Application of Life Cycle Costing in Building Energy Performance

Mohammad Hossein Jahangir and Reza Alimohamadi

1 Basic Concepts

Due to the problems of excessive energy consumption and the growth of greenhouse gas emissions, as well as the need for sustainable development in the construction industry, employers and designers in this field are forced to follow specific tips and requirements to achieve the desired goals (Lu et al., 2021; Whole Life-Cycle Costing: Risk and Risk Responses, 2004). But compliance with these requirements is still not mandatory in many countries of the world and is not properly implemented (De Boeck et al., 2015). Considering this issue and due to the higher initial costs of these requirements, investors are not eager to fulfill them voluntarily. In such cases, an economic analysis of the projects and, as a result, economic justification of the requirements, can be very helpful. One of the most widely used and powerful economic analyses is the life cycle costing (LCC) analysis. Life cycle cost analysis is a method that is used for the economic evaluation of different proposed options according to their cost in a given period of time (Dwaikat & Ali, 2018a). For example, in the building sector, it can be related to the economic evaluation of the use of the heating system or the use of different materials in the external walls of the building. The LCC calculation method is completely in accordance with the principles mentioned in engineering economics, and in order to understand its concept correctly, one must master some of the basic concepts of this branch (Kinch, 2003). The life cycle cost can be used at any stage of the service life of the building. The LCC method includes all costs and revenues of the project, from the stages of feasibility, engineering, and implementation to the construction

M. H. Jahangir (✉) · R. Alimohamadi
Faculty of New Sciences and Technologies, Renewable Energies and Environmental Department, University of Tehran, Tehran, Iran
e-mail: MH.Jahangir@ut.ac.ir

S. S. Muthu (ed.), *Life Cycle Costing*, Environmental Footprints and Eco-design of Products and Processes, https://doi.org/10.1007/978-3-031-40993-6_1

and operation of the building and, finally, their disposal to the environment. Some of the things wherein LCC analysis can be used for evaluation in the building sector are given below:

- Individual building systems.
- Newly built buildings.
- Plans for a partial or major renovation of a building.
- Comprehensive plans for the development and renovation of facilities.

In choosing the proposed options, the extent of their impact on the various goals of the building, such as reducing water and energy consumption, thermal comfort, system reliability, flexibility against possible changes and risks, compliance with building standards and rules, and even the appearance of the building, should be considered and should lead to their improvement (Kneifel & Webb, 2020). In order to prioritize options, in addition to technical issues, economic issues should also be given sufficient attention because, in many cases, choosing these options may lead to an increase in the initial or operational costs of a project, which discourages the investor from implementing them. In such cases, life cycle cost analysis can be useful for ranking different options and determining whether or not they are economical. For example, the life cycle cost analysis can suggest the option with a high initial cost as the optimal option due to the lower operating and maintenance costs during the building's operation period. For this reason, using this analysis is very useful to determine the optimal options for long periods of time, whereas many economic methods are only focused on initial costs or operational costs at the beginning of the project (Zhao & Li, 2022).

In this regard, energy-saving projects provide excellent examples for the application of LCC. For example, it is possible to reduce energy consumption by making changes in the external envelope of buildings (such as walls, ceilings, and windows); replacing old heating, ventilation, and air conditioning (HVAC) systems with more modern systems; using renewable technologies in buildings, etc.; and maintaining thermal comfort. When such actions increase the initial cost of the building, with the help of LCC, it can be determined whether such actions are economically justified or not. There are usually several optimal solutions in an energy retrofit project (Dwaikat & Ali, 2018b). For example, to reduce heat transfer from the walls around the building, thermal insulation can be used in a wide range of thermal resistance values. Or in the case of windows, windows with heat resistance and different glasses can be used. Or using air conditioning systems with higher efficiency instead of the current systems is an example of these cases. Many of these solutions are also cost-effective, but usually, an LCC analysis can help select the most optimal alternative. Also, LCC can be used to prioritize the allocation of funds to a specific option in case of budget constraints. In order to rank the available options and choose the best of them, a number of influential indicators such as saving-to-investment ratio (SIR) or adjusted rate of return (AIRR) are explained below (Kneifel & Webb, 2020).

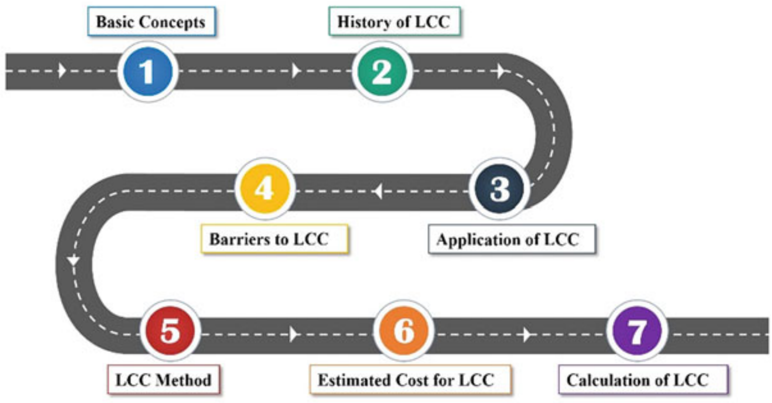

Fig. 1 Road map of the chapter

Life cycle cost analysis is one of the most powerful economic analyses. For this reason, it requires more economic knowledge than other economic analyses. To perform life cycle cost calculations, the analyst must have a sufficient understanding of economic concepts such as investment and operating costs, discounts, inflation, interest, and similar issues (Kim et al., 2020). In order to see the overall outline of the chapter, the road map of this chapter is shown in Fig. 1.

2 History of LCC

It is not possible to talk about the history of life cycle cost analysis in detail, but according to articles, it was probably first used in the 1960s by the United States in the military industry. Then, in the following years, this concept was developed in various industrial and social fields. In the early 1990s and with the emergence of a concept called green buildings, the concept of LCC entered a new phase, and many researchers and experts have been trying to interpret this issue and provide methods and tools to facilitate the calculations of this analysis. At the end of the period, they revolutionized life cycle costing by performing a life cycle costing analysis for the entire duration of a project, from the extraction and manufacturing of raw materials to their disposal in the environment (Cole & Sterner, 2010; Asiedu & Gu, 1998).

In this regard, in 1987, Promilo and Pawsey used mathematical models in the LCC analysis of Australian university buildings. They were able to predict the life cycle pattern of the investigated buildings using these models (Bromilow & Pawsey, 2013). They did this by identifying and costing the activities that need to be done to maintain the building. At the same time, other organizations and researchers around the world also developed LCC methods in building design. For example, many US government agencies, during their research on the LCC of buildings, have developed guidelines to examine investments in the different aspects of the building (Kneifel & Webb, 2020).

3 Applications of LCC

Today, according to the progress made in the field of life cycle costing, it is used in a wide range of industrial and nonindustrial applications, and as mentioned earlier, one of these applications is related to the use of LCC in buildings, which are analyzed in order to improve energy performance. Due to this issue and the increasing growth of research on buildings with high-energy performance, there are a large number of articles and projects that were devoted to the application of LCC analysis as an economic analysis tool in relevant projects. Considering the high initial cost of materials, equipment and systems used in residential buildings, the use of life cycle costing analysis can show the economic benefits of retrofit options and justify building optimization projects (Goh & Sun, 2016). In the following, some studies conducted regarding the use of LCC tools in improving the energy performance of buildings will be reviewed.

In a study, Aye et al. analyzed their proposed options for the construction of an office building using the traditional methods of life cycle cost analysis (Aye et al., 2010). In another research, Ellingham et al., after conducting a life cycle cost analysis for the building studied in their research, concluded that the use of LCC analysis, in the context of project uncertainties, can help the owner in choosing a suggested option (New Generation Whole-Life Costing, 2006). Also, Cole et al. used several different LCC methods in order to justify the economic performance of green buildings. In the end, they stated as a result that the use of LCC analysis to examine the existing solutions in a project will lead to a definite benefit (Cole & Sterner, 2010).

In a number of articles, considering the high initial costs of green buildings compared to traditional buildings, using life cycle costing analysis, it has been proven that despite the higher initial costsof these buildings, the operation costs in the years then it will decrease (Weerasinghe et al., 2021). In s similar study, Kats et al. calculated the life cycle cost of 30 schools located in ten different states. They stated that the initial cost of such buildings will be only 2% more than that of traditional buildings, while the optimization of energy performance and the reduction of thermal losses, in a period of 20 years, is 20 times its traditional examples (Teachers et al., 2006).

The economic usefulness and added value of these types of buildings should be clarified for investors through life cycle cost analysis. This analysis helps project owners invest in green buildings and, thus, reduce the emission of environmental pollution. In this regard and in order to investigate this issue, Zuo et al. indicated that paying attention to the economic aspects of green buildings is very important, and for the growth of this industry, the use of such analyses is necessary and vital (Zuo &

Zhao, 2014). In addition, they reviewed the literature related to the evaluation of green buildings with a focus on life cycle costs. As a result of their review, they found that the use of LCC analysis in this industry is relatively slow (Zuo et al., 2017). Other authors also investigated various simplified methods of life cycle cost analysis in the early stages of green building design to identify more effective options. LCC studies have continued in the field of construction, and many people have chosen the optimal solution from among the proposed options using it. For example, Tam et al. used this analysis to investigate wooden options for saving building energy. In another work, Ilankon et al., by means of life cycle cost analysis, investigated the use of cementitious supplementary materials in building envelopes and announced the proposed options (Tam et al., 2017).

4 Barriers to LCC

In the previous sections, it was stated that the use of life cycle cost analysis for the economic analysis of the energy performance of a building can be very helpful in many areas, including choosing the optimal option from among a number of proposed options. But it should also be noted that the use of LCC, due to possible complications and the lack of familiarity of building owners and designers with its process, can put double pressure on construction projects (Kirk & Dell'Isola, 1995; ISO, 2017). For this reason, the use of this technique is limited, and there are still many problems with its widespread use. Other reasons that can be mentioned are the lack of explanation and justification of the economic benefits of this method during the project period and after, the lack of complete and reliable financial and nonfinancial data of the buildings to perform the LCC process, uncertainties that may affect various parameters of the LCC analysis during the existence of the project, incomplete or wrong implementation of the LCC analysis process, and so on (Dwaikat & Ali, 2018b).

Therefore, more efforts should be made in the area of the development of life cycle cost calculation methods according to the type of project under study, as well as the proper training of existing methods by experts so that it can be expected that the use of this technique in the construction industry becomes widespread.

5 LCC Method

As mentioned before, for the purpose of the economic analysis of proposed solutions to optimize different objectives in a building, the LCC method is used. In fact, life cycle costing analysis includes all costs related to the discovery, extraction and preparation of building materials, engineering and construction of buildings and equipment used (such as HVAC equipment), operation and costs related to building maintenance and related equipment and finally, the costs related to the disposal of construction materials and equipment that have reached the end of their life (Dwaikat

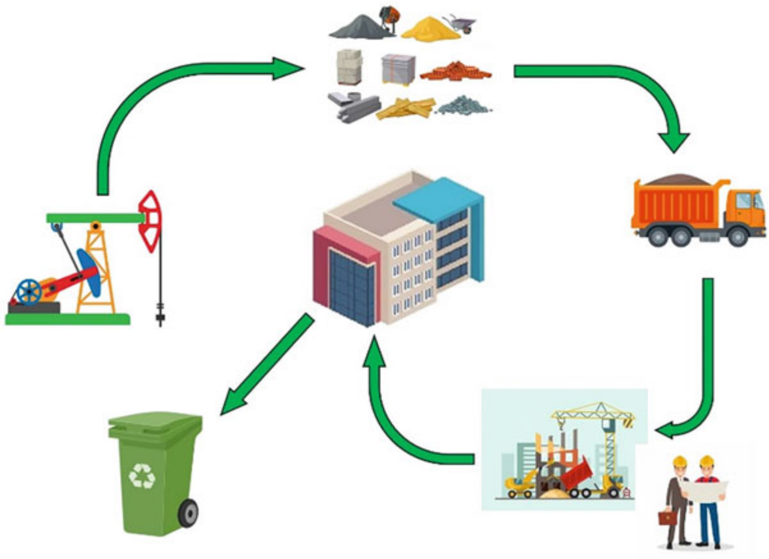

Fig. 2 LCC process

& Ali, 2018b). Figure 2 shows the different parts of the LCC process for the economic analysis of the energy performance of a building. One of the sources that can be used to obtain the data required for the LCC process is the international standard ISO 15686-5:2017. In the project cost breakdown structure that this standard provides, an LCC analysis is divided into four main components: (1) costs related to engineering and construction, (2) costs related to project execution processes, (3) costs related to maintenance, and (4) costs related to the disposal of materials and equipment used during the project to the environment. Of course, each of these categories includes smaller components that can be used to cover all project costs (ISO, 2017). By adding the stage of project concept and definition to the stages mentioned above, it is possible to see the whole life cycle costing process in a project (Dwaikat & Ali, 2018b).

It is important to mention that the failure structure provision contained in the ISO 15686-5:2017 standard is general, and the process of calculating the life cycle cost of the building has complications, which will be mentioned below.

One of the main advantages of using this analysis is that when several options have the same performance, it is possible to determine which option will be more economical than others with the help of LCC calculation. Considering that only one alternative can be chosen for each item of the project, these options are called mutually exclusive (Schmidt & Crawford, 2017).

As mentioned, based on many articles, to know the details of the LCC process and how it works, the ISO 15686-5 standard, which is a reference standard, can provide useful information. According to this standard, the different parts of the life cycle cost analysis that should be adjusted for LCC calculation are the life span of the building, the analysis period, the future inflation rate, the discount rate of future prices to the current price, engineering and construction costs, repair costs and maintenance, and the costs of material disposal into the environment, each of which will be described below (Dwaikat & Ali, 2018b; ISO, 2017).

5.1 Life Span of the Building

First of all, it should be said that the service life of a building means its useful life. The useful life of a building is the period when the building's equipment and materials can provide the minimum required performance level (ISO, 2008). The correct identification of the useful life of a building is very important and necessary to determine the parameters related to the duration of the project that will be used in the existing relationships to calculate the LCC. However, determining the overall life span of a building, considering the type of equipment in it, is a challenging issue and requires sufficient attention because, for example, doing and not doing the correct maintenance of the building facilities can greatly affect the life of the building (Whole Life-Cycle Costing: Risk and Risk Responses, 2004; Kirk & Dell'Isola, 1995). In this regard, solutions have been proposed, among which a number of authorities, including ISO 15686-5, have stated that the estimated life of a building is at least equal to its design life (ISO, 2017).

5.2 Project Analysis Course

The next phase of life cycle analysis refers to the project analysis period. In fact, this period means the duration of the project. The basis of this concept is also the fact that the life cycle cost is not supposed to cover the entire life of a system or product; rather, it includes a period when devices and materials can meet the minimum requirements set in a project (Kirk & Dell'Isola, 1995; Schmidt & Crawford, 2017). In this regard, many economic experts have suggested that the time horizon of the project should be during the useful life of the project (the time period when the project is economically justified) (Whole Life-Cycle Costing: Risk and Risk Responses, 2004; Kirk & Dell'Isola, 1995; 135, S.F.-N. Handbook, 1996). For example, Kirk and Delizola have concluded in their research that this numerical period is between 25 and 40 years, which varies according to the building and its cultural and geographical conditions. In their view, the reason for determining the maximum period for analysis is that considering an analysis period of more than 40 years can lead to the devaluing of the current value of future cash flows (Kirk & Dell'Isola, 1995). The ISO 15686-5:2017 standard also recommended that in LCC calculations, the analysis period should not exceed 100 years. At the same time, to comply with the requirements of sustainable development, it is suggested that the

LCC analysis includes the entire service life of the building or the system on which this analysis is performed (ISO, 2017).

5.3 Discounting in LCC Analysis

One of the most important parameters in LCC analysis is the discount rate. The correct determination of this rate plays a very important role in the correctness of the performed analysis. The discount rate is actually an expression of the present value of money that will be earned in the future (Kirk & Dell'Isola, 1995; ISO, 2017; Junkes et al., 2012). This rate basically refers to the time value of money and determines the equivalent value of money that is supposed to be used in the future (Bull, 2003). In expressing the concept of the discount rate, interest rate should also be mentioned. The interest rate works the opposite of discount rate; that is, if the value of the money that is currently used is calculated in the future, it is called interest rate. It should be noted that in order to calculate the life cycle cost of a project in order to compare the proposed options and choose the optimal option among them, the discount rate used should be calculated for all options at a common base time (Whole Life-Cycle Costing: Risk and Risk Responses, 2004; Kirk & Dell'Isola, 1995; Bull, 2003).

Correctly calculating the discount rate of a project is an important and challenging issue. There are different ways to calculate this rate, such as using mathematical relationships in engineering economics or using methods recommended by international handbooks and standards (Kneifel & Webb, 2020). In this regard, the ISO 15686-5:2017 standard has recommended that the appropriate discount rate for privately owned projects should be determined in such a way as to cover the opportunity cost of the investment (ISO, 2017). For this purpose, the interest cost of a loan taken to invest in a project, the lost profit due to the cash reduction of deposits, the profit rate of other projects that were lost due to lack of investment, the actual profit rate, or the forecast profit rate resulting from the new project can be used as the discount rate for the project. This standard declares the appropriate discount rate for government projects to be the discount rate announced by the central bank of that country or the International Monetary Fund (Dwaikat & Ali, 2018a). Due to the importance of the correct calculation of the discount rate, below is a brief description of the method of calculating the discount rate of a construction project from the NIST 150 manual (Kneifel & Webb, 2020).

5.4 Discounting Future Amounts to Present Value

As mentioned earlier, in an LCC analysis, all cash flows in a project (both positive and negative), from the time of their discovery and extraction to their engineering and implementation, as well as after their construction and use until their disposal into the environment, should be discounted to the present value. This rate is usually determined based on the employer's capital. This rate, for projects with personal ownership, is determined by a parameter, such as the minimum acceptable rate of return of the investor (MARR) for investments with equivalent risk and duration. According to the description and variety of investment opportunities, the exact amount of the discount rate is different for each project. In many countries, the value of this rate is published by related institutions for different applications and uses.

An important point that should be taken into account in the calculation of the cash flows of the life cycle cost analysis is the payback time of an investment project. To explain further, it is very important for investors (both public and private) when they receive their capital. For example, an investor would rather earn $500 in five $100 installments over 5 years than earn the same amount at the end of the fifth year. The reason for this is a problem called inflation. In fact, the value of the cash flow decreases over time due to the effect of inflation. Also, another reason for this issue is that if the return on investment occurs in a shorter period of time, the investor can use it to invest in other projects (Kneifel & Webb, 2020).

5.5 Inflation

Another influential parameter in calculating the life cycle cost is the inflation rate. This rate directly indicates the decrease or increase in the price of goods and services (Kirk & Dell'Isola, 1995; ISO, 2008). Nominal or real costs can be used to determine the inflation rate in the calculation of life cycle cost analysis. To correctly identify the inflation rate, the concept of nominal and real costs should be well understood. Nominal costs are costs whose estimated price is estimated according to the effect of inflation. On the other hand, real costs are those costs that are not considered in the estimation of costs and the effects of increasing or decreasing inflation, and in a way, they represent the current value of goods or services (Kirk & Dell'Isola, 1995; ISO, 2017; Junkes et al., 2012). According to the literature, it is recommended to use the actual costs when analyzing life cycle costs in order to reduce the effects of possible uncertainties due to inflation. On the other hand, when the future value of money is evaluated, it is recommended to use nominal costs for the life cycle cost analysis (Kirk & Dell'Isola, 1995; ISO, 2017; Junkes et al., 2012; Bull, 2003).

To know the inflation rate at different times, you can use the statistics published by the central bank or statistics office of each country or the International Monetary Fund (IMF). In these reports, information on a parameter called the consumer price index (CPI) is usually discussed for various types of goods and services. The consumer price index is the rate of change in the price of a fixed amount of goods or services over time (Dwaikat & Ali, 2018b). The World Bank also announces the inflation rate of different countries in its annual reports (World Bank, n.d.). Another important point that should be noted is that it is better to consider the price inflation rate of the energy group separately from other groups of goods and services. The reason for this is that the increase or decrease in the price of energy is different from other goods and services. In fact, the price of energy is sensitive to many political, social, environmental, and other events, and with any change in them, it undergoes severe fluctuations. This is the reason why many countries, in presenting their inflation report, divide different groups and services and report the corresponding inflation rate for each group (Dwaikat & Ali, 2018b).

5.6 Design and Construction Cost

Costs related to engineering, construction, and implementation are one of the most important and influential parts in calculating the life cycle cost of construction projects (Whole Life-Cycle Costing: Risk and Risk Responses, 2004; Bull, 2003). These steps usually take a lot of time from the project. The actual cash flows that are spent during this stage are considered sunk costs. In economic applications of life cycle analysis of buildings, these costs should be ignored. But considering that one of the goals of the life cycle cost analysis is to determine the total life cycle cost of the building, engineering and implementation costs are inevitably included in the LCC (Whole Life-Cycle Costing: Risk and Risk Responses, 2004; ISO, 2017).

5.7 Operating Cost of the Building

The operating costs of a building are mainly related to the costs that must be incurred during the construction and operation of the building. There is a wide range of costs, and based on the international standard ISO 15686-5:2017, they can include things such as rent, water and electricity costs, taxes, insurance, etc. Each of these costs alone may not affect the total budget, but their sum will definitely include significant amounts (ISO, 2017).

5.8 Building Maintenance Cost

Every building, after its construction and operation, during its useful service life, will need repair as well as the maintenance of the materials and equipment used in it. In fact, building maintenance costs refer to those expenses. that are necessary to maintain the function of the building and the equipment used in it. These include expenses for the restoration and protection of the body of the building; the replacement or repair of the building's mechanical and electrical facilities; compensation for damages caused by accidents, such as earthquakes; and similar costs (Olanrewaju & Abdul-Aziz, 2015). In other words, the cost of maintenance is the sum of the cash flows spent for this purpose. As with other phases of the life cycle cost analysis, the ISO 15686-5:2017 standard categorizes maintenance costs, as shown below (ISO, 2017):

1. Costs related to maintenance.
2. Building renovation and retrofitting.
3. Partial repair and replacement cost.
4. Cost of replacing systems or main parts.
5. Cleaning.
6. Ground conservation.
7. Equipment renovation and maintenance tax.

5.9 End-of-Life Cost

The last part of the calculation steps of the life cycle cost analysis is the cost of the disposal of construction components and materials to the environment (Whole Life-Cycle Costing: Risk and Risk Responses, 2004; Kirk & Dell'Isola, 1995). These costs include things such as the costs related to equipment inspection at the end of its life, destruction and disposal of hazardous materials, or other such costs that should be taken into account in the LCC analysis (Whole Life-Cycle Costing: Risk and Risk Responses, 2004; Kirk & Dell'Isola, 1995; ISO, 2017).

Regarding the destruction of building materials and equipment, it should be said that there are methods of destruction that are usually used. These methods include mechanical destruction, destructive destruction, and a combination of these two methods (Pun et al., 2007). In the mechanical destruction method, construction equipment and materials are destroyed directly. In this method, due to the destruction of all the components that have reached the end of their life, it takes more time, but it does not require much precision (Kibert & Hazardouse, 2000). On the contrary, according to the goals of sustainable development and greater compatibility with the environment, there is a deconstructive method. In this method, all building components and materials are checked very carefully so that they are not destroyed if it is possible to recycle and reuse them. In this method, due to the reduction of the amount of waste generated after the end of the building's life, much less damage is done to the environment (Pun et al., 2007; Kibert & Hazardouse, 2000). In the combined method, both mentioned destruction methods are put together to increase both the speed and accuracy of destruction (Pun et al., 2007).

Nowadays, due to the need to pay enough attention to sustainable development in all sectors, including the construction sector, it is necessary to use appropriate techniques for the destruction and reuse of construction equipment (Sustainable Construction: Green Building Design and Delivery, n.d.). Considering that in many countries no law has been established to oblige the owners to comply with the principles of destruction, there is no good information in this field. However, it is recommended to use these techniques in the destruction process, considering the advantages and income that material recycling can have (Pun et al., 2007; Kibert & Hazardouse, 2000).

As mentioned earlier, in the process of calculating the LCC of a project, all project cash flows must be discounted to the net present value. For this, indicators and parameters can be used. Next, based on NIST Manual 135, which is a very reliable calculation basis around the world, the method of using the discount rate to discount future cash flows to their present value is described. First, it should be said that parameters have been introduced that, although they are not part of the main process of LCC calculations, are compatible with this method. These parameters include net savings, the amount of savings to the initial cost, and also the adjusted internal efficiency, which will be described in the following sections. It is also important to mention that all the stated parameters are based on the same cost rate during the service life of the project, which is completely consistent with the life cycle cost analysis (Kneifel & Webb, 2020).

Each of the criteria mentioned above can help in different parts of the LCC analysis. For example, to determine the lowest cost of an option among other available options, the net savings criterion can be used. In this way, the proposed solutions with lower LCC lead to higher net savings. Alternatively, savings-to-investment ratios and adjusted internal rates of return can be used for ranking (e.g., using materials with different heat transfer coefficients for the wall) (Fregonara et al., 2017).

Before entering the cost estimation part in the LCC calculation process, it should be said that life cycle cost analysis can also be calculated annually. In this case, the annual value of the depreciation cost of all project components is considered in the same way and according to the value of money at a certain time.

6 Estimated Costs for LCC

In the previous sections, the basic concepts and main stages of the life cycle cost analysis were discussed. As mentioned earlier, LCC analysis is an economic analysis, and to calculate its different parts, all costs and revenues of a project must be determined. Some of these financial flows can be based on official statistics, and others should be estimated. In the following, we will try to explain the cash flows of a project and the topics related to it.

6.1 Related Effects

In every construction project, there are various costs, including the costs of engineering and construction, operation and repairs, and their destruction as well as returning them to the environment (Hong et al., 2021). The first decision that must be made at the beginning of the process of calculating the life cycle cost of a building is to identify the factors affecting the predetermined goals, such as optimizing building consumption, using renewable energy technologies, or choosing different options for building envelope so that they can be used in the calculation of the life cycle cost of the building. To answer this question, the financial effects that each of the proposed options imposes on the project should be examined. When considering these impacts, impacts should be considered in terms of monetary quantities (e.g., in dollars) whenever possible. For other effects that cannot be expressed in monetary terms, alternative methods such as the quantification of values should be used so that it is possible to use them in the life cycle cost calculation process. It should be noted that these items are effective as a result of the analysis due to their extensiveness and many interactions with other components and the direct and indirect effects they may leave behind (Kneifel & Webb, 2020).

Considering that construction projects consist of many parts and components with different effects, including all costs in an LCC analysis can impose a large computational cost (Morrissey & Horne, 2011). Therefore, usually in an LCC analysis, those costs are considered which are significant in terms of quantity and are necessary for the analysis to be done correctly. In general, cost is considered relevant to a decision when it changes from one option to another proposed option. In this case, the common costs between all options cannot have a significant effect on the choice between them, and they can be removed from the calculation process in order to avoid increasing the computational burden. It should be noted that if these costs are not avoided in the implementation of an LCC, it does not mean that a wrong answer will be produced; it will only lead to added computational load and increased costs related to data analysis and collection. In an LCC analysis, costs will be influential when they can make a significant difference between the proposed options (Kneifel & Webb, 2020). For example, energy costs for replacing building air conditioning systems can be very effective and significant, while the energy cost for replacing light bulbs in a part of a house can be less effective. Unfortunately, there is no specific method for determining the importance of the costs of a construction project, and a large part of it depends on experts. But despite this, there are guides in articles and books around the world that can help people with this.

In examining the economic effects of decisions, attention should be paid to the elimination of sunk costs. Sunk costs are costs that have been incurred in the past and cannot be recovered. In effect, sunk costs are excluded from future economic decisions because they remain constant regardless of the outcome of a decision. For example, the cost of providing a cooling tower for an air conditioning system that has just been replaced with an air-cooled air conditioning system is considered a sunk cost. These costs should be avoided in calculating the LCC analysis (Kneifel & Webb, 2022).

Project cost estimation can be done in different ways (Almeida et al., 2015). They can be obtained directly from existing prices or from methods such as the interpolation of data available in industrial cost collection databases or even the extrapolation of current costs according to their current and future prices. The use of a specific method or a combination of them depends on the available information and the economic conditions. In the following, explanations are given about the sources and methods of cost estimation, but it should be noted that the expert should identify the best method of cost estimation according to his knowledge and experience and use them in his analysis (Kneifel & Webb, 2022).

6.2 Classification of Expenses

The different parts of the cost of an LCC can be classified in different ways. In most of these categories, cash flows related to investment and project implementation costs are considered separately. Some of these categories include initial and future cash flows, annual recurring cash flows, and recurring expenses, which will be described below (Kneifel & Webb, 2020).

6.2.1 Investment Costs Versus Operating Costs

Usually, the financial flows of the life cycle cost analysis are divided into two main groups of cash flows related to investment and operation. Understanding the concept of these costs and how they differ from each other is helpful when calculating supplementary measures of the life cycle cost (Kneifel & Webb, 2022). It should be noted that in the case of the growth of project investment costs, employers try to save on possible costs that may occur after operation. In fact, the differences between these two costs do not affect the final result of the life cycle cost so much and do not make a proposed option out of priority. It is only possible that the priority of choosing the desired option will change according to the amount of available capital (Kneifel & Webb, 2020).

It should be noted that the initial cash flows include costs such as project feasibility, engineering and implementation, and the preparation of the required materials, all of which are related to the preconstruction and initial stages of construction. On the other hand, the future cash flows of a project include costs such as income from material recycling, positive cash flows from the production of building components, costs related to the disposal of building materials that have expired, and initial costs for replacing defective parts. It becomes healthy with parts (Biolek & Hanák, 2019).

On the other hand, the costs of water and electricity consumption, the costs of cleaning the building, and subscription are related to the operating costs of the building. It should be noted that the costs of repairing parts (for example, repairing the rotor of the engine room electric pump or repairing the windows of the building) are considered part of the operational costs (OM&R). These costs include various examples of building components, which are usually related to the postoperational period of the building (Biolek & Hanák, 2019).

6.2.2 Initial and Future Cash Flows

The importance of separately considering the initial and future cash flows of the project is necessary for calculating some supplementary criteria of LCC analysis. Amounts spent in the initial stages of construction, such as feasibility studies, engineering, and project implementation, belong to the first category, i.e., initial costs. These costs, as their name suggests, are related to the initial stages of construction. Other costs of a project, such as maintenance costs, replacement costs and costs that will exist after the operation of the building and the launch of the existing systems, are related to the future costs of the project. Also, the cash flows that will remain after the building's lifetime are likewise considered future cash flows (Kneifel & Webb, 2020).

6.2.3 Annual Recurring and Nonrecurring Amounts

This category is related to the number of occurrences of a cost during the study period of the project. Also, this category is used to identify the type of present value factor for discounting future amounts:

- Nonrecurring costs occur without a specific pattern and at unknown times during the project period. Initial cash flows, replacement costs, revenues from a project, and costs resulting from the repair of defective equipment are included in this category. Also, to discount the future amounts to the present value, the single present value (SPV) factor is the appropriate factor for this purpose. Due to the lack of a specific model, this category of expenses is usually not predictable, and forecasts should be made for them from the total budget in the early stages of the project.
- This category of expenses has a specific pattern and will exist every year. The important thing about these costs is that either the amount of these costs is constant during the life of the building or the amount of their increase can be predicted every year. Costs caused by water and electricity consumption, costs caused by cleaning the building, routine maintenance costs, and such things are included in this group. Also, coefficients such as UPV or UPV* are suitable present value factors for this type of expense. The difference between these two coefficients is that if the amount of costs is a constant value every year, the UPV coefficient is used to discount the future values, and if the costs have a certain increase every year, the UPV* coefficient will be used (Kneifel & Webb, 2020, 2022).

6.3 Cash Flow Schedule

Life cycle cost analysis, like many other processes, requires schedules. For this reason, the cash flows of the project (both positive and negative) should be collected according to the time of occurrence. Preparing a detailed schedule may be a bit time-consuming; for this reason, it is quite common to produce simplified schedules instead of detailed models. Using simpler time schedule models means that cash flows can occur every year and at certain times. It should be noted that building life cycle cost calculation software can be very helpful in preparing these schedules (Kneifel & Webb, 2020).

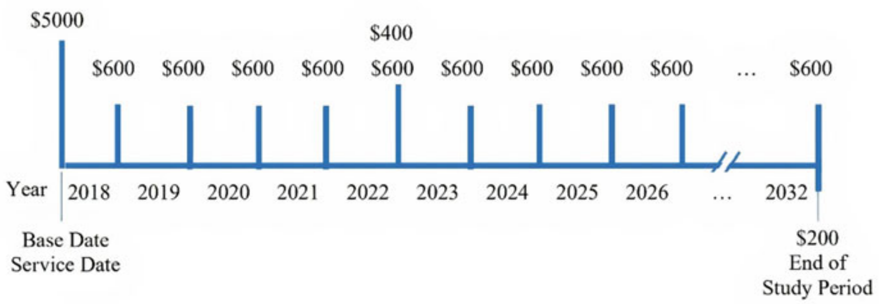

Fig. 3 Cash flow diagram (Kneifel & Webb, 2020)

6.3.1 Cash Flow Charts

Usually, to better understand the timing of costs and revenues of a project, cash flow diagrams are used, as shown in Fig. 3. The diagrams are prepared for each of the alternative projects. In the graphs, the horizontal axis corresponds to the studied years. The numbers on the horizontal axis can correspond to any year of the building's life, specific dates, or any arbitrary time division. It is even possible to consider the horizontal axis based on the year the building service started and add one unit to it every year. The vertical axis also shows the numerical value of costs. There is no specific requirement to show positive and negative cash flows, but typically, positive cash flows are shown at the top of the chart, and negative cash flows are shown at the bottom of the chart (Kneifel & Webb, 2020).

Figure 3 shows the cash flow diagram of a construction project that has a service life of 15 years. As can be seen from the figure, in the year of starting the project, an amount of 5000 dollars has been invested. At the end of the service period of the building, an amount of $200 has been created as a residual. From this chart, there is other information about project costs, which can be referred to as recurring and nonrecurring costs (Kneifel & Webb, 2022).

6.4 Estimating Future Cash Flows Using Base Year Prices

Considering that the calculation of the life cycle cost of construction projects is usually done before the construction of a building, many values and parameters considered in the analysis should be used as estimates. For this purpose, future costs that are discounted based on the year of the start of building services are usually used for estimation. Despite its simplicity, this method usually has high accuracy and can be used in life cycle cost analysis projects.

In estimating costs, if the price increase of a commodity or option is consistent with general inflation, the analysis can be considered a constant dollar. In constant-dollar analysis, the inflation index is removed from the calculation process, which means that the future value of the commodity will be equal to its current value. In many articles and LCC projects, the prices of all goods and services, except for water, electricity, and gas, are considered fixed in dollars. But if the rate of increase in the price of goods or services is clear, that rate should be used in the analysis (Kneifel & Webb, 2022).

7 Calculation of Life Cycle Costs

The classical LCC method is the simplest method for the economic analysis of a project during its lifetime. In general, life cycle cost analysis is used when there are several proposed options to achieve a specific goal (for example, using windows with different heat transfer coefficients or using boilers with different efficiencies to provide thermal comfort). In this method, the LCC value (as described below) should be calculated separately for all proposed options and should be compared with the LCC value calculated to the base building. In this case, if the LCC of the proposed option was lower than the LCC of the base case, it can be said that the proposed option has economic justification. It should be noted that in performing the life cycle cost analysis, one case should be considered as the base case. Also, the basis of LCC analysis is comparison (either with the base case or with other proposed options). It should be noted that for a correct comparison between the options, all common parameters of the LCC process should be considered the same for all options. Finally, the condition of meeting the minimum requirements of the project for choosing the proposed option must be met so that only the options that lead to the improvement of the considered goal (goals) are selected (Kneifel & Webb, 2020).

In the previous parts, we tried to describe the different parts of the life cycle costing process and how it works. In the following, the basic equations used to calculate the life cycle cost of the project are described. These equations are expressed in a basic way, and the overall equations may undergo changes in each project according to the conditions of that project. The different terms needed to calculate LCC are the same costs described in the previous sections, such as maintenance costs, initial costs, or even project revenues. Also, after presenting the main relationships of LCC calculation, a number of supplementary parameters in LCC calculation are likewise described, and their main relationships are stated (Kneifel & Webb, 2022).

The basic equation for calculating the life cycle cost of a project is shown below:

$$LCC = \sum_{t=0}^{N} \frac{C_t}{(1+d)^t} \tag{1}$$

which in the above equation, *LCC*, represents the current value of an alternative solution in terms of dollars, C_t, represents the difference in project costs, including initial costs, maintenance, operation, etc., with all financial flows entering the project, such as income from the sale of electricity produced from renewable energies to the grid in year *t*, *N* is the duration of the project and finally *d* is the discount rate to convert the units to the present value (Kneifel & Webb, 2020).

The above formula, despite its simplicity, may require a lot of computational costs, especially when the study time is very long. Therefore, for building-related projects, the above relationship is rewritten as follows:

$$LCC = I + Repl - Res + E + W + OMR + X \tag{2}$$

In the above equation, *I* is investment costs in dollars, *Repl* is replacement costs in dollars, *Res* is the remaining amount related to inputs in dollars, *E* is the cost of electricity and gas, *W* is the cost of water consumption, *OMR* is the cost of repairs and maintenance, and finally, *X* is related to other costs that may be incurred during the life of the project (Kneifel & Webb, 2020).

After stating the main relationships in LCC calculation, it is time to explain additional concepts in life cycle cost calculation. These indicators can be calculated by values such as current and future net costs, discount and inflation rates, and project duration. In fact, a number of these criteria are used at certain times in the calculation of the life cycle cost. For example, we use indices such as SIR and AIRR when we want to rank the most optimal among several alternative solutions from a financial point of view.

– *Net savings (NS)*: one of the most important indicators related to LCC analysis is net savings. In fact, *NS* is a modified version of the net profit (NB) measure. For the purpose of further explaining, the NB criterion is used in case incoming financial flows are also considered in the investment analysis. On the other hand, the net savings criterion is used when reducing operating costs is considered in the future. As stated earlier, the NS method discounts the amount of cash flow that the proposed solution is expected to save over the useful life of the project to its present value, and other quantities that can be expressed in monetary terms and are among the advantages The proposed solution is considered as cost reduction. To calculate NS, the difference between the LCC of the proposed solution and the base case can be considered, so that

$$NS = LCC_{\text{Base Case}} - LCC_{\text{Alternative}} \tag{3}$$

If the answer to the above equation is greater than zero, it means that the proposed option is financially optimal. This concept can be expressed in another way; thus, when considering multiple alternatives, the solution with a higher net savings rate will always have a lower LCC. This case shows that the LCC method and the NS criterion are completely compatible with each other.

NS also represents the reduction or increase in the cost of different parts of the life cycle costing process between the proposed options and the base case. Although this method creates more computational load than the previous one, these steps are necessary to calculate the *SIR* and *AIRR* indices. In this case, by calculating *NS*, calculations related to other supplementary parameters compatible with LCC calculation are checked. Also, if the *NS* is calculated correctly, the answer obtained from both methods is the same. In the following, the NS calculation method using individual differences is briefly described (Kneifel & Webb, 2020).

$$NS_{A:BC} = \sum_{t=0}^{N} \frac{S_t}{(1+d)^t} - \sum_{t=0}^{N} \frac{\Delta I_t}{(1+d)^t} \tag{4}$$

which in the above equation, $NS_{A:BC}$, represents the net savings amount of the proposed solution *(A)* compared to the base solution *(BC)*, S_t is the amount of reduction in year t in operating costs associated with the proposed solution, ΔI_t, other initial costs of the proposed solution in the year t, t is the year of applying the proposed solution, d is the discount rate, and finally, N is the number of years under study.

Considering that the above relationship can lead to a high calculation load, for building-related projects, the following formula can be used to calculate *NS*:

$$NS_{A:BC} = [\Delta E + \Delta W + \Delta OMR + \Delta X] - [\Delta I_0 + \Delta Repl - \Delta RV] \tag{5}$$

In the above equation, $NS_{A:BC}$ is the amount of cash flow saved by deducting miscellaneous initial costs for option *(A)* compared to the base case *(BC)*, ΔE is the amount of reduction in the energy costs of the proposed option and the base case, ΔW is the amount of reduction in the water cost of the option proposed and the base case, ΔOMR refers to the amount of reduction in the OM&R costs of the proposed option and the base case, ΔX is the amount of reduction in the miscellaneous costs of the proposed option and the base case, ΔI_0 refers to the amount of initial miscellaneous cost of the proposed option, $\Delta Repl$ is the amount of cost required to replace the proposed option, and ΔRV is the difference between the residual cash flow value of the proposed option and the base option (Kneifel & Webb, 2020).

– *Savings-investment Ratio (SIR)*: *SIR* is the ratio between the savings of a proposed solution and its initial cost. This criterion is used when reduced project operating costs are considered an advantage. This criterion, like the *NS* criterion, is relative and should be calculated according to a base case. In this criterion, if the *SIR* is greater than 1, the proposed option will be economically justified. If this case is expressed in proportional form, it will be in such a way that the savings of this option are higher than the initial costs and its investment, and as a result, its net savings rate will be positive. Unlike the previous criterion, in the evaluation of several proposed options, the option with the lowest LCC does not necessarily have the highest *SIR* and should be checked on other aspects as well. Therefore, this index should not be used in choosing unique options in a project.

To calculate this index, it is possible to act like the *NS* calculation method as follows:

$$SIR_{A:BC} = \sum_{t=0}^{N} \frac{S}{(1+d)^t} \Big/ \sum_{t=0}^{N} \frac{\Delta I_t}{(1+d)^t} \quad (6)$$

In this regard, $SIR_{A:BC}$, Savings-to-investment ratio of the proposed solution *(A)* to the base solution *(BC)*, S_t, the amount of reduction in operating costs of the proposed solution in year t, ΔI_t, other initial costs of the proposed solution in year t, t years of applying the solution, d is the discount rate of the project, and N is the service life of the project (Kneifel & Webb, 2020).

Considering that in the above formula the incoming and outgoing cash flows are calculated every year, the following formula is suggested for construction projects:

$$SIR_{A:BC} = \frac{\Delta E + \Delta W + \Delta OMR + \Delta X}{\Delta I_0 + \Delta Repl - \Delta RV} \quad (7)$$

The important point in calculating the values of the formula above is that all values must be discounted to the present value (Kneifel & Webb, 2020).

– *Adjusted internal rate of return (AIRR)*: the AIRR measure determines the annual return on investment in a project according to the duration of the study. This criterion is also a relative criterion, like the other criteria mentioned so far. This concept means that parameters such as base year, discount rate, and inflation are considered the same for the proposed solution and the base case. In general, AIRR is equal to the discount rate used in calculating the LCC of a project. The way to analyze this index is that if the calculated AIRR is greater than the project's MARR, the investment will be profitable. Also, if the AIRR number is equal to the MARR of the project, it means that the amount of savings of the project is equal to its costs, and as a result, the project is neutral. It should be noted that the requirements for using this index are the same as those for the SIR index, and it is generally used to rank the proposed solutions.

To calculate AIRR, SIR must be calculated first; then the following relation can be used:

$$AIRR = (1 + r).(SIR)^{\frac{1}{N}} - 1 \quad (8)$$

In this formula, r is equal to the reinvestment rate and N is the longevity of project services (Kneifel & Webb, 2020).

– *Discounted payback (DPB)*: this measure and SPB are the payback measures. This criterion calculates the time required to recover the investment costs in the initial stages of the project. DPB calculates the payback period of the project by means of the amounts spent or obtained from the project each year. As stated, the output of this index will be in the form of time; as a result, if the DPB of the project is less than the study period, the project will have economic justification (Kneifel & Webb, 2020; Kneifel & Webb, 2022).
– *Simple payback (SPB)*: unlike the DPB criterion, which used discounted inflows and outflows to calculate the project's payback period, the SPB criterion does not account for price changes during the payback period. This criterion is usually set in a certain period of time, which is much less than the study period. Assuming the discount rate is greater than 0 because the undiscounted costs and revenues are more than the discounted financial flows, the SPB index is shorter than the DPB of that project (Kneifel & Webb, 2020; Kneifel & Webb, 2022).

Among the mentioned criteria, the first three are compatible with the LCC analysis. That is, they will reach the same results when determining the cost-effectiveness of an alternative project solution. However, in calculating the LCC of the unique proposed options to select the optimal solution, the only criterion compatible with the life cycle costing process is the net savings rate criterion.

The important thing about the explained criteria is that all of them express the relative economic performance of the options. It means that these indicators are used for a proposed solution in comparison with the base case. In the meantime, the correct diagnosis of the basic case is very important. In this choice, it should be noted that, usually, the basic model has a low investment cost while investment costs are higher than other options.

To clarify, in projects that are not mandatory and are carried out due to the improvement of the overall efficiency of the building (such as the use of intelligent systems of building facilities), the initial state is the same as the existing state. But in projects that are not optional (such as the breakdown of a piece of equipment and replacing it with a new piece of equipment), it is probably the base case that is the project's proposed replacement (Kneifel & Webb, 2020, 2022).

7.1 Some Software to Perform LCC Analysis

Since the formation of life cycle costing analysis, many researchers have been trying to provide a tool to facilitate the calculation of this economic process. These tools can include relationships and analytical methods, as well as the use of computer programs. The advantage of using a computer to calculate LCC is that long calculations can be done in a shorter time and with less error. Today, these tools are so widespread that many people use this software in their industrial and scientific projects. In the following, a number of famous and widely used software in this field will be described.

7.1.1 BLCC

Building life cycle cost analysis software is a tool to facilitate life cycle cost analysis calculations provided by the National Institute of Standards and Technology (NIST). This software is provided based on ASTM standards and the NIST 135 manual. Based on its description and according to some articles, with the help of this software, various alternative solutions can be checked simultaneously, and the most suitable proposed solution can be identified based on the relationships in the LCC analysis. It should be noted that this software is capable of calculating supplementary LCC analysis criteria, such as the criteria described above, and as a result, the accuracy of the calculations is also increased (Office of Energy Efficiency & Renewable Energy, Department of Energy, n.d.).

7.1.2 EERC

Another life cycle cost analysis software is the EERC software. Considering that the energy price forecasts by the International Energy Organization are different every year, this software, for the sake of simplicity, includes a fixed price increase rate in its calculations. Then each of the proposed solutions is weighted and included in the calculations. The rate of increase according to different energy price scenarios can be determined based on information from the International Energy Agency or NIST forecasts. The important point of this software is to predict energy prices based on carbon-based policies. For more information, you can refer to this software's website (Office of Energy Efficiency & Renewable Energy, Department of Energy, n.d.).

7.1.3 BEopt

This software, in fact, is a building energy consumption optimization software, which can also check different proposed designs and identify the lowest ones in terms of LCC. This software simulates building energy performance using the Energy Plus and Building America DOE calculation engine. These calculation tools that BEopt software uses to simulate the energy of buildings are based on different characteristics of houses, such as the type of building cover, people, HVAC systems, etc. Also, this software uses the sequential search optimization technique to find multiple optimal solutions according to the owner's opinion (Reopt software, n.d.).

7.1.4 REopt

REopt software is a specialized software for optimizing energy systems, such as photovoltaic panels, wind turbines, grid electricity, wave converters, geothermal systems, etc., for buildings with various uses. This software identifies available strategies to reduce life cycle costs for a given location. The interesting thing about this software is that over the past 10 years, this software has been used to measure the potential of building more than 10,000 power plant projects, among which power plants with a total capacity of 260 megawatts have been created so far (Reopt software, n.d.).

8 Conclusion

Life cycle cost analysis provides a powerful tool for the financial management of all costs related to different parts of a building, including materials, energy systems, operation, etc., in a specific study period. In fact, in order to identify financially suitable options in a construction project at all stages, this analysis is required. This analysis can show whether or not the costs caused by the changes are recoverable during the life of the project compared to the base case. Meanwhile, the following points are very important when using LCC:

- It helps find the most financially optimal option among several proposed solutions.
- In performing LCC analysis, the condition of estimating the minimum requirements for the project, such as financial, technical, and other requirements, must be met.
- All the parameters mentioned in the previous sections, such as the discount rate, inflation, etc., should be assumed to be the same for all solutions.
- In order to improve the results and make the analysis more realistic, all input costs should be correctly identified and included according to formula 2.
- Parts that are not quantitative and cannot be measured with monetary units should be somehow included in the analysis.
- In order to perform some LCC calculations, some supplementary features described in Sect. 7 should be calculated.
- A wide range of software programs have been developed to facilitate the calculation of the LCC of a construction project, which can be used according to the type of project and design requirements.
- Determining some influential parameters in the LCC process should be done based on expert judgment and experience. Therefore, in order to correctly perform life cycle cost analysis, one should have a relative mastery of the economic issues.

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