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ECONOMIC PERFORMANCE OF BUILDINGS THROUGH LIFE CYCLE COSTING

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Abstract: This paper aims at contributing to the dissemination of Life Cycle Cost as a management tool to face current construction market challenges in terms of economic performance. Recent developments, methodology, advantages, weaknesses, and potential benefits of performing an LCC analysis are presented and discussed. A simplified case study illustrates detailed economic performance calculations for a hypothetical office building whose results presented in Net Present Value are discussed and complemented with case studies reported in the literature. Operation costs related to electric energy consumption for heating and cooling are commonly the main contributors to the LCC of buildings, followed by maintenance costs, which evidences the need to equate costs and energy efficiency, especially to meet the objectives of a sustainable construction market. LCC plays an important role in minimizing costs throughout building's lifespan when performed in the building design phase.

Keywords: Net present value. Economic performance. Sustainability. Service life planning.

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INTRODUCTION

The term Life Cycle Cost (LCC) became popular in the sixties when decision-making used to be merely based on acquisition costs. Since then, concepts that comprise key stages of the life cycle of constructed assets have started to be taken into account (Rodrigues, 2014). Nowadays, LCC is used for the economic evaluation of buildings, either in new construction projects or in the renewal of existing construction assets, based on engineering economic analysis that considers all relevant construction, maintenance, operating, and end-of-life costs, throughout the lifespan, in net present value at the base point.

LCC analysis provides a significantly better assessment of the long-term cost-effectiveness of constructed assets than alternative economic methods that focus only on the initial investment costs or the operational costs in the short run (Mangan & Oral, 2016). For this reason, LCC is becoming a significant decision tool to support decision-making and improve construction competitiveness (Rodrigues, 2014; Heralova, 2017). When performed in the early design phase of a building, LCC analysis guides the main actors and final decision-makers toward more sustainable buildings (Emekci & Tanyer, 2018).

In fact, contemporary approaches to support design decision-making already consider properly balanced costs and environmental impacts over the lifespan, together with functional requirements (Wang *et al*., 2010; Oliveira *et al*., 2013 Rohden & Garcez, 2018; Pedinotti-Castelle *et al*., 2019). Thus, despite not being originally developed in an environmental context, LCC has been used as an economic sustainability indicator (Ahmad & Thaheem, 2018) applied to quantify the costs of whole buildings, systems, and/or components and materials. When incorporated with environmental and social dimensions, LCC results form part of the WLC that may be used to give an insight into building sustainability potential. Recent publications have used WLC analysis to prove that sustainable buildings are not necessarily more expensive than standard buildings (Kapsalaky *et al*., 2012; Tam *et al*., 2017; Huang *et al*., 2018; Robati *et al*., 2018), which contributes to the construction market progress towards green development.

This paper aims to contribute to the dissemination of Life Cycle Cost (LCC) as a management tool to face current construction market challenges in terms of economic performance. Foremost, recent developments, methodology, advantages, weaknesses, and potential benefits of performing an LCC analysis are discussed. Considering that a few publications present mathematical descriptions of the procedures used to perform an LCC analysis, this paper presents a simplified case study whose objective is to illustrate detailed economic performance calculations for a hypothetical office building. Apart from the costs usually accounted for in an LCC analysis, the simplified case study also encompasses non-construction costs and incomes. Results are discussed and complemented with case studies reported in the literature, performed in different countries.

LIFE CYCLE COSTING

Definitions

ISO 15686-5 (ISO, 2017) provides requirements and guidelines for performing LCC analyses of buildings and constructed assets and their parts, attempting to create a usable cost structure for assessing LCC in construction. LCC is formally defined as the cost of an asset or its parts throughout its life cycle while fulfilling the performance requirements. As stated in **Fig. 1**, LCC is part of Whole Life Cost (WLC), which includes all significant and relevant initial and future costs and benefits of an asset.

Life Cycle Costing and Whole Life Costing are defined in ISO 15686-5 (ISO, 2017) as methodologies for the systematic economic evaluation of the life cycle costs and life cycle cost and benefits over the period of analysis, as defined in the agreed scope. Through these methodologies, it is possible to plan new building projects or to compare competing alternatives, account for management decisions, or even address specific needs, taking into account all relevant economic factors in terms of costs or costs and benefits. Typical evaluations that can be performed through LCC analyses encompass building concepts, structural systems, mechanical and electrical systems, building envelopes, etc.

Classification of costs

Costs included in LCC are classified as construction, operation, maintenance, and end-of-life costs. ISO 15686-5 (ISO, 2017) presents a typical scope of costs that may be used to develop cost plans for specific projects, which should consider all basic building elements such as structure, envelope, services and finishes, fixtures, and fittings.

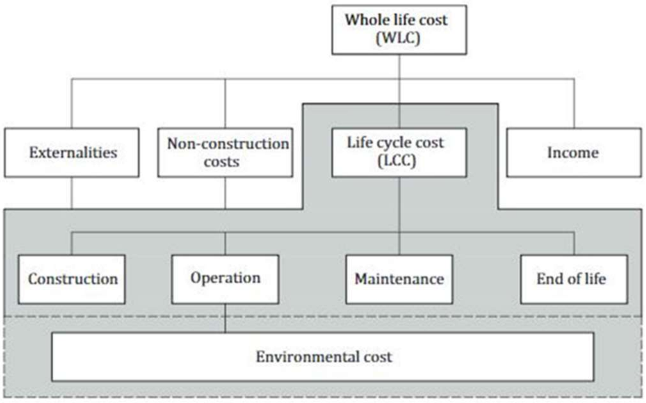


Fig. 1 LCC and WLC elements, based on ISO 15686-5 (ISO, 2017).

In this context, construction costs are those related to professional fees related to statutory consents, project design, and engineering, temporary works, construction of an asset, and initial adaptation or refurbishment of the asset, including infrastructure, fixtures, fitting out, commissioning valuation, and handover, besides taxes and project contingencies.

Operation costs comprehend rent, insurance, cyclical regulatory costs, local and environmental taxes, utilities including energy costs for heating, cooling, power, lighting, and water sewage costs, and costs related to allowance for future compliance with regulatory changes.

Maintenance costs comprise maintenance management, adaptations or refurbishment of an asset in use, including infrastructure, fitting out commissioning, validation, and handover, repairs, and replacement of minor and major components, cleaning, grounds maintenance, redecoration, and taxes on maintenance goods and services.

Finally, end-of-life costs includes disposal inspections, decommissioning, disposal of materials, and site cleanup, reinstatement to meet contractual requirements, taxes on goods and services.

Non-construction costs, incomes, and externalities are referred to as whole-life costs. Non-construction costs are those related to landing and enabling works, interest or cost of money and wider economic impacts, and user support costs related to strategic property management, use charges, and administration, apart from taxes on non-construction items. Income costs include income from sales, third-party income during operation, taxes on income related to land transactions, disruption, downtime, and loss of income. Social, environmental, or business costs or benefits of production and consumption are examples of externalities not valued as market prices for construction. Some examples of externalities related to environmental impacts are air and water pollution outside the construction site that is not priced within the construction costs. Social costs and benefits are those associated with society in general, such as the provision of transport infrastructure whose allowances can be positive, e.g. speedier journeys that improve efficiency, or negative, e.g. costs associated with delay. positive, e.g. speedier journeys that improve efficiency, or negative, e.g. costs associated with delay.

Procedures for LCC analysis

Typically, an LCC analysis may be used in four different key stages of the whole life cycle of a building, according to ISO 15686-5 (ISO, 2017): project investment and planning, design and construction, occupation including maintenance and operation, and disposal. It is complicated, however, to develop a generic methodology to be applied to all cases, which can be justified by the specific characteristics of each asset, as well as by the different customer requirements (Rodrigues, 2014). Gluch and Baumann (2004) argue that due to the complexity of the building process and the many components of a building, an LCC analysis is a data-intensive process.

The first step is to define the purpose of the LCC analysis and the scope of costs included and excluded based on the object that can be a complete or a specific part of new or existing assets. The second step comprehends the estimative costs of each alternative based on the classification of costs described in section 2.2 and illustrated in Figure 1. It is worth noting that this step depends on data such as service, level, and period covered by the LCC analysis, maintenance, major repairs, adaptation, and replacement plans and procedures, end of life plan, etc. LCC is computed first by establishing basic economic parameters such as base point, bid date, bond rate, nominal and real discount rates, escalation rate, and inflation/deflation. Costs of each alternative are compiled based on the respective cash flows, and all cash flows are then discounted to the base point. Finally, a sensitivity analysis may be performed by altering one or more initially set parameters.

Measures of Economic Performance

Several analysis techniques such as simple payback, discounted payback, internal rate of return, the benefit-to-cost ratio, savings-to-investment ratio, net benefit and savings, equivalent annual cost, and net present value have been used to perform an economic evaluation of buildings and building systems. However, Net Present Value (NPV) is the most used technique to calculate the present monetary sum that should be allocated to a future expenditure on an asset or even to compare different alternatives of a building or building systems over the same period of analysis (ISO 15686-5, 2017). Equivalent annual cost (EAC), on the other hand, is more suitable for the assessment of alternatives with different lifespans. More information on building economics and methods for evaluating the economic performance of buildings and building systems can be found in ASTM E833-14 (ASTM, 2014), ASTM E917-17 (ASTM, 2014), and ASTM E1185-15 (ASTM, 2015).

Eq. (1) presents a general LCC model used to determine NPV, calculated by discounting cash flows of costs over the service life to the base point. In Equation 1, NPVc represents the sum of discounted construction costs, NPVo is the sum of discounted operation costs, NPVm expresses the sum of discounted maintenance costs, and NPVeol is related to the discounted end-of-life costs. When performing a WLC analysis, discounted non-construction costs, incomes, and externalities must be included in **Eq. (1). Fig. 2** presents a generic diagram showing cash flow examples for costs and benefits during the period of analysis for a building project.

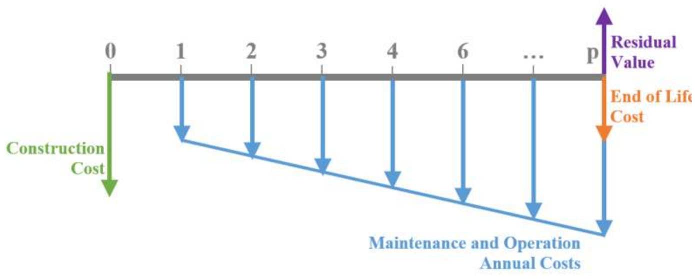


Fig.2 Cash Flow Diagram

$$NPV = NPVc + NPVo + NPVm + NPVeol \quad (1)$$

Costs and benefits discounted to the base point are determined through **Eq. (2,)** where Cn is the real cost or benefit in a year, d is the expected real annual discount rate, q is the discount factor, n is the number of years between the base point and the occurrence of the cost or benefit, and p is the period of analysis. The discount rate used to convert cash flows to the base point reflects the time value of money, which is not constant over the period of analysis.

$$NPV = \sum_{n=1}^{p} \frac{Cn}{(1+d)^{n}} = (Cn\ x\ q) \qquad (2)$$

The real discount rate, in general, assumes that inflation or deflation applies equally to all costs and benefits. Thus, escalation rates, which reflect the differential increase or decrease in the price level of a commodity or resource, allow the simulation of specific scenarios, such as increasing annual energy costs, for instance.

In the private sector, the discount rate represents the opportunity cost of investing the capital, while in the public sector, the discount rate is determined based on value judgments and assumptions that reflect how the government values the future when making decisions on behalf of society (Creedy & Passi, 2017). Social Opportunity Cost of Capital (SOC) and the Social Rate of Time Preference (SRTP) are described by Zhuang *et al*. (2007) as the most common approaches used to define social discount rates in public investments. While for SOC, the discount rate is the rate of return that a decision-maker could earn on a hypothetical next-best alternative to public investment, the SRTP approach defines the discount rate as the rate of return that a decision-maker requires in order to divert resources from use in the present, to public investment (Creedy & Passi, 2017).

ISO 15686-5 (ISO, 2017) recommends the use of real costs/benefits to allow the application of current known information. However, the discount rate allows for inflation/deflation if nominal costs or benefits are considered. The annual nominal discount rate can be calculated by multiplying (1 + d) x (1 + a), where a is the expected annual inflation or deflation. On the other hand, nominal costs or benefits can be calculated by multiplying the real value by $(1 + a)^{n}$, where n is the number of years between the base point and the occurrence of the cost or benefit.

Discount factor q mentioned in **Eq. (2)** may be calculated from compound interest formulas or selected from compound interest factor tables provided in Engineering Economic Analysis books (Newman *et al*., 2017). **Table 1** shows examples of the relationship between the present amount of money (P), future amount of money (F), uniform series (A), arithmetic gradient (G), geometric gradient (g), compound interest formulas, and compound interest factors, using the terminology of Engineering Economics.

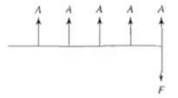
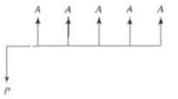
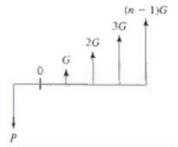
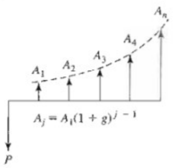
It is worth noting that economic parameters are significant elements of LCC and WLC analysis. As general inflation rates, discount rates, and bond rates values, for instance, are highly affected by changes in economic conditions, accurate long-range forecasts are extremely difficult to make. In fact, the long lifetime of buildings, together with the commercial nature and different increase rates of individual product prices, compared to the average, may decrease the accuracy of economic parameters forecasts (Islam *et al*., 2015). The effects of these uncertainties may be estimated through a sensitivity analysis performed to test the reliability of the LCC or WLC analysis. Sensitivity analysis recalculates original results based on a range of likely economic parameter values to identify over what range such parameters can vary without changing the original results.

Service Life

Service life is defined by EN 15643-2 (BSI, 2011) as the period of time after installation during which a building or an assembled system (part of works) meets or exceeds the technical requirements and functional requirements. Service life and LCC concepts are widely connected since LCC analysis of buildings or building systems are performed over their lifespan.

Eurocode EN 1990 (CEN, 2002) gives indicative design working lives of 10 years for temporary structures, 10 to 25 years for replaceable structural parts, 15 to 30 years for agricultural and similar buildings, 50 years for building and other common structures, and 100 years for bridges and monumental structures. The UK National Annex A1 2005 (BSI, 2005) of BS EN 1990 (CEN, 2002) modifies the indicative design working life of bridges and monumental structures for 120 years. Design working life is defined in EN 1990 (CEN, 2002) as the assumed period for which a structure or part of it is to be used for its intended purpose with anticipated maintenance but without necessary major repair.

Table 1. Relationship between P, F, A, G, and compound interest formulas and factors (adapted from Newman *et al*., 2017).

	To Find	Given	Using Compounding Interest Formula	Using Compound Interest Factor*
Single Payment 	Compound Amount F	P	$F = P(1+i)^n$	$F = P(F/P, i, n)$
	Present Worth P	F	$P = F\frac{1}{(1+i)^n}$	$P = F(P/F, i, n)$
Uniform Series 	Series Compound Amount F	A	$F = A\frac{(1+i)^n - 1}{i}$	$F = A(F/A, i, n)$
	Series Present Worth P	A	$P = A\frac{(1+i)^n - 1}{i(1+i)^n}$	$P = A(P/A, i, n)$
	Capital Recovery A	P	$A = P\frac{i(1+i)^n}{(1+i)^n - 1}$	$A = P(A/P, i, n)$
	Sinking Fund A	F	$A = F\frac{i}{(1+i)^n - 1}$	$A = F(A/F, i, n)$
Arithmetic Gradient 	Arithmetic Gradient Present Worth P	G	$P = G\frac{(1+i)^n - in - 1}{i^2(1+i)^n}$	$P = G(P/G, i, n)$
Geometric Gradient 	Geometric Series Present Worth P	A_1 and g	$P = A_1\left[\frac{1-(1+g)^n(1+i)^{-n}}{i-g}\right]$	$P = A_1(P/A, g, i, n)$

* *i* is the interest rate per interest period, *n* is the number of interest periods, and *g* is the uniform rate of cash flow increase or decrease.

Table 2. Minimum building systems design service life suggested by NBR 15575-1 (ABNT, 2013).

Building Systems	Minimum Design Service Life (years)
Structural System	50
Internal Flooring System	13
External Vertical Enclosure System	40
Internal Vertical Enclosure System	20
Roofing System	20
Hydro-Sanitary System	20

NBR 15575-1 (ABNT, 2013), on the other hand, suggests minimum values of design service life for building systems (**Table 2**) and provides information on the design service life of several building components, with no information about different categories of structures. Thus, in contrast to Eurocode, the design service life of different categories of structures in Brazil is highly influenced by the subjective choices of structural designers. The design service life of a building or building system mentioned in NBR 15575-1 (ABNT, 2013) is the period of use as intended by the designer after which it may need to be replaced.

Recent developments, advantages, weakness, and potential benefits of performing an LCC analysis

Heralova (2017) points out that LCC provides a holistic view of real costs in buildings, however, its acceptance and utilization in the construction sector remain limited mainly due to the incomplete understanding of the advantages by professionals. The lack of a common methodology and confusion over scoping and terminology has not allowed LCC to become widely used in civil engineering practice (Green, 2009). However, the recent publication of ISO 15686 (ISO, 2017) has been helping to make it clearer and easier to understand the complexity of building projects. Gluch and Baumann (2004), on the other hand, emphasize that the complexity of building projects, which comprehends collecting data, estimating future events, and identifying environmental aspects throughout the life cycle, contributes to the understanding of the diversity of a building cost estimation and help to translate this complex reality into a more familiar dimension to the business world.

It is important to highlight that availability and reliability of input data are crucial in minimizing LCC uncertainties that may occur due to the inherent specificities of each building project. In this sense, sensitivity analysis helps to identify how regional cost differences, economic parameter variations, and differences in the escalation of prices for products and services over the lifespan of the building will influence LCC results.

Buildings life cycle assessment, in general, focus on either the economic or the environmental perspective. Environmental assessment, in general, is not in the scope of an LCC analysis (see Figure 1) but comprehends an externality accounted for only in WLC analysis. Contemporary approaches that combine LCC with environmental Life Cycle Assessment (LCA) allow for ascertaining if environmental impacts are in line with the LCC analysis (Pedinotti-Castelle *et al*., 2019). Chiang *et al*. (2015) demonstrated that it is possible to minimize life cycle cost, labor requirement, and carbon emissions of buildings, encompassing social, economic, and environmental aspects of sustainability, with different combinations of repair and maintenance materials.

A perspective towards the improvement of LCC analysis proposed by Gluch and Baumann (2004) is the use of the classical structured analytical tools with the incorporation of tools that integrate people's impressions and experiences in the decision process (brainstorming, for instance). In addition to this, whereas LCC works on an attributional approach that considers the sum of each activity cost in the building life cycle, Pedinotti-Castelle *et al*. (2019) proposed a consequential LCC approach by quantifying the potential cost benefits generated by a change in the reference case. The consequential approach opens a new perspective on LCC analysis by allowing costs to be perceived beyond the point of view of a single investor or user. In an attempt to incorporate economic and sustainability assessment in building design process, an innovative approach proposed by Ahmad *et al*. (2018) integrates Building Information Modeling (BIM) with economic and sustainability assessment and improves economic analysis by combining traditional (LCC) and non-traditional (affordability, manageability, and adaptability) indicators.

ECONOMIC PERFORMANCE CALCULATIONS: EXAMPLE PROBLEM

This section presents an example problem to illustrate economic performance calculations for the construction of a hypothetical office building. Thus, the scope of this example problem encompasses the economic performance analysis of a 20,000GSF office building with a 50 years' service life, considering selected non-construction costs, incomes, construction, operation, and maintenance costs, for a study period of 25 years. Economic parameters, time factors, costs, and benefits applied to the example problem are presented in **Tables 3−4**.

Table 3. Economic parameters and time factors applied to the example problem.

Basic Economic Parameters	
GSF*	20,000
Service Life	50 years
Design Service Life:	50 years
Period of analysis (n)	25 years
Base Point	Bid Date
Real Annual Discount Rate (d)**	6.50%
Annual Real Inflation Rate (a)***	3.75%
Annual Nominal Bond Rate (b)	9.50%
Annual Nominal Discount Rate (d_n)****	10.49%

* Gross Square Footage; ** Special System of Liquidation and Custody Rate (SELIC) established by the Brazilian Monetary Policy Committee in December 2018; *** Price Index to Consumer Rate (IPCA), defined by the Brazilian Institute of Applied Economic Research (IPEA) for December 2018; **** obtained by (a+d +ad).

Table 4. Costs and benefits data.

Costs and Benefits			Details*
Whole Life Cost		Non-Construction Costs	Land purchased two years prior to the bid date: $100,000**
		Incomes	Considerations to determine residual value: • Building: service life of 50 years • No depreciation for land • Roof replacement: service life of 20 years
		Externalities	Not included in this analysis
	Life Cycle Cost	Construction Costs	$1,000,000 at base point**
		Operation Costs	Electric Energy Consumption: 295,000kWh/year Electric Energy Cost at year base point: $0.65/kWh Annual Escalation Rate: 6.00%****
		Maintenance Costs	Annual Recurring Cost at the base point: $5.00/GSF/year Annual Escalation Rate for Recurring Costs: 7.00%**** Non-Annual Recurring Cost at the base point: • Paint at 8th, 16th, and 24th years: $50,000 (every 8 years) • Internal Flooring at the 15th year: $60,000 (every 15 years) Replacement Cost at the base point: • Roofing at the 20th year: $80,000 (every 20 years)
		End of Life Costs	***

* $ used as generic currency symbol; ** financed over a 20-year period with annual nominal bonding rate lower than the annual nominal discount rate; *** not in the scope since the period of analysis of 25 years is lower than the service life of 50 years; **** nominal rates to take into account that energy and maintenance costs increase faster than the annual inflation rate.

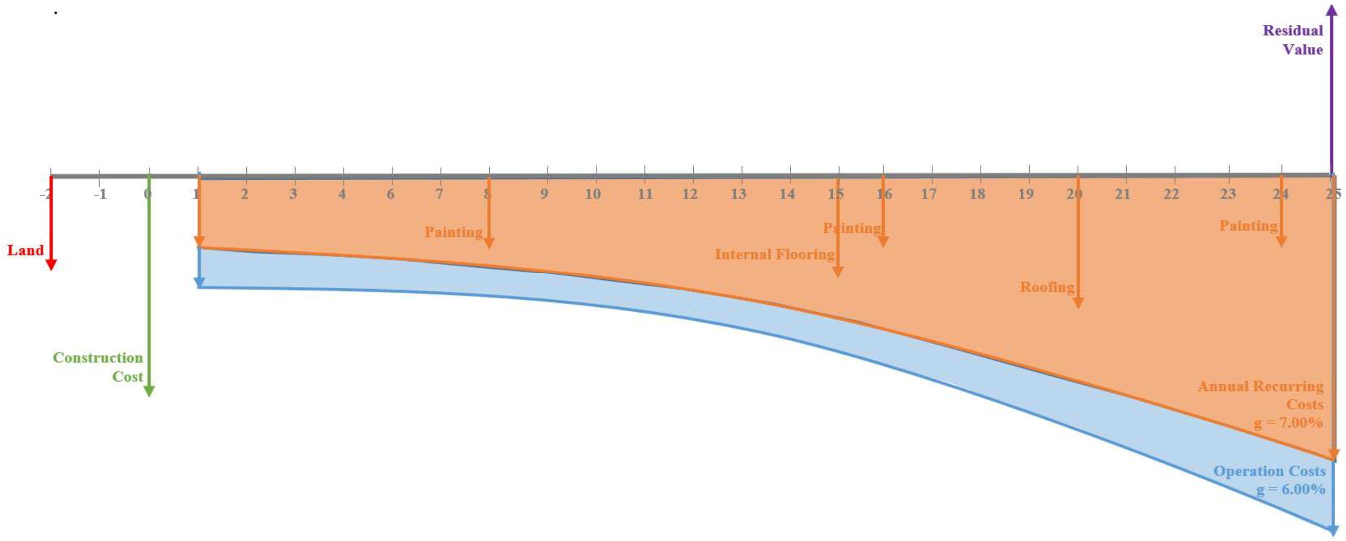


Fig. 3 Cash flow of costs and benefits considered in the example problem.

NPV, in this case, will be calculated by discounting cash flows of costs and benefits presented in Table 3 and Fig. 3 over the period of analysis to the base point.

Non-Construction Costs

NPVnc, associated with the net present value of non-construction costs at the base point, is determined through **Eq. (3).** First, the value related to land purchase ($100,000) two years priory is converted to an equivalent future value at the base point by applying the annual nominal discount rate (dn) to account for the time value of money used to purchase the land two years prior. Finally, **Table 4** reports that land purchase cost has been financed with an annual bonding rate lower than the nominal discount rate, which results in a cash flow spread over the 20-year bond period. In such case, a Bonding Present Value Factor (BPV) calculated through **Eq. (4)** is applied to discount the annual bond payments to the base point using the annual nominal bond rate (b) and the annual nominal discount rate (dn). As the annual nominal bond rate is less than the annual nominal discount rate, which means that present value of the bonded land purchase cost over the 20 year bond period is less than the present value of the cash funded land purchase cost (BPV less than unity).

$$NPV_{nc} = -100{,}000(F/P, 10.49\%, 2)BPV \tag{3}$$

$$BPV = (A/P, 9.50\%, 20)(P/A, 10.49\%, 20) \tag{4}$$

Construction Costs

NPVc represents the net present value of construction costs at the base point. Because construction has been financed with an annual nominal bonding rate lower than the annual nominal discount rate, NPVc is determined by multiplying the construction cost at the base point presented in **Table 4** by the BPV factor of Eq.(4), as shown in Eq. (5).

$$NPV_c = -1{,}000{,}000BPV \tag{5}$$

Operation Costs

In this example, the net present value NPVo comprises only electric energy annual costs, which are associated with providing heating and cooling to the office building. Estimated energy consumption depends on the engineering and design factors inherent in the building, as well as on ventilation requirements, local climate conditions, etc. In general, energy costs reflect the cost and quantity of energy delivered to the building based on the local utility rates estimated at the base point. Electric energy consumption provided in Table 4 (295,000 kWh⁄year) multiplied by the electric energy cost ($0,65⁄(kWh)) results in the annual energy cost at the base point (**Eq. 6**).

$$\begin{aligned} &Annual\ Energy\ Cost_{\ at\ base\ point} \\ &= 295{,}000\, kWh/year\ x\ \$0{,}65/kWh \\ &= \$191{,}750/year \end{aligned} \tag{6}$$

Considering that energy costs may increase at a faster rate than the annual real inflation rate, it is convenient to apply an escalation rate to reflect the increase in the energy cost over the period of analysis. The increase in the energy cost over the period of analysis can be represented by the geometric series shown in **Fig. 3**, with the net present value estimated by the corresponding compounding interest formula or factor presented in **Table 1**. Thus, because operating costs are estimated from one year to the base point, it is necessary to convert the annual energy cost at the base point (**Eq. 7**) to an equivalent future value one year after the base point, by applying the annual escalation rate for electric energy of 6% (**Table 4**). NPVo is then determined through **Eq. 8** by calculating the present value of the geometric series that represents the escalation of electric energy costs from year 1 up to year 25, using the annual escalation rate for electric energy of 6% (**Table 4**), and the annual nominal discount rate (dn).

$$NPV_o = -191{,}750(F/P, 6.00\%, 1)(P/A_1, 6.00\%, 10.49\%, 25) \tag{7}$$

Maintenance Costs

The net present value of maintenance costs is calculated by **Eq. (8)**, through the sum of net present values corresponding to annual recurring costs (NPVar), non-annual recurring costs (NPVnar), and replacement costs (NPVr).

$$NPV_m = NPV_{ar} + NPV_{nar} + NPV_r \tag{8}$$

Annual Recurring Costs

Annual recurring costs include maintenance costs that occur on a continuous basis over the service life. Taking into account that building systems or components may require an increasing level of maintenance with age, annual recurring costs are considered to increase faster than the annual real inflation rate over the period of analysis. Thus, the annual escalation rate for recurring costs of 7% (**Table 4**) represents the increase in the annual recurring costs greater than the annual inflation rate. Annual recurring costs may be represented by a geometric series starting at one year after the base point, as illustrated in **Figure 3**. It is then necessary to convert the annual recurring cost at the base point obtained through **Eq. (9)** to an equivalent future value at one year after the base point, by applying the annual escalation rate for recurring costs of 7% (**Table 4**). NPVar is determined through **Eq. (10)** by calculating the present value of the geometric series that represents the escalation of annual recurring costs from year 1 up to year 25, using the annual escalation rate for recurring costs of 7% (**Table 4**) and the nominal discount rate (dn).

$$\begin{aligned} &Annual\ Recurring\ Cost_{\ at\ base\ point} \\ &= \$5.00/GSF/year * 20.000 \\ &= \$100{,}000/year \end{aligned} \tag{9}$$

$$\begin{aligned} &NPV_{ar} \\ &= -100{,}000(F/P, 7.00\%, 1)(P/A_1, 7.00\%, 10.49\%, 25) \end{aligned} \tag{10}$$

Non-Annual Recurring Costs

Non-annual recurring costs include maintenance whose costs are not the same each year nor increases at a constant rate over the period of analysis. Paint services as considered in this example are non-annual recurring costs of \$50,000 at base point (**Table 4**) to be accounted 3 times: at 8th, 16th, and 24th years. Internal flooring maintenance services, on the other hand, costs \$60,000 at base point (**Table 4**) to be accounted once at 15th year. The NPVnar is calculated using **Eq. (11)** by discounting each paint and internal flooring maintenance services to the base point using the real annual discount rate (d).

$$\begin{aligned} &NPV_{nar} \\ &= -[50{,}000(P/F, 6.50\%, 8) \\ &+ 50{,}000(P/F, 6.50\%, 16) \\ &+ 50{,}000(P/F, 6.50\%, 24) + 60{,}000(P/F, 6.50\%, \end{aligned} \tag{11}$$

If the cost of each paint service, for instance, would increase faster than the annual inflation rate, future values of paint services at years 8, 16, and 24 should be determined, using an appropriate compound interest factor, prior to discount. The same is valid for the case of internal flooring maintenance services.

Replacement Costs

Replacement costs are related to replacement or remodeling of major building systems and components during the period of analysis to maintain its functionality. The NPVr in this example is calculated using **Eq. (12)** by discounting the roofing replacement cost at the 20th year to the base point, using the real annual discount rate (d). Roofing costs at the base point, to be accounted at the 20th year is \$80,000 (**Table 4**).

$$NPV_r = -80{,}000(P/F, 6.50\%, 20) \tag{12}$$

If replacement costs presented in **Table 4** at the base point would increase faster than the annual inflation rate, future values of roofing replacement cost at the 20th year should be determined, using an appropriate compound interest factor, prior to discount. Additionally, if replacement costs would be financed with an annual bonding rate lower than the nominal discount rate, a Bonding Present Value Factor (BPV) should be applied to discount the annual bond payments to the base point using the bonding period (n), the annual nominal bond rate (b), and the annual nominal discount rate (dn), as expressed in **Eq. (13)**.

$$BPV = (A/P, b\%, n)(P/A, d_n\%, n) \tag{13}$$

Incomes

Incomes, in this example, refer to residual values remaining at the end of the period of analysis. Thus, the net present value of incomes NPVi is given by the sum of net present values related to residual values for building (NPVbr), land (NPVlr), and components replacement (NPVrr) at the end of the period of analysis, as shown in **Eq. (14)**. It is worth noting that NPVi is a credit to the total life cycle cost.

$$NPV_i = NPV_{br} + NPV_{lr} + NPV_{rr} \tag{14}$$

Building Residual Value

Building residual value is determined first by depreciating the building construction cost at the base point over the service life of 50 years (**Fig. 4a and 4b**) through the compound interest factor (A/P, d%, service life). Then, the compound interest factor (P/A, d%, service life – the period of analysis) is applied to discount the un-depreciated value to the end of the period of analysis, from year 50 to year 25 in this example, as illustrated in **Fig. 4c** and **4d**. Finally, the compound interest factor (P/F, d%, period of analysis) is used to shift the residual value at the period of analysis to the base point (**Fig. 4e** and **4f**), as shown in (**Eq. 15**).

$$NPV = +1{,}000{,}000\ (A/(P,6.50\%,50)(P/A,6.50\%,25)(P/(F,6.50\%,25) \tag{15}$$

Land Residual Value

Considering that the land purchase value will not depreciate (see details presented in **Table 4**), the land value at the end of the period of analysis will be the same value at the base point. First, land purchase value two years prior, given by **Table 4**, is converted to the base point by applying the compound interest factor (P/F, dn%, 2), as described in Non-Construction Costs section. Thus, land residual value is determined by multiplying the land value at the end of the period of analysis (same land purchase value at the base point) by the compound interest factor (P/F, d%, period of analysis) to shift the land residual value at the period of analysis to the base point, as shown in **Eq. 16**.

$$NPV_{lr} = +100{,}000(F/P, 10.49\%, 2)(P/F, 6.50\%, 25) \tag{16}$$

Replacement Components Residual Value

In this example, roofing replacement occurs at years 20 and 40 (**Table 4**). Thus, at the end of the period of analysis of 25 years, there is a residual value corresponding to the roofing replacement occurred at year 20, whose design service life ends at year 40. Roofing components residual value is determined first by depreciating the roofing replacement cost at year 20 (same roofing replacement value at the base point) over the component design service life of 20 years (**Fig. 5a and 5b**) through the compound interest factor (A/P, d%, component design service life). Then, the compound interest factor (P/A, d%, end of component design service life – period of analysis) is applied to discount the un-depreciated value to the end of the period of analysis, from year 40 to year 25 in this example, as illustrated in **Fig. 5c** and **5d**. Finally, the compound interest factor (P/F, d%, period of analysis) is used to shift the residual value at the period of analysis to the base point (**Fig. 5e** and **5f**), as shown in **Eq. 17.**

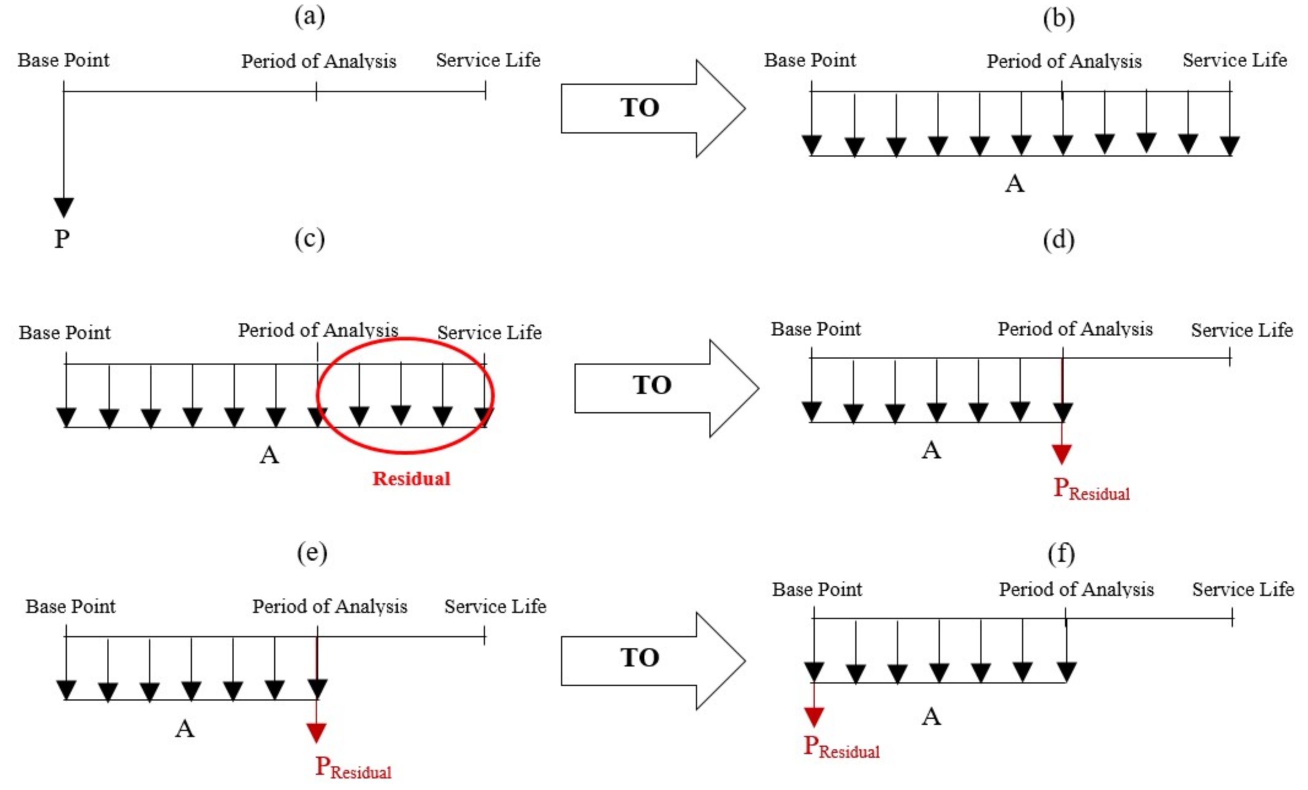


Fig. 4 Sequence for building residual value calculation.

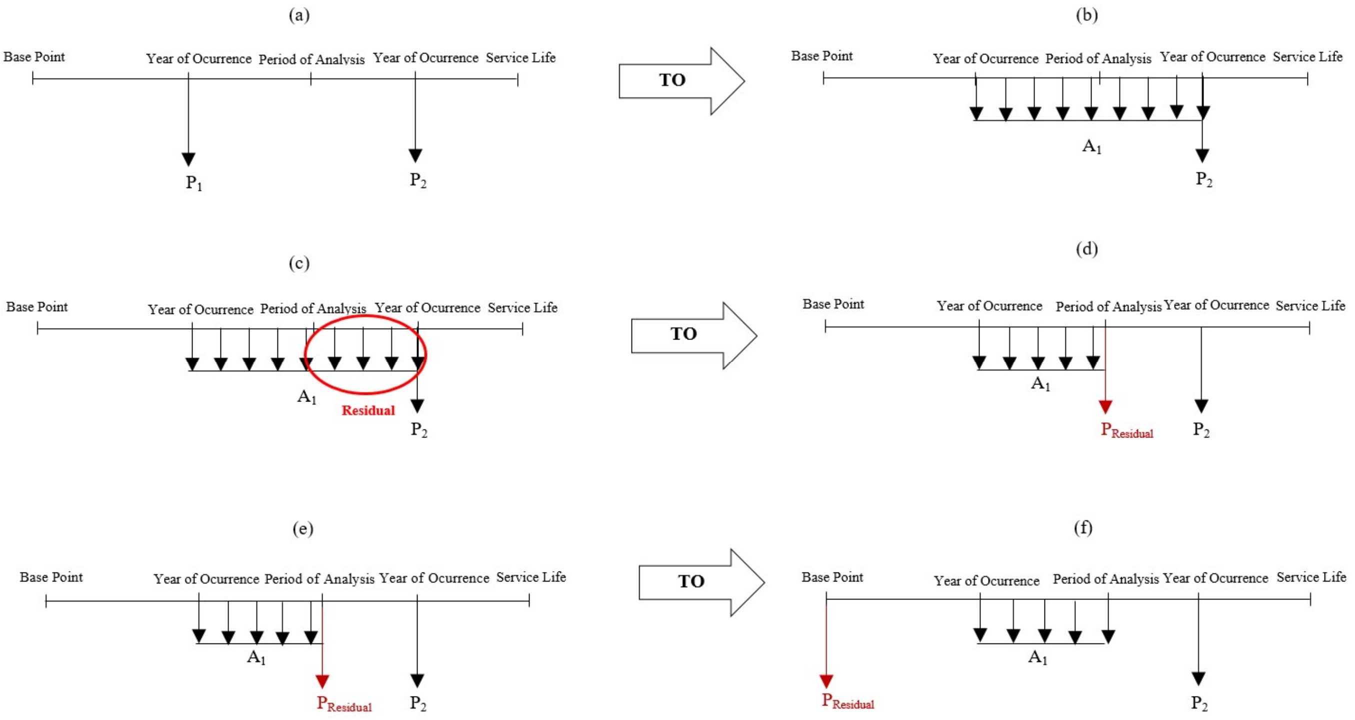


Fig. 5 Sequence for replacement components residual value calculation.

$$NPV_{rr}=+80{,}000(A/P,6.50\%,20)(P/A,6.50\%,15)(P/F,6.50\%,25) \quad (17)$$

RESULTS AND DISCUSSION

Table 5 and **Fig. 6** show the results of economic performance calculations related to the hypothetical office building presented in this example problem. It is important to consider that calculations presented in this paper do not concern all issues related to an economic performance assessment, but it approaches fundamental conceptual topics and mathematical descriptions of the procedures used to perform WLC and LCC analyses.

Results of **Table 5** and **Fig. 6** indicate that operation and maintenance costs are the dominate part of the life cycle cost of the hypothetical office building over the period of study, which corroborates to findings of case studies presented by Wang et al. (2010) and Huang *et al*. (2018) in China, Chiang *et al*. (2015), in Hong Kong. It is worth noting that operation costs related to electric energy consumption for heating and cooling constitutes the main element of a building LCC analysis over the lifespan (Keoleain *et al*., 2000; Lazzarin *et al*., 2008; Islam *et al*., 2015; Mangan & Oral, 2016), which encourage the seek for more energy efficient buildings.

Wang *et al*. (2010) report that energy consumption related to building construction and operation accounts for almost half of the annual energy consumption in China. Heating and cooling represent 40% of energy consumption in Canadian buildings (Pedinotti-Castelle *et al*., 2019). In a global level, buildings and construction industry consumed about 36% of the total final energy use in 2016, according to the UN Environment and IEA (2017) program towards a zero-emission, efficient, and resilient buildings and construction sector. In this sense, the usage of scarce and exhaustible non-renewable resources for electric energy generation, the consequent negative impacts on the environment and the increasing energy costs have been stimulating the evaluation of energy performance of buildings on a life cycle basis considering the different climate zones (Mangan & Oral, 2016). UN Environment and IEA (2017) publication warns that buildings sector floor area will double by 2060 and presents strategies to reduce the energy and climate impact of buildings, which comprehends reducing the operating energy and emissions as well as encouraging life cycle planning from the design stage to building operation and occupation.

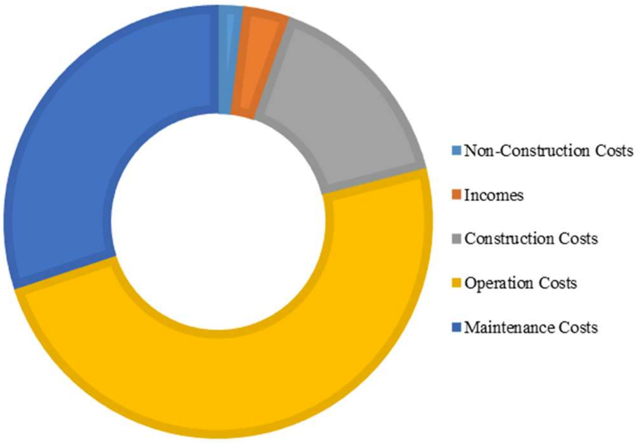


Fig. 6 Costs and benefits of the hypothetical office building.

Table 5. Costs and benefits of the hypothetical office building.

		Costs and Benefits	Reference	Compound Interest Factors and Net Present Values of Costs and Benefits
Whole Life Cost		**Non-Construction Costs** $NPV_{nc} = -100{,}000(F/P, 10.49\%, 2)BPV$ $BPV = (A/P, 9.50\%, 20)(P/A, 10.49\%, 20)$	Eq. 3 Eq. 4	*(A/P, 9.5%, 20) = 0.113* *(P/A, 10.49%, 20) = 8.236* *BPV = 0.935* *(F/P, 10.49%, 2) = 1.221* ***$NPV_{nc} = -\$114{,}101.31$***
		Incomes $NPV_i = NPV_{br} + NPV_{lr} + NPV_{rr}$ - ***Building Residual Value*** $NPV_{br} = +1{,}000{,}000(A/P, 6.50\%, 50)(P/A, 6.50\%, 25)(P/F, 6.50\%, 25)$ - ***Land Residual Value*** $NPV_{lr} = +100{,}000(F/P, 10.49\%, 2)(P/F, 6.50\%, 25)$ - ***Replacement Components Residual Value*** $NPV_{rr} = +80{,}000(A/P, 6.50\%, 20)(P/A, 6.50\%, 15)(P/F, 6.50\%, 25)$	Eq. 14 Eq. 15 Eq. 16 Eq. 17	*(A/P, 6.5%, 50) = 0.068* *(P/A, 6.5%, 25) = 12.198* *(P/F, 6.5%, 25) = 0.207* ***$NPV_{br} = +\$171{,}594.31$*** *(F/P, 10.49%, 2) = 1.221* *(P/F, 6.5%, 25) = 0.207* ***$NPV_{lr} = +\$25{,}287.49$*** *(A/P, 6.5%, 20) = 0.091* *(P/A, 6.5%, 15) = 9.403* *(P/F, 6.5%, 25) = 0.207* ***$NPV_{rr} = +\$14{,}140.94$*** ***$NPV_i = +\$211{,}022.74$***
	Life Cycle Cost	**Construction Costs** $NPV_c = -1{,}000{,}000BPV$ $BPV = (A/P, 9.50\%, 20)(P/A, 10.49\%, 20)$	Eq. 5 Eq. 4	*(A/P, 9.5%, 20) = 0.113* *(P/A, 10.49%, 20) = 8.236* *BPV = 0.935* ***$NPV_c = - \$934{,}640.68$***
		Operation Costs $NPV_o = -191{,}750(F/P, 6.00\%, 1)(P/A_1, 6.00\%, 10.49\%, 25)$	Eq. 7	*(F/P, 6%,1) = 1.060* *$(P/A_1, 6\%, 10.49\%, 25) = 14.377$* ***$NPV_o = -\$2{,}922{,}235.93$***
		Maintenance Costs $NPV_m = NPV_{ar} + NPV_{nar} + NPV_r$ - ***Annual Recurring Costs*** $NPV_{ar} = -100{,}000(F/P, 7.00\%, 1)(P/A_1, 7.00\%, 10.49\%, 25)$ - ***Non-Annual Recurring Costs*** $NPV_{nar} = -[50{,}000(P/F, 6.50\%, 8) + 50{,}000(P/F, 6.50\%, 16) + 50{,}000(P/F, 6.50\%, 24) + 60{,}000(P/F, 6.50\%, 15)]$ - ***Replacement Costs*** $NPV_r = -80{,}000(P/F, 6.50\%, 20)$	Eq. 8 Eq. 10 Eq. 11 Eq. 12	*(F/P, 7%,1) = 1.070* *(P/A1 ,7%, 10.49%, 25) = 15.809* ***NPV_{ar} -\$1,691,612.37*** *(P/F, 6.5%, 8) = 0.604* *(P/F, 6.5%, 16) = 0.365* *(P/F, 6.5%, 24) = 0.221* *(P/F, 6.5%, 15) = 0.389* ***$NPV_{nar} = -\$82{,}826.02$*** *(P/F, 6.5%, 20) = 0.284* ***$NPV_r = -\$22{,}703.76$*** ***$NPV_m$ -\$1,797,142.15***
			Whole Life Cost	***-\$5,557,097.33***
			Life Cycle Cost	***-\$5,654,018.76***

On the other hand, although operation and maintenance phase currently dominate energy consumption over the building lifespan, the importance of materials production and manufacturing, in terms of environmental impacts and costs, are expected to increase as design becomes more energy-efficient (Keoleain *et al*., 2000).

Data of Table 5 show that operation and maintenance costs estimated to the hypothetical office building of this example problem over the period of analysis are five times higher than the construction costs. Such data endorses LCC results of case studies reported by Shade (2007) and Wang *et al*. (2010), whose remarks lead to the conclusion that, in certain cases, higher construction costs might decrease total LCC. In this perspective, Pedinotti-Castelle *et al*. (2019) point out that retrofits in existing buildings could become cost-effective although apparently expensive if associated with future energy savings in the operation phase.

Uncertainties could be accounted, in this example, by varying economic parameters such as discount rate and escalation rates or even by assessing different cost ranges for particular items in the different stages considered in the LCC or WLC analysis. Thus, it is possible to identify which parameters and cost items lead to the greatest impacts in each stage over the period of analysis. In this sense, different design strategies, systems, and components could be selected as well as replacement and maintenance operations could be redesigned.

It is important to highlight that results of WLC and LCC analysis do not refer to actual budget amounts or a projection of actual costs and can only be used to evaluate and compare different alternatives for buildings, systems, and/or components and materials, for instance. It is clear that LCC analysis helps to create sustainable built environments in terms of energy efficiency and cost-effectiveness. Comparing different alternatives in the design stage supports accurate decisions and avoid changes during the operation stage that affects a great number of users

CONCLUSIONS

LCC is an effective tool that, when performed in the building design phase, contributes to minimizing costs throughout buildings lifespan. Electric energy consumption for heating and cooling during buildings operation phase are commonly the main contributor to the LCC of buildings, followed by maintenance costs. Thus, decision makers face a challenge to equate the equilibrium between costs and energy efficiency through the life cycle of buildings, especially to meet the objectives of a sustainable construction market.

The recent publication of ISO 15686 (ISO, 2017) plays an important role in connecting theory and practice of building service-life planning since it helps to make clearer and easier to understand the complex relationship that involves design specificities, life-time, costs estimation over time, social and environmental aspects of a building project.

REFERENCES

Associação Brasileira De Normas Técnicas (2013). NBR 15575-1: Edificações habitacionais — Desempenho, Parte 1: Requisitos gerais. Rio de Janeiro.

Ahmad, T. & Thaheem, M. J. (2018) Economic sustainability assessment of residential buildings: A dedicated assessment framework and implications for BIM. *Sustainable Cities and Society*, 38, 476 – 491, 2018.

American Society for Testing and Materials (2014). ASTM E833-14: Standard Terminology of Building Economics. Philadelphia.

American Society for Testing and Materials (2017). ASTM E917-17: Standard Practice for Measuring Life-Cycle Costs of Buildings and Building Systems. Philadelphia.

American Society for Testing and Materials (2015). ASTM E1185-15: Standard Guide for Selecting Economic Methods for Evaluating Investments in Buildings and Building Systems. Philadelphia.

British Standards Institution (2011). BS EN 15643-2: Sustainability of construction works. Assessment of buildings. Framework for the assessment of environmental performance. London.

British Standards Institution (2005). EN 1990+A1: The UK National Annex A1 of EN1990. London.

Chiang, Y. H., Li, J., Zhou, L., Wong, F. K. W., Lam, P. T. I. (2015). The nexus among employment opportunities, life-cycle costs, and carbon emissions: a case study of sustainable building maintenance in Hong Kong. *Journal of Cleaner Production*, 109, 326-335.

Creedy, J. & Passi, H. (2007). *Public Sector Discount Rates: A Comparison of Alternative Approaches*. Treasury Working Paper Series, New Zealand Treasury, New Zealand.

Emekci, S. & Tanyer, A. M. Life Cycle Costing in Construction Sector: State of the Art Review. In: *Fifth International Project and Construction Management Conference* (IPCMC2018, North Cyprus, 2018). 8p. North Cyprus: Cyprus International University, Department of Civil Engineering, GR.

European Committee for Standardization (2002). *EN 1990: Eurocode - Basis of structural design*. Brussels.

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

Heralova, R. S. (2017). Life cycle costing as an important contribution to feasibility study in construction projects. *Procedia Engineering*, 196, 565 – 570.

Huang, L., Liu, Y., Krigsvoll G., Johansen, F. (2018). Life cycle assessment and life cycle cost of university dormitories in the southeast China: Case study of the university town of Fuzhou. *Journal of Cleaner Production*, 173, 151-179.

Islam, H., Jollands, M., Setunge, S. (2015). Life cycle assessment and life cycle cost implication of residential buildings - A review. *Renewable and Sustainable Energy Reviews*, 42, 129-140.

International Organization for Standardization (2017). *ISO 15686-5: Buildings and constructed assets - Service life planning - Part 5: Life-cycle costing*. Geneva.

Kapsalaky M., Leal V., Santamouris M., (2012). A methodology for economic efficient design of net zero energy buildings. *Energy & Buildings*, 55, 765-778.

Keoleain, G. A., Blanchard S., Reppe P. (2000). Life-Cycle Energy, Costs, and Strategies for Improving a Single-Family House. *Journal of Industrial Ecology*, 4, 2, 135-156.

Lazzarin R. M., Busato F., Castellotti, F. (2008) Life cycle assessment and life cycle cost of buildings' insulation materials in Italy. *International Journal of Low Carbon Technologies*, 3(1), 44-58.

Mangan S. D. & Oral G. K. (2016). Assessment of residential building performances for the different climate zones of Turkey in terms of life cycle energy and cost efficiency. *Energy & Buildings*, 110, 362-376.

Newman, D. G., Eschenbach T. G., Lavelle, J. P. (2017). *Engineering Economics Analysis*. Oxford University Press, New York, USA.

Oliveira F. R. M., Silva M. G., Gomes V. (2013). Exploring life cycle-based sustainability indicators for building structural frames in concrete. *IBRACON Structures and Materials Journal*, 6(5), 832-843.

Pedinotti-Castelle, M., Astudillo, M. F., Pineau P.-O., Amor B. (2019). Is the environmental opportunity of retrofitting the residential sector worth the life cycle cost? A consequential assessment of a typical house in Quebec. *Renewable and Sustainable Energy Reviews*, 101, 428–439.

Robati, M., McCarthy T. J., Kokogiannakis, G. (2018). Integrated life cycle cost method for sustainable structural design by focusing on a benchmark office building in Australia. *Energy & Buildings*, 166, 525-537.

Rodrigues, J. V. D. (2014). O custo do ciclo de vida de edifícios como suporte à gestão de ativos físicos construídos: Metodologia aplicada a edifícios não residenciais. MSc Thesis, Instituto Superior Técnico, Lisboa, Portugal.

Rohden, A. B. & Garcez, M. R. (2018). Increasing the sustainability potential of a reinforced concrete building through design strategies: Case study. *Case Studies in Construction Materials*, 9, e00174.

Shade J. (2007). Life cycle cost calculation models for buildings. In: *Fourth Nordic Conference on Construction Economics and Organisation: Development Processes In Construction Mangement* (Luleå, 2007), 321-329. Luleå Tekniska Universitet, SE.

TAM, V. W. Y., Senaratne, S., Le, K. N., Shen L.-Y., Perika, J., Chethana, I. M., Illankoon, S. (2017). Life-cycle cost analysis of green-building implementation using timber applications. *Journal of Cleaner Production*, 147, 458-469.

Wang, N., Chang, Y.-C., Nunn, C. (2010). Lifecycle assessment for sustainable design options of a commercial building in Shanghai. *Building & Environment*, 45, 1415–1421.

Zhuang, J., Liang, Z., Lin, T., De Guzman, F., (2007). *Theory and practice in the choice of social discount rate for cost-benefit analysis: a survey.* Economics and Research Department Working Paper Series No. 94, Asian Development Bank, Philippines, 2007.