs for economic activities correlated to the project), indirect benefits (e.g. higher wage incomes), and intangible benefits (not directly quantifiable in monetary terms).

A further distinction is made between direct costs and benefits, which are the investment and running costs that compete to the subject responsible of the execution and management of the investment work, and indirect costs and benefits, for investment and running, that compete to other subjects. These last can furtherly be articulated in cost items related to collateral works, necessary to the functioning of the work under evaluation, costs related to economic activities induced by the intervention, and, finally, externalities. Notice that the investment costs are referred to the public work execution and to the induced/derived works, including renewals, replacements, and extraordinary maintenance. Whilst running costs are referred to cost items for the management of the public work and induced/derived ones, including ordinary maintenance costs.

To conclude this section, it is worth mentioning that one commonly used synthetic profitability indicator, in financial and economic analyses, is the Net Present Value (NPV). It indicates the discounted project value calculated through the discounted sum of the net cash-flows, both in relation to the financial analysis and to the economic one. Still in a temporal perspective, the NPV is accompanied by the Internal Rate of Revenue (IRR), which indicates the rate that makes the value of the investment equal to the initial cost (maximum weighted remuneration/risk), and, finally, the Discounted Benefit/Cost Rate which indicates the benefit amount against the total cost, when comparing alternative projects.

Formally, as reported in the literature, the NPV can be expressed as in Equation (1):

$$NPV = \left(\sum_{i=0}^{N} \frac{B_p}{(1+r)^t} - \sum_{i=0}^{N} \frac{C_p}{(1+r)^t} \right) - \left(\sum_{i=0}^{N} \frac{B_{wp}}{(1+r)^t} - \sum_{i=0}^{N} \frac{C_{wp}}{(1+r)^t} \right) \tag{1}$$

where: B_p stands for the benefit in presence of the project, C_p stands for the costs in presence of the project, B_{wp} represents the benefits in the hypothesis without intervention (or conservation scenario), C_{wp} the costs in the hypothesis without intervention, r stands for the discount rate and, finally, N represents the lifespan of the analysis.

The Equation (1), as reported in the literature, can be rewritten as follows, where NB_p stands for the net benefits with intervention and NB_{wp} stands for the net benefits without intervention:

$$NPV = \sum_{t=0}^{N} NB_p \cdot \frac{1}{(1+r)^t} - \sum_{t=0}^{N} NB_{wp} \cdot \frac{1}{(1+r)^t} \tag{2}$$

Despite the simplicity of the formula, the input calculation is complex. A wide literature is devoted to the costs and benefits calculation, specifically for the external components, and the discount rate determination is still an open issue. More demanding is quantifying the social cost and benefit components by means of shadow prices or other alternative methods: for example, it is usually difficult defining the boundaries of the territorial basin within which to quantify costs and benefits, in particular the indirect ones (i.e. costs and benefits induced by the realization of a project). As concern the discount rate, in general, this is conceived in terms of public discount rate, or cost-opportunity rate, or social rate of time preference, and it is normally assumed lower than the private one.

Finally, the project lifespan determination is another delicate step, due to the long time horizon in public projects evaluation and its direct impact on the discounting operation. The service life, which represents the "economic life" of the project, is another crucial point of the analysis. In some case it is defined as the timespan beyond which the net marginal annual benefit, discounted to the initial year, produces irrelevant increases in the net economic present value. A suggested solution, among the others, is to adopt weighted time horizons on the basis of the relevance of the yearly discounted values (also with the support of reference thresholds).

In conclusion, for reminding the base rule to support the decision-making processes, even in the case of infrastructure projects (as roads, highways or bridges), the net benefits must be higher than the costs, considering that the net benefits must also be higher than the net benefits obtainable through any other alternative use of the capital considered for the analysis. Notice that, when in presence of environmental/social damages, cost estimation is the core of the evaluation and decision process. Then, it is worth notice that CBA founds on incomes and outcomes cash-flows according to the Discounted Cash Flow Analysis Anglo-Saxon approach, moreover object of advanced application in private-public partnership interventions (Tajani et al., 2019). The financial flows stream over a project time horizon that covers the design, execution and management stages, differently from the circular view illustrated in the next section.

3. Life Cycle Cost Benefit Analysis: the "circular" perspective

The LCCA, or Life Cycle Costing (LCC) approach, is widely studied in the literature (Department of Energy, 2014; Flanagan, 1983; Langdon, 2007). As said before, LCCA is normed by the Standard ISO 15686:2008, revised by ISO 15686-

5:2017. In Italy, as a decision criterion it is introduced on April 18, 2016, through the Legislative Decree no. 50, implementing Directives 2014/23/EU, 2014/24/EU and 2014/25/EU of the European Parliament and European Council of 26 February 2014 "on public procurement and awarding concession contracts, procurement by entities operating in the water, energy, transport and postal services sectors and on the reorganization of the Public Procurement Regulation" (New Code).

The methodology, aimed at evaluating the economic sustainability of projects favouring the assessment of project performance in terms of energy consumptions and savings, founds on the calculation of the Global Cost. This last, as indicated by the Standard EN 15459:2007 – Energy performance of buildings – Economic evaluation procedure for energy systems in building, revised by Standard EN 15459-1:2017, formally is expressed by the following Equation (3):

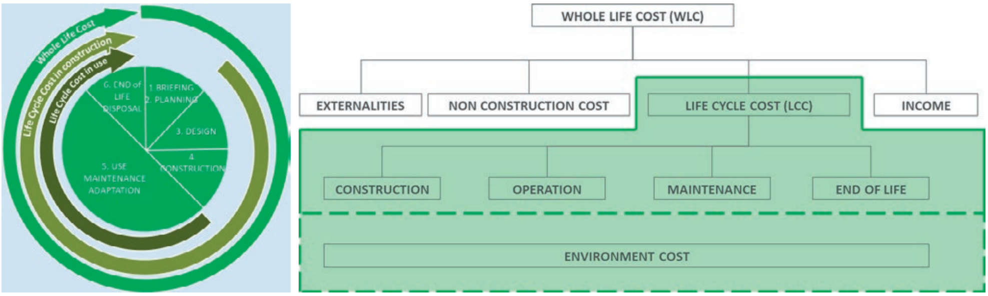
$$C_G(T) = C_I + \sum_{J} \left(\sum_{i=0}^{N} (C_{a,i}(J).R_d(i)) - V_{fT}(J)\right) \tag{3}$$

where $C_G(T)$ stands for global cost to the initial year T, C_I stands for initial investment costs, $C_{a,i}$ (J) stands for annual cost during year i of the component J (this cost item includes the annual running costs such as energy, operational and maintenance costs, and periodic replacement costs), R_d (i) stands for discount factor referred to the year i, finally $V_{f,T}$(J) stands for (eventual) residual value of the component J at the end of the project time horizon, referred to the initial year.

It is worth noting that, at the basis of the operative modality, the Life Cycle Cost concept is assumed. In Figure 1, left side, the life cycle phases in the construction process are graphically represented, as illustrated in the ISO 15686-5:2008, and, in the same Figure, right side, the Life Cycle Cost and the Whole Life Cost concepts are schematized.

As can be seen from the figure, Whole Life Cost and the Life Cycle Cost are different. The Whole Life Cost refers to the overall set of relevant initial/future costs/benefits, that come up in the course of the entire construction life cycle given specific performance requisites. In other words, the Whole Life Cost is a broad-

Figure 1. Life cycle stages in the construction sector. Life Cycle Cost and Whole Life Cost concepts (Source: Author's elaboration based on Standard ISO 15686-5:2008).



ened concept of cost, directed to include external factors (externalities), costs not directly related to construction, and incomes (for example, savings on management investments or "negative costs"). Instead, the Life Cycle Cost covers cost items of a project/component during its life cycle, to meet the performance required. Both consider some component of environmental costs, for two reasons. Firstly, the environmental costs are themselves streamed along the life cycle of the project. Secondly, both Whole Life Cost and Life Cycle Cost include energy costs (electricity/gas consumptions during the life cycle) which can be considered as a proxy of environmental negative impacts Notice that, in some cases, environmental costs can include also the Embodied Energy and the Embodied Carbon in each life cycle phase, quantified (through Life Cycle Assessment - LCA approach), and transposed into monetary terms.

The difference between the two cost categories is fundamental for the coming considerations.

According to our knowledge, the LCC analysis seems poorly explored in the context of public projects. Among the rare studies emerges the research conducted at the Aalborg University in Denmark (Thoft-Christensen, 2004, 2006, 2008, 2009, 2012). The research founds on the use of the LCC analysis, opportunely integrated, as a tool for supporting the management activities in the case of infrastructures (such as roads, highways, bridges, etc.), and, specifically, to support infrastructure maintenance planning.

The Thoft-Christensen's proposal founds on some preliminary theoretical/operative assumptions, synthetized below. In the case of infrastructures and considering their life cycle, the Author distinguishes the following three analytical approaches:

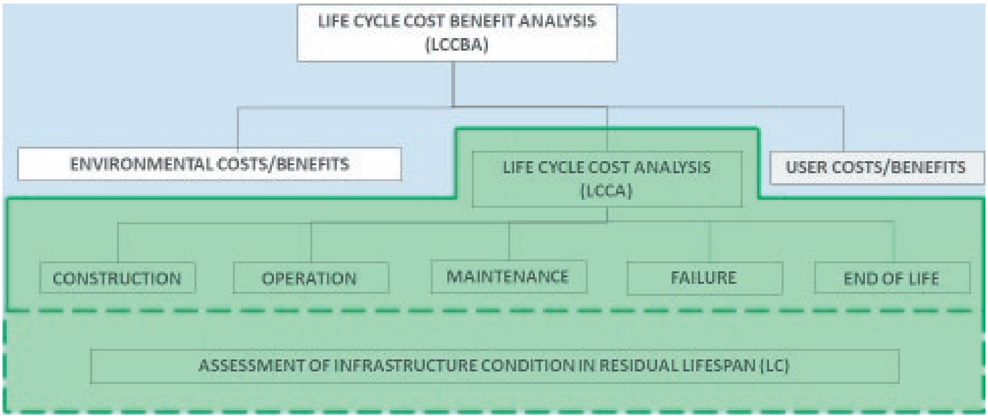
- LC - Life Cycle analysis. This is a simple assessment of the infrastructure condition in the residual lifespan (estimated maintenance costs, failure costs and environmental costs are not considered);
- LCC - Life Cycle Cost analysis (or LCCA). This is a LC analysis including estimated maintenance and failure costs;
- LCCB - Life Cycle Cost Benefit analysis (or LCCBA). This is a LCC analysis that includes also user costs/benefits and environmental costs/benefits.

As emerges from this first assumption, LCCB analysis is an "extended LCC analysis", in coherence with the difference between Life Cycle Cost and Whole Life Cost concepts traced before, in that Whole Life Cost category includes social and environmental costs/benefits (externalities).

Summing up, similarly to the Figure 1, in the following Scheme 1 the comparative difference between LC, LCC and LCCB is presented.

Operatively, LCCB analysis avails of benefits and costs calculated considering the whole life cycle of the project. Specifically, as illustrated in (Thoft-Christensen, 2012), the benefits are expressed by the sum of benefit components produced by the project in the society, for owners, users, and on the environment, as in the following Equation (4), in which the benefits are intended as net benefits:

Scheme 1. LCCBA, LCCA, LC Analyses. Schematic comparison.



$$LCCB = B_{society} + B_{owner} + B_{user} + B_{environment} \tag{4}$$

Similarly, costs are expressed by the sum of cost components produced by the project in the society, for owners, users, and on the environment, as follows:

$$LCC = C_{society} + C_{owner} + C_{user} + C_{environment} \tag{5}$$

Notice that the cost items in Equation (5) include, also, the costs items foreseen by the LCC analysis, distinguishing and spreading the parts that fall on the different subjects/contexts (society, owner, user, environment). For example, maintenance and failure costs compete to owners, but the negative effects deriving from a maintenance intervention (translated in monetary terms for example by quantifying the costs due to the working time losses) compete to users.

Then, notice that these components are to be intended as expected values, assuming the presence of uncertainty (as will be discussed in the section 4 of the present paper).

It is useful to point out that the owner cost/benefit items are deeply studied in the consolidated literature related to the evaluation of life cycle projects in the infrastructure sector, whilst society and user cost/benefit components (direct and indirect) are less explored. Thus, the recent research is highly focused on user costs estimation, for compensating the gap in the literature but above all for the following motivations (Thoft-Christensen, 2012):

- firstly, user costs can be (even sensibly) higher than the total costs, and therefore it is not methodologically acceptable to omit their calculation;
- secondly, the cost items estimation frequently allows benefit calculation (at lease in relation to some specific item), in terms for example of savings, negative costs, avoided costs, etc.

Similarly, the environmental cost/benefit components are particularly difficult to assess. The following aspects are to be considered:

- usually, environmental costs/benefits are treated in terms of impacts due to emissions in the environment, waste production, consumptions, recycling and disposal, according to the Circular Economy and the Green Economy principles;
- other items – as traffic delays, time lost, disruptions, detours, etc. – must be considered, being deeply relevant for the evaluation process: these items can be sensibly higher than repair, maintenance and adaptation costs.

Despite the complexity, costs and benefits calculation is fundamental for supporting management strategies, which aim is to maximize the benefits and minimize the costs, both in the case of new built infrastructures and in the case of interventions on existing ones, for example after a structural assessment. In this last case, when input data on deterioration, repair intervals/cost amounts are available (for example from direct observations or experts' opinions), the maintenance strategy can be defined as illustrated by the Author on the basis of the following Equation (6):

$$\max LCCB = \max \left(B - C_{repair} + C_{user} + C_{environment}\right) \quad (6)$$

The Author continues with the implementation of an operative modality for supporting the decisions between alternative interventions (repairs), by optimizing the following (adapted) Equation (Thoft-Christensen, 2012):

$$\max_{t_R, n_R} \sum_{t=0}^{nL} \left(B(t_R, n_R) - C_{repair}(t_R, n_R) - C_{failure}(t_R, n_R) - C_{user}(t_R, n_R)\right) \quad (7)$$

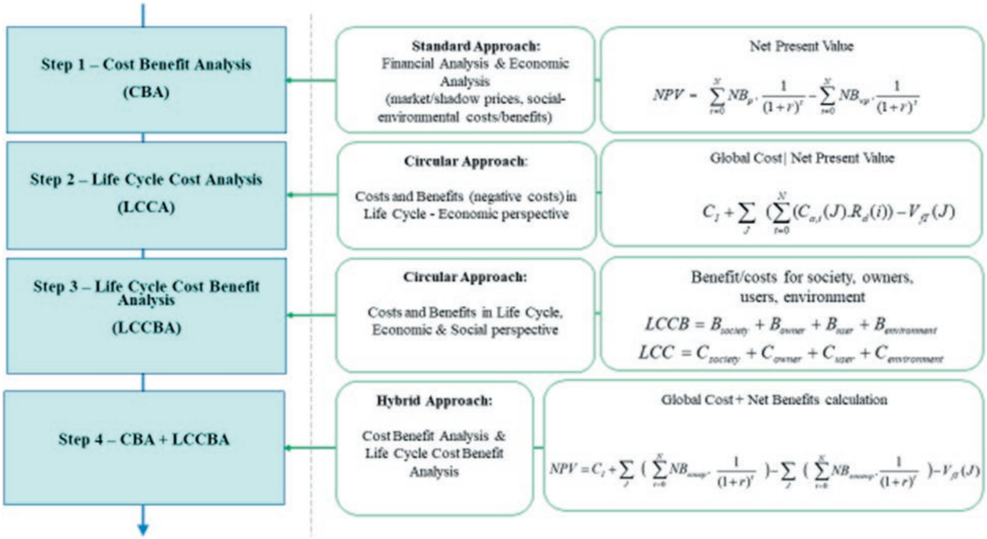
where n_R represents the expected number of repairs in the residual lifespan (first optimization variable), t_R represents the time of the first repair (second optimization variable), B represents the total expected benefits in the residual lifespan. The value of B, detracted the expected repair costs C_{repair} and the expected failure costs $C_{failure}$, both discounted at the initial time t=0, is to be optimized.

To conclude, notice that the literature demonstrates that costs for repair and/or failure of infrastructures are considerably higher than repair or replacement costs; furthermore, that user costs are higher than repair costs. These costs are directly related to maintenance planning strategies and investments: thus, these last must be minimized not only in relation to the owners' component but also to the users' one. This justifies the use of LCCB analysis in the evaluation and planning of infrastructure interventions.

4. An operative modality based on CBA-LCCBA for infrastructure management

To support the reading of the work, the graphic abstract illustrated in the following Scheme 2 may be useful. In the scheme, the methodological steps are summed up.

Scheme 2. The methodological steps of the proposed operative modality. Schematic abstract.



According to the classic CBA model, the economic and financial analyses are solved through the calculation of synthetic financial/economic indicators, above all the NPV and the IRR. As said in section 2, the NPV is calculated by hypothesizing the scenario "with intervention", and the scenario "without intervention" (or "option zero"), for testing the acceptability of an investment. When in presence of alternative project options, the NPV supports the preferability ranking of alternatives. Through an intergenerational approach future generation impacts in terms of costs and benefits are included in the model, by monetizing the effects potentially produced by the intervention on environment, society, economy, culture, according to a broad concept of feasibility.

As highlighted in section 3, Circular Economy and Life Cycle Thinking principles introduce a more complete perspective for treating the impacts/effects of a project over time, particularly suitable for comparing technological scenarios under an economic viewpoint. Practically, the work breakdown of the alternative scenarios is fundamental for the cost/benefit assessment.

Following the LCCBA idea, the project/intervention preferability can be calculated by the difference between benefits and costs produced by the project/intervention during its life cycle (or during the residual lifetime), as in the following Equation (8):

$$LCCBA = LCCB - LCC \tag{8}$$

The acceptability of a single investment is verified through the positivity of LCCBA; the highest LCCBA represents the preferable alternative project, when in presence of a set of project options. Considering the Equations (4) and (5) illustrated in the previous section, the Equation (8) can be rewritten as:

$$LCCBA = (B_{society} + B_{owner} + B_{user} + B_{environment}) - (C_{society} + C_{owner} + C_{user} + C_{environment}) \tag{9}$$

Evidently, the presence of social costs/benefits, negative/positive impacts on users and environment due to the intervention represents a fundamental difference between LCCA and LCCBA; thus, as said before, LCCBA can be defined as an "extended" and more complete LCCA, likewise the Whole Life Costing approach.

Considering a single intervention, for example the repairing of the road paving as a part of a maintenance work, the Equation (1) integrated by Equation (9) can be rewritten as follows:

$$\begin{aligned} NPV = &\left(\sum_{t=0}^{N} \frac{B_{p_{society}} + B_{p_{owner}} + B_{p_{user}} + B_{p_{environment}}}{(1+r)^t} - \sum_{t=0}^{N} \frac{C_{p_{society}} + C_{p_{owner}} + C_{p_{user}} + C_{p_{environment}}}{(1+r)^t} \right) + \\ &- \left(\sum_{t=0}^{N} \frac{B_{wp_{society}} + B_{wp_{owner}} + B_{wp_{user}} + B_{wp_{environment}}}{(1+r)^t} - \sum_{t=0}^{N} \frac{C_{wp_{society}} + C_{wp_{owner}} + C_{wp_{user}} + C_{wp_{environment}}}{(1+r)^t} \right) \end{aligned} \tag{10}$$

This last formula, according to Equation (2) and to Equation (3), can be rewritten as follows:

$$NPV = C_I + \sum_J \left(\sum_{t=0}^{N} NB_{souep} \cdot \frac{1}{(1+r)^t} \right) - \sum_J \left(\sum_{t=0}^{N} NB_{souewp} \cdot \frac{1}{(1+r)^t} \right) - V_{fT}(J) \tag{11}$$

This formula represents a "hybrid procedure", being obtained by integrating the NPV calculation according to CBA approach and the NPV (or Global Cost) calculation according to LCCA. Once verified the positivity of NPV, the preferability of the alternative options is assigned according to "the highest the best" NPV value.

Recalling the above mentioned example, the initial investment costs are not included, being the evaluation referred to the use-maintenance-adaptation phase in the infrastructure life cycle, with a repair intervention at a certain point in the lifetime of the construction.

Despite the simple change made to the calculation modality, the potentialities are remarkable. Nevertheless, the effective applicability of the procedure depends on some operative issues which must be furtherly explored as will be traced below.

4.1 Global Cost vs Annuity Method

As known, the norm EN 15459:2007/2017 illustrates two alternative modalities for calculating the energy performance in the building sector: Global Cost and the Annuity Method. The first one is widely explored in the literature, being the fundamental of LCCA, even in the infrastructure sector (Paganin et al., 2020), whilst the second one is poorly studied, at least to our knowledge. Among the rare studies on the second approach, can be also mentioned applications in the road pavements context (Diependaele, 2018).

The Annuity Method, or Equivalent Annual Cost approach, is based on the calculation of the annual costs of a building/system/component, through the combination of all the relevant costs into a single annualized mean cost, by means of the annuity factor a(n). Substantially, this last is the reciprocal of the discount factor, or the "present value of the discount factor". Formally, the Annuity Cost can be expressed as in the following Equation (12):

$$AC = C_r + \sum_i (a(i).\sum_j V_0 \ (j)) + \alpha(\tau\_{Building}).(\sum_j V_0 \ (j)) \tag{12}$$

for j, where τ (j) = i < t _ Building for j, where τ_n (j) ≥ t _ Building

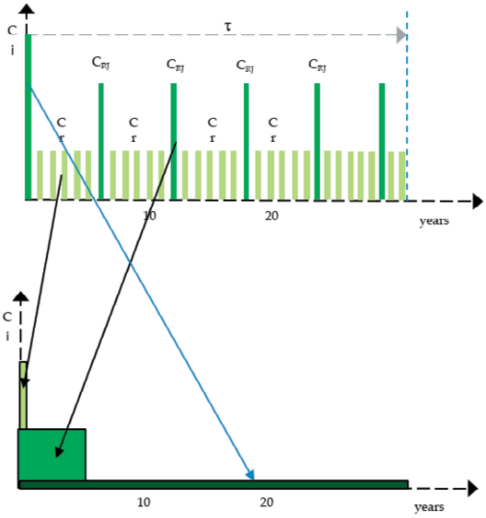
where AC is the Annuity Cost, C_r is the annual running cost (energy, operation, maintenance, etc.) yearly distributed, Σ(a(i).(Σ V_0(j)) is the total annualized cost related to j components/systems replacement, when the service life is lower than the building life cycle, α(τ_Building).(Σ V_0(j)) is the total annualized cost related to j components/systems replacement, when the service life is unchanged during the building life cycle, being the life cycle longer than the building's one, Σ(a(i) is the annuity factor when the component service life is lower than the building life cycle, α(τ_Building) is the annuity factor when the component service life is longer than the building service lifespan. Notice that the whole Equation (12) is describing the Annuity Cost for a single building/system/component, thus the expression (τ_Building) is referred to the single building lifespan considered for the calculation, and compared to the system/component lifespan.

In the formula, the cost components are summed – not discounted –, and the yearly costs are supposed constant (see the schematic example in Figure 2).

The method, particularly in presence of alternative technological scenarios, can effectively support the preferability ranking of projects. The lowest Equivalent Annual Cost is the preferable result, in view of "optimal maintenance planning": it corresponds on one side to the lowest preventive maintenance cost, and, on the other side, to the time interval between maintenance interventions capable to guarantee the required asset efficiency given limited financial resources. Implicitly, the time interval between each intervention is "expressed" through a monetary amount (as will be clarified in the next sub-section).

Thus, analogously to the Net Present Value hybrid formula expressed in Equation (11), by interpreting the Equivalent Annual Cost in a social-environmental-economic view, the following Equation can be obtained:

Figure 2. Annuity cost calculation – schematic example (Source: Author's elaboration based on CEN 15459:2007 – Energy performance of buildings – Economic evaluation procedure for energy systems in buildings, Final Draft, p.17).



$$AC_{soue} = C_{r\,soue} + \sum_i (a(i).\sum_j V_{0\,soue}(j)) + \alpha(\tau\_Building).(\sum_j V_{0\,soue}(j)) \tag{13}$$

where AC_{soue} is the Annuity Cost including costs/benefits for society, owner, user, environment, C_{rsoue} is the annual running cost (energy, operation, maintenance, etc., including society, owner, user, environmental costs/benefits) yearly distributed, $\Sigma(a(i) * (\Sigma V_{0soue}(j))$ is the total annualized cost/benefit related to j components/systems replacement, when the service life is lower than the building life cycle, $a(\tau\_Building) * (\Sigma V_{0soue}(j))$ is the total annualized cost/benefit related to j components/systems replacement, when the service life is unchanged during the building life cycle, being the life cycle longer than the building's one, $\Sigma(a(i)$ is the annuity factor when the component service life is lower than the building life cycle, $a(\tau\_Building)$ is the annuity factor when the component service life is longer than the building service life.

As argued in a recent study (Fregonara and Ferrando, 2020), the Annuity Method is suitable for testing maintenance interventions sustainability: in that case, two alternative building components are compared, assuming the perspective of the owner and a middle-term evaluation lifespan. All the more so in the case of the infrastructures, assuming a multiple perspective – owner, user, society, environment –, making reference to public works, and dealing with long-term lifespan projects.

Even if the Net Present Value and the Equivalent Annual Cost can solve equally the evaluation exercise, the Equivalent Annual Cost is preferable when the budget is defined on annual basis (according to the owner viewpoint), and, we can argue, even in long-term preventive cost planning. Furthermore, annualized amounts can better support the decision making process specifically when comparing different options, by giving less relevance to the total cost amounts of each alternative. For these reasons, and above all for the possibility to include also user/society/environmental costs into the model, it is worth exploring the effective applicability of (13).

4.2 Service life estimate, maintenance time intervals and durability

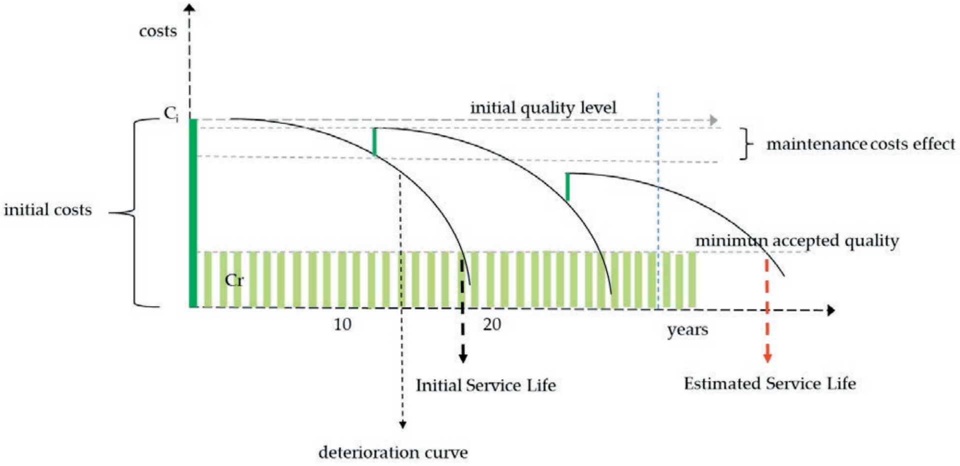
The operative modality presented in this section and formalized in (11) is suggestable for calibrating infrastructure optimal maintenance strategies. Nevertheless, the service life estimate represents a delicate step for the applicability of the approach. In fact, service life estimation implies the definition of maintenance time intervals capable to guarantee the maximum durability of the product, at the lowest investment on management costs. Durability in turn is a function of investments in maintenance and management activities.

This issue is faced in recent studies by exploring LCCA as a tool to support maintenance costs planning in the construction sector capable to guarantee the durability of a building/component/system/infrastructure given an acceptable quality level. The service life estimation is explored under different views, and, in general, deterministic or probabilistic approaches are used for modelling uncertain economic lives into the models application. Among the studies produced in the estimative-evaluative context, for example, researches propose the "engineering approach" through the stochastic approach to Factor Method, in order to estimate the service lives according to the probabilistic approach (Aarseth and Hovde, 1999; Fregonara and Ferrando, 2018; Galbusera et al., 2014; Gaspar and de Brito, 2008; Hovde and Moser, 2004; Moser and Edvardsen, 2002; Silva et al., 2016).

Many other studies produced in the civil engineering context are based on the analysis of the effects of maintenance interventions on construction performance, with the support of specific tools as, for example, the deterioration analyses. The reasoning capable to join the technological dimension to the economic one is fundamental for the present study, as for the generality of researches that streams from the concept of service life. In the schematic example in Figure 3, a simple performance curve is presented. Given an initial investment cost able to guarantee the higher quality level, to which corresponds an initial service life, for improving the quality level after the deterioration of the component, a maintenance investment is necessary. With each maintenance intervention the quality level increases, but less than proportionally, as far as the minimum acceptable quality level is reached. Obviously, the equilibrium between maintenance investments and improvements in quality level over time is variable. The aim is to identify the optimal point, which corresponds to the maximum service life at the lowest cost.

Thus, the "optimal maintenance planning" in function of life cycle costs and in presence of financial constraints is a second research address to be explored according to an economic viewpoint at the infrastructure scale.

Figure 3. Preventive maintenance cost effects: improvement of quality level and component durability. Schematic example.



4.3 Uncertainty in life cycle approaches

As mentioned before, the input data in the Equations presented in the study should be considered as expected values. In fact, uncertainty for example in deterioration processes as well as uncertainty in the market due to the variability in prices and demand dynamics, is capable to generate relevant consequences in maintenance costs/benefits prediction and in infrastructure projects/interventions/maintenance strategies. As recommended in literature, the uncertainty and risk should be controlled by introducing flexibility into the model, both in model input estimates, and in model output calculation. Among the studies, a first group aims at modelling the uncertainty in LCCA application through deterministic approaches. Despite the simplicity, the results of the analyses are limited. A step forward is represented by the probabilistic approaches to the LCCA as proposed in recent or relatively recent works (Arja et al., 2009; Boussabaine and Kirkham, 2004; Flanagan et al., 1987; Fregonara et al., 2018), some of which referred to the infrastructure sector (Del Giudice et al., 2014; Frangopol, 2011; Menendez and Gharaibeh, 2017; Padget et al., 2010; Scope et al., 2016; Sun and Carmichael, 2018). Thus, the stochastic Global Cost and the stochastic Annuity Method can be formalized, by modelling input data as stochastic variables and by solving the models through the Probability Analysis and the Monte Carlo Method.

The shift from the deterministic approach to LCCBA to the probabilistic one represents a third address for implementing the research.

5. Conclusions

In this article a methodology for supporting the maintenance investments planning in function of life cycle costs and benefits was presented, assuming the presence of uncertainty over time and focusing on the use-maintenance-adaptation stage in the infrastructures' life cycle. An operative modality was proposed for ranking the economic sustainability of alternative project options, which implies different cost/benefit amounts for maintenance-replacement interventions over time.

Assuming the Circular Economy principles, the work tried to implement the evaluation of potential impacts on production and consumption processes, specifically in terms of costs and benefits impacting on consumers and producers behaviours. The objective was to ensure sustainable dynamics in the public/private construction processes, since the early design stages till the end-of-life stage and focusing on the use-maintenance-adaptation phase. Implicitly, it was assumed that new concepts of economic development are deriving from the awareness of environmental issues, for protecting natural systems: among these, the Circular Economy concept involving different activities: raw materials extraction, use-maintenance-adaptation, final disposal, reuse or recycle. By tracing back the Circular Economy concept to the theoretical approach of Life Cycle Thinking, and thus considering the project as a process which develops along its whole life cycle, at the different scales and from the single technological component to the whole building, the Life Cycle Costing Approach in conjunction with Cost Benefit Analysis was explored.

Considering that the paper intended to be a methodological reflection and that the proposed modality must be supported by empirical evidence and applications, some potentialities and limits emerge. Among the potential advantages, the modality can be capable to support decision-making between alternative technological scenarios in public projects including impacts on society, users and environment, overcoming the LCC analysis and other consolidated approaches for which the owner viewpoint prevails. Moreover, in the case of infrastructures, the operative modality could be less time-expensive than the traditional CBA approach, and more suitable for treating the technological-economic components beside the social ones in the project evaluation. Nevertheless, a limit is represented by the input data detection as in the generality of the economic evaluation models. As the CBA, it requires the recourse to methods capable to quantify, when possible, externalities and social effects associated directly/indirectly with the interventions. Then, the concrete application of the approach requires the integration with competences from other disciplines (structural engineering, materials science and technology, environmental technology, etc.). Finally, three research directions are still to be explored: the applicability of the Annuity Method as an alternative to the Global Cost one, durability and the life cycle estimate, the probabilistic approach to solve the proposed methods by modelling uncertainty over time.

Summing up, the potentialities and limits of the methodology suggest its application for the socio-economic sustainability of public projects in decision-making contexts that involve the management and maintenance of existing infrastructures/assets, in presence of consistent technical-operational information. More specifically, the potentialities can be valorised (and the limits overcome) when in synergy with Facility Management competences, able to integrate the management of services and processes oriented to constructions, maintenance activities and technical-operational approaches, for supporting in the meanwhile spaces and communities involved in the decisions.

This last consideration highlights, in a certain way, the application domain of the proposed operational steps.

Above all, given the methodological nature of the present study, and given the aim of sharing the knowledge with the scientific community, the application on a concrete case-study is demanded to a future research.

References

Aarseth, L.I., & Hovde, P.J. (1999). A stochastic approach to the Factor Method for estimating service life. In Lacasse M.A., & Vanier D.J. (Eds.), *Durability of Building Materials and Components 8*. Ottawa, Canada, Institute for Research in Construction.

Arja, M., Sauce, G., & Souyri, B. (2009). External uncertainty factors and LCC: A case study. *Building Research and Information,* 37(3), 325–334.

Boussabaine, A., & Kirkham, R. (2004). *Whole Life-Cycle Costing: Risk and Risk Responses*. Oxford, UK, Blackwell Publishing.

Boyle, K.J., & Bishop, R.C. (1985). The Total Value of Wildlife Resources: Conceptual and Empirical Issues. In *Economists Workshop on Recreational Demand Modeling. Association of Environmental Resources,* Boulder Col. 17–18.

Coase, R. (1960). The Problem of Social Cost. *Journal of Law and Economics*, 3 (1), 1–44.

Coscia, C., Fregonara, E., & Rolando, D. (2015). Project Management, briefing and territorial planning. The case of military properties disposal. *Territorio*, 73,135–144.

Del Giudice, V., Passeri, A., Torrieri, F., & De Paola, P. (2014). Risk analysis within feasibility studies: An application to cost-benefit analysis for the construction of a new road. *Applied Mechanics and Materials,* 651–653, 1249–1254.

Department of Energy - DOE (2014). Life Cycle Cost Handbook Guidance for Life Cycle Cost Estimate and Life Cycle Cost Analysis. Washington, DC, USA, Department of Energy (DOE).

Diependaele, M. (2018). A Guide on the Basic Principles of Life-Cycle Cost Analysis (LCCA) of pavements. Brussels, Eupave, European Concrete Paving Association.

Eckstein, O. (1957). Investment Criteria for Economic Development and the Theory of Inter-temporal Welfare Economics. *Quarterly Journal of Economics,* 711, 56–85.

Ellen MacArthur Foundation (2012). Towards the Circular Economy. Economic and Business Rationale for an Accelerated transition. Cowes, UK, Ellen MacArthur Foundation. (Available online:https://www.ellenmacarthurfoundation.org/publications).

Ellen MacArthur Foundation (2015). Growth within: A Circular Economy Vision for a Competitive Europe. Cowes, UK, Ellen MacArthur Foundation. (Available online: https://www.ellenmacarthurfoundation.org/publications).

European Committee for Standardization – CEN (2017). Standard EN ISO 15459-1:2017. Energy Performance of Buildings-Economic Evaluation Procedure for Energy Systems in Buildings. Brussels, Belgium, European Committee for Standardization.

European Union, European Commission (2014). Communication from the Commission to the European Parliament, the council, the European Economic and Social Committee and the Committee of the Regions. Towards a Circular Economy: A Zero Waste Programme for Europe. Brussels, Belgium, 2 July 2014, COM 398 Final. (Available online: http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A52014DC0398).

European Union, European Commission (2015). Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. Closing the Loop—An EU Action Plan for the Circular Economy. Brussels, Belgium, 2 December 2015, COM 614 Final. (Available online: http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52015DC0614).

Farahani, A., Wallbaum, H., & Dalenback, J.O. (2018). Optimized Maintenance and Renovation Scheduling in Multifamily Buildings – A Systematic Approach Based on Condition State and Life Cycle Cost of Building Components. *Construction Management and Economics,* 37 (3), 139–155.

Flanagan, R., & Norman, G. (1983). *Life Cycle Costing for Construction*. London, UK, Royal Institution of Chartered Surveyors.

Flanagan, R., Kendell, A., Norman, G., & Robinson, G.D. (1987). Life cycle costing and risk management. *Construction Management and Economics,* 5, 53–71.

Frangopol, D.M. (2011). Life-cycle performance, management, and optimisation of structural systems under uncertainty: accomplishments and challenges. *Structure and Infrastructure Engineering: Maintenance, Management, Life-Cycle Design and Performance,* 7(6), 389–413.

Fregonara, E., Ferrando, D.G., & Pattono, S. (2018). Economic-environmental sustainability in building projects: introducing risk and uncertainty in LCCE and LCCA. *Sustainability,* 10(6), 1901.

Fregonara, E., & Ferrando, D.G. (2018). How to Model Uncertain Service Life and Durability of Components in Life Cycle Cost Analysis Applications? The Stochastic Approach to the Factor Method. *Sustainability,* 10(10), 3642.

Fregonara, E., & Pattono, S. (2018). A sustainability indicator for building projects in presence of risk/uncertainty over time: a research experience. *Aestimum,*73, 173–205.

Fregonara, E., & Ferrando, D.G. (2020). The stochastic Annuity Method for supporting maintenance costs planning and durability in the construction sector: a simulation on a building component. *Sustainability,* 12(07), 2909.

Galbusera, M.M., de Brito, J., & Silva, A. (2014). Application of the Factor Method to the prediction of the Service Life of Ceramic External Wall Cladding. *Journal of Performance of Constructed Facilities*, 29(3).

Gaspar, P.L., & de Brito, J. (2008). Service life estimation of cement-rendered facades. *Building Research and Information,* 36(1), 44–55.

Hovde, P.J., & Moser, K. (2004). Performance based methods for Service Life Prediction - State of the Art Reports. Rotterdam, Netherlands, CIB Report, Publication 294.

International Organization for Standardization (2006). ISO 14040:2006, Environmental Management—Life Cycle Assessment—Principles and Framework, ISO/TC 207/CS 5. Geneva, Switzerland, International Organization for Standardization.

International Organization for Standardization (2008). ISO 15686-5:2008, Buildings and Constructed Assets—Service-Life Planning—Part 5: Life Cycle Costing, ISO/TC 59/CS 14. Geneva, Switzerland, International Organization for Standardization (revised July 2017, ISO 15686-5:2017).

König, H., Kohler, N., Kreissig, J., & Lützkendorf, T. (2010). *A Life Cycle Approach to Buildings. Principles, Calculations, Design Tools.* Regensburg, Germany Detail Green Books.

Krutilla, J.V. (1967). Conservation Reconsidered. *American Economic Review,* 62(4).

Langdon, D. (2007). Life Cycle Costing (LCC) as a Contribution to Sustainable Construction: A Common Methodology—Final Methodology. (Available online: http://ec.europa.eu/enterprise/sectors/construction/studies/life-cycle-costing_en.htm).

Marglin, S.A. (1963). The Social Rate of Discount and the Optimum Rate of Investment. *Quarterly Journal of Economics,* 771), 95–111.

Mishan, E.J. (1974). *Analisi costi-benefici*. Milano, Etas Libri.

Menendez, J.R.; & Gharaibeh, N.G. (2017). Incorporating Risk and Uncertainty into Infrastructure Asset Management Plans for Pavement Networks. *Journal of Infrastructure Systems,* 23(4).

Moser, K., & Edvardsen, C. (2002). *Engineering Design Methods for Service Life Prediction*. Proceedings of the 9th International Conference on the Durability of Building Materials and Components, Brisbane, Australia.

Padgett, J.E., Dennemann, K., & Ghosh, J. (2010). Risk-based seismic life-cycle cost–benefit (LCC-B) analysis for bridge retrofit assessment. *Structural Safety,* 32(3), 165–173.

Paganin, G., Dell'Ovo, M, Oppio, A., & Torrieri, F. (2020). An integrated decision support system for the sustainable evaluation of pavement technologies. In Mondini G., Oppio A., Stanghellini S., Bottero M., Abastante F. (Eds)*Values and Functions for Future Cities*. Greeen Energy and Technology, Springer, 117–141.

Pearce, D.W. (1971). *Cost-Benefit Analysis*. London, Macmillian.

Pearce, D.W., & Nash, C.A. (1981). *The Social Appraisal of Project. A text in Cost-Benefit Analysis*, London, Macmillian.

Pigou, A.C. (1932). *The Economics of Welfare*, London, Macmillian.

Salem, O., AbouRizk, S., & Ariaratnam, S. (2003). Risk-based Life-cycle Costing of Infrastructure Rehabilitation and Construction Alternatives. *Journal of Infrastructure Systems,* 9(1), 6–15.

Scope, C., Ilg, P., Muench, S., & Guenther, E. (2016). Uncertainty in life cycle costing for long-range infrastructure. Part II: guidance and suitability of applied methods to address uncertainty, *The International Journal of Life Cycle Assessment,* 21(8), 1170–1184.

Silva, A., de Brito, J., & Gaspar, P.L. (2016). Stochastic Approach to the Factor Method: Durability of Rendered Façades. *Journal of Materials in Civil Engineering,* 28(2).

Sun, Y., & Carmichael, D.G. (2018). Uncertainties related to financial variables within infrastructure life cycle costing: a literature review. *Structure and Infrastructure Engineering,* 14, 1233–1243.

Tajani, F., Morano, P., Di Liddo, F., & Lo Curcio, M. (2019). An innovative interpretation. of the DCFA evaluation criteria in the public-private partnership for the enhancement of the public property assets. *Smart Innovation, Systems and Technologies*, 100, 305–313.

Thoft-Christensen, P. (2004). Life-Cycle Cost Design – Why is it not being used? *Proceedings IABMAS 04 (CD) on "Bridge Maintenance, Safety, Management and Cost"*. Kyoto, Japan, Taylor and Francis.

Thoft-Christensen, P. (2006). User Costs in Life-Cycle Cost-Benefit (LCCB) Analysis of Bridges. In Cruz, P.J.S., Frangopol, D.M., Neves, N.C. (Eds.), *Proceedings IABMAS 06 (CD) on "Bridge Maintenance, Safety, Management and Cost"*, Porto, Portugal.

Thoft-Christensen, P. (2008). Modelling User Costs in Life-Cycle Cost-Benefit (LCCB) Analysis, *Proceedings (CD) IFIP WG7.5 Conference on "Reliability and Optimization of Structural Systems"*. Toluca, Mexico, August 6-9.

Thoft-Christensen, P. (2009). Life-Cycle Cost-Benefit Analysis of Bridges from a User and a Social Point of View. *Structure and Infrastructure Engineering*, 5, 49–57.

Thoft-Christensen, P. (2012). Infrastructures and Life-Cycle Cost-Benefit Analysis. *Structure and Infrastructure Engineering*, 8(5), 507–516.

Torre, C.M., Morano, P., & Tajani, F. (2017). Experimenting CIE and CBA in urban restoration. *Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)*, 10406 LNCS, 639–650.

Weisbrod, B.A. (1964). Collective-consumption Services of Individual Consumption Goods. *Quarterly Journal of Economics,* 78(3), 471–477.