Life Cycle Costing: Evaluate Sustainability Outcomes for Building and Construction Sector

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Synonyms

Costs-in-use; Life cycle cost (LCC); Through-life costing (TC); Total life cycle costing (TLC); Total-cost-of-ownership; Whole life cycle (WLC); Whole-life-cycle costing (WLCC)

Definition

Life cycle cost (LCC) has been defined and redefined in different studies undertaken on this topic previously. However, life cycle cost in this entry is considered as a sum of all costs related to a life cycle of a building from the phase of investment to the phase of deconstruction. For a sustainable building, it is anticipated that the environmental impacts associated with the design, construction, and operation of this building are also lower than a business-as-usual building. Sustainable buildings or green buildings are still not mainstreamed in many parts of the world.

Introduction

The building and construction sector has a significant impact on the planet. The sector consumes more than 40% of the world's resources, requires 40% of global energy, emits 30% of GHG emissions, and uses 25% of the global water supply (UNEP 2016). Further, this sector contributes to 39% of energy-related CO2 emissions when upstream power generations are included (UN Environment and IEA 2017). The sector continues to grow in different parts of the world, particularly in the rapid city building regions of Asia, Africa, and Latin America. To the year of 2060, in excess of half the buildings expected to be built will be designed and constructed in the next 20 years. This means that the impact to the planet from this sector will continue in the near future. To eliminate this impact, the building and construction sector has made a deliberate move to sustainability as proactive approaches and efficient solutions are needed to protect the environment as well as to meet economic and societal needs.

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This entry commences with an understanding of the Sustainable Development Goals placing in the context of the building and construction sector. The primary focus is to reduce environmental impacts and improve the economic outputs while supporting social cohesion. Following this is an understanding of LCC and its implementation in this sector. An exploration of how LCC and its variations are used to assess sustainability contributions across environmental, economic, and social considerations is provided before concluding this entry.

Sustainable Development Goals

The Sustainable Development Goals (SDGs) came into effect on January 1, 2016, with 17 goals and 169 targets (UN 2020a). SDGs provide a clear direction to integrate and embrace sustainability into every facet of human lives. SDGs primarily address issues related to water, energy, climate, oceans, biodiversity, urbanization, transport, science, and technology. It supports and promotes peace and prosperity of humans in the planet from present to future human generations. Although the SDGs have come into effect recently, there has been a history to develop and implement the underlying intent upon which they are based, supported by different UN agencies and other international bodies since 1987 (UN 2020b). Currently, SDGs are tracked, updated, and reported for ongoing monitoring by High Level Political Forum (HLPF) on an annual basis to the end of 2030.

Of all the SDGs, the goal of SDG 9 focuses on industry, innovation, and infrastructure. The target of this SDG is to “build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation” (UN 2020a). SDG 9 directly engages the building and construction sector, especially form the perspective of impacting energy, water, and land resulting in environmental impacts. Other SDGs such as SDG 11 also directly impact building and construction as it is focused on making cities and human settlements safe, sustainable, inclusive, and resilient. Similarly, SDG 13 focuses on climate change and its impacts. However, as this entry is a part of the volume on SDG 9, direct connections to this SDG relevant to life cycle costing are considered.

Based on SDG9’s targets and indicators, it can be said that the sector of building and construction associated with the intent of this entry is directly affected by target 9.4 and indicator 9.4.1.

Target 9.4 is:

> *By 2030, upgrade infrastructure and retrofit industries to make them sustainable, with increased resource-use efficiency and greater adoption of clean and environmentally sound technologies and industrial processes, with all countries taking action in accordance with their respective capabilities.*

Indicator 9.4.1 states:

> *CO2 emission per unit of value added.* (UN 2020a)

Additionally, indirectly affecting the building and construction sector is target 9.5 to encourage innovation through scientific research expressed through two indicators. The first indicator focuses on proportion of GDP spent on research and development, and the second indicator centers on the numbers of researchers engaged in undertaking scientific investigations. Likewise, target 9. a calls for financial support for least developed countries and small island developing states (SIDS) manifested in its corresponding indicator of international support provided for infrastructure in the mentioned country contexts.

To satisfy these and similar targets assisting the building and construction industry to meet its goals of sustainability outcomes, it is essential for the sector to urgently implement sustainability practices and to fast track and accelerate the adoption of sustainability underpinnings. However, sustainability practices and outcomes in the building and construction industry have had to satisfy the trade-offs between costs and benefits, causing a predicament to decision-makers. To provide a transparent approach for assessing sustainability contributions, LCC is one of the well-known methods to address this issue. LCC and its variations have been developed and implemented to capture and evaluate sustainability contributions in such projects.

Life Cycle Cost

Life cycle cost (LCC) has been understood by different names, including whole lifecycle cost (WLC), through-life costing (TC), costs-in-use, total life costing (TLC), total-cost-of-ownership, and whole-life-cycle costing (WLCC) (Hunter et al. 2005; Edwards et al. 2000). One of the most used LCC definition is: “the present value of total cost of that asset over its operational life. This includes initial capital cost, finance costs, operational costs, maintenance costs and the eventual disposal costs of the asset at the end of its life. All future costs and benefits are reduced to present day values by the use of discounting techniques” (Addis and Talbot 2001) (p. 1). Based on varied names and definitions, a primary principle of life cycle cost is the consideration of costs and benefits over the assessment period (BS ISO 15686-5 2008). The costs include land cost, income from the building, and any externalities related to building activities. Although LCC and WLC have been used interchangeably in previous studies for assessing sustainability contributions to construction projects (Meng and Harshaw 2013; Zuo et al. 2017), LCC is used in this entry.

LCC’s approach is to focus on the cost related to construction and operation of a building project, defined as “a technique which enables comparative cost assessments to be made over a specified period of time, taking into account all relevant economic factors, both in terms of initial costs and future operation costs” (BS ISO 15686-5 2008). LCC is also defined as “a process to determine the sum of all expenses associated with a product or project, including acquisition, installation, operation, maintenance, refurbishment, discarding and disposal costs” (Standards Australia/Standards New Zealand 1999).

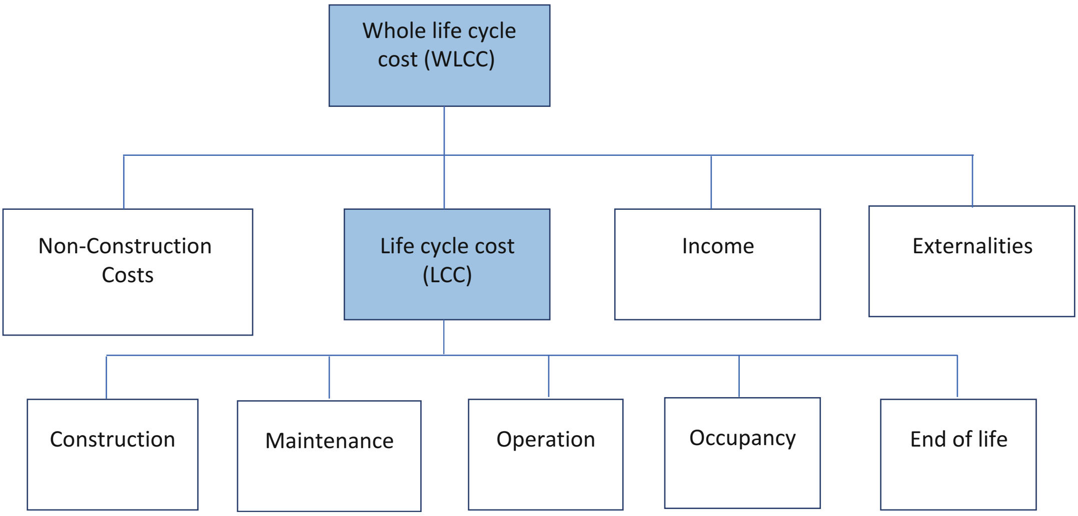
With the aim of examining sustainability construction during a project time, LCC is one of the most effective tools for evaluating sustainability contributions during a building and construction project. The application of LCC is rapidly increased with respect to sustainability considerations in construction as it encourages life cycle thinking with a long-term and systematic consideration of development of a project. In addition, it supports decision making for achieving sustainability outcomes (Kirkham 2005). LCC supports a trade-off between long-term economic, societal, and environmental performances and the higher initial costs for sustainability features and technologies in projects (Goh and Sun 2016).

LCC was first implemented in the procurement of military equipment of US Department of Defense, which integrated environmental costing into decision-making management (Epstein and Research 1996). This was followed by LCC use in the construction industry with efforts directed to consider future energy costs in project plans and designs (Marshall 1987). Following its successful use in the construction industry, LCC has been used across different countries.

LCC may be aligned to the Sustainable Development Goals (SDGs) as indicated earlier as it presents an important framework on developing global sustainability (Wulf et al. 2018). This has also been shown particularly in relation to SDG 9, but also cuts across other SDGs when considering the building and construction sector. Indeed, LCC needs to be aligned now more than ever to the SDGs as the goals cut across environmental, economic, and social dimensions. LCC may be used as an efficient tool for achieving SDG 9 in prevailing economic, environmental milieu and developing technologies and innovation to meet environmental objectives (UNEP 2016). It has been applied across different projects for assessing sustainability efficiencies of these projects. The various definitions of LCCs can be summarized as shown in Fig. 1.

LCC Approach in Building Projects for Sustainability Outcomes

Many studies have been carried out by using LCC as a primary research method for assessing sustainability contributions. A study of Marszal and Heiselberg (2011) used LCC for the assessment of energy efficiency in building projects. It considered LCC under four cost elements: investment cost (IC), operation and maintenance cost



Life Cycle Costing: Evaluate Sustainability Outcomes for Building and Construction Sector, Fig. 1 Definition of LCC. (Source: BS ISO 15686-5 2008)

(O&MC), replacement cost (RC), and demolition cost (DC) in Eq. 1.

$$LCC = IC + O\&MC + RC + DC \tag{1}$$

The equation was used to assess nine case studies that applied different energy efficiency methods. The life cycle of these projects was more than 30 years. This study demonstrated that LCC was the best tool for assessments of financial investment, cost efficiency, and cost optimal systems to support selection of energy efficiency methods.

Another study conducted by Worth et al. (2007) used LCC for comparing four types of roof constructions including steel sheeting, concrete tiles, softwood timber trusses, and lightweight structural steel framing. LCC of each roof construction was estimated by material costs for embodied energy and CO2 emissions. Based on this, LCC comprised of material installation costs and maintenance costs calculated by input-output models, which has been developed for building materials in New Zealand. By integrating LCC and discounted rate of net present values (NPV), the research found that concrete tiled roof structures had lower LCC costs. However, steel sheeting had greater durability while concrete tile cladding had lower embodied energy. This study contributed to guiding the selection of roofing materials to meet energy efficiency requirements, as an inherent element of sustainability outcomes in the building sector. The pros and cons of each material were transparent that assisted in decision making.

LCC is also used for determining cost optimal solutions between alternatives of renewable energy strategies. LCC has been integrated with net savings and returns to consider all costs of a construction project (Tabrizi and Sanguinetti 2015). The LCC model included investment cost (I), replacement cost (Repl), residual value (Res), and operating and maintenance cost (O&MC). Of the cost elements, residual value was defined as the remaining value at the end of a building life cycle (see Eq. 2)

$$LCC = I + Repl - Res + O\&MC \tag{2}$$

The LCC model notably considered residual value instead of deconstruction cost for assessing value returns at the end of a building life cycle. The residual value emphasized the value of sustainability contributions to the end of a project which is quite different with a traditional project. Therefore, LCC may be considered as an innovative approach to assist in decision making and risk management within the construction industry

(Ellingham and Fawcett 2007). It can be applied for comparison among different alternatives and supports the right option. LCC interacts with building projects, costs, and sustainability properties/characteristics in its assessment. LCC may be individually estimated for every competing option in a project. By using this method, operational costs of sustainable options are normally lower than with traditional options. The next section now examines how life cycle costs may be used to assess and understand sustainability contributions.

Development of Life Cycle Cost to Assess Sustainability Contributions

Sustainability has been defined and interpreted many times over the last few decades. It has been commonly defined based on the definition of sustainability development by WCED (1987, p. 43) as "… to ensure that it meets the needs of the present without compromising the ability of future generations to meet their own needs." Sustainability may be understood through the triple bottom line (TBL) approach (Elkington 1997) where it is the interpretation of the relationship between economic prosperity, environmental quality, and social justice. Sustainability outcomes result through the process of innovating new measures for minimizing environmental issues, while supporting economic growth and delivering on social outcomes. Usually, economic, environmental, and social considerations are compromised to support sustainability outcomes.

From this perspective, LCC is developed for assessing these TBL outputs and outcomes with the inclusion of environment and society beyond purely economic assessment.

Research has shown the t split analysis of economic and environmental aspects during project life cycle. Ristimäki et al. (2013) and Islam et al. (2015) showed the importance of integration of LCA and LCC for evaluating energy efficiency and cost. According to Wang et al. (2010), lifecycle assessment (LCA) was the best tool to evaluate long-term environmental and economic issues of a sustainable building, while lifecycle cost (LCC) was the primary cost driver that controlled the cost during a project.

LCA is defined as "the compilation and evaluation of the inputs, outputs and potential environmental impacts of a product system throughout its life cycle" (ISO 14040 2006). In the study by Wang et al. (2010), LCC was used for the assessment of cost and LCA was used for the assessment of carbon reduction and greenhouse gas emissions. This integration aimed to improve the evaluation accuracy of cost savings and carbon emission reductions. It showed the alignment of economic and environmental interests through support of LCC and LCA in sustainability assessment.

Similarly, Kovacic et al. (2016) implemented LCC and LCA for assessing three options of façade systems including steel liner tray, steel sandwich panels, and cross laminated timber panels for achieving energy efficiency. In this study, LCC was derived from investment costs, following operational costs and demolition costs, estimated by Eq. 3.

$$LCC = I + \sum_{t=0}^{n}\left(\frac{U_t}{(1+i)^t}\right) + \frac{A}{(1+i)^n} \qquad (3)$$

Notes: I-Investment cost, U-Operational costs, and A-Demolition cost.

While LCC has been the driver as indicated, LCA was used for assessing environmental impacts. The life cycle of LCA was drawn from the production phase (material extraction, production) to the end of its life, through deconstruction/disposal of waste, recycling potential, and/or deconstruction or disposal management. LCA was evaluated by indicators of impact assessment including Global Warming Potential (GWP), Acidification Potential (AP), Primary Energy nonrenewable potential (PEnr), and Primary Energy renewable potential (PEr). Based on the analysis of LCC and LCA, this study found that construction cost was the major difference among the options considered. For GWP, it noted that cross laminated timber façade provided the best performance although it had the highest initial costs. This study concluded that LCC and LCA were applicable tools for supporting decision-making for design and investment stakeholders.

Along these lines, research by Tam et al. (2017) applied LCC for guiding designers and builders for selecting timber types in residential projects to achieve sustainability outcomes as well as timber credits in Green Star ratings in Australia. The research considered six types of timber materials including radiata pine, red gum, blue gum, hoop pine western red cedar, pacific jarrah, and cypress pine. This study noted that LCC determined the capital cost of timber materials, its common applications within a building, expected service life, maintenance work required, and cost of maintenance and demolition or removal. LCC was calculated by

Present value $=$ Future value$/(1+\mathrm{r})^{\mathrm{n}}$ for considering the time value of money

This study highlighted that radiata pine was the best timber application from the perspective of cost efficiency. However, for structural application, radiata pine was more expensive than hoop pine. All these findings assisted in developing guidelines for selecting the best timber applications for residential projects in Australia.

Life cycle assessment tools are used for sustainable projects through the integration of other aspects of sustainability (Onat et al. 2014). LCA has also been extended to social assessment with the model of life cycle sustainability assessment (LCSA) (Kloepffer 2008; Guinée 2016). This extension was the separation of TBL sustainability: society, economics, and environment along a project life cycle. The model of LCSA is expressed as:

$$\mathrm{LCSA}=\mathrm{LCA}+\mathrm{LCC}+\mathrm{SLCA} \qquad (4)$$

In this model, LCC and LCA represent efficient tools for economic and environmental assessments, while SLCA incorporates the assessment of society. The most challengeable feature of this model was the need of data for the SLCA variable and quantitative methods of SLCA indicators. In other words, SLCA in this model represents the theoretical assessment of society. However, this model still provides an assessment tool for every important pillar of the TBL, at least in theory.

A study undertaken by Fortier et al. (2019) used social life cycle assessment (SLCA) for assessing positive and negative social impacts through life cycle of a system or a product. This study focused on energy justice towards low carbon energy sources for highlighting the importance of energy transitions in implanting energy technologies. SLCA was undertaken by the assessment across four key stakeholders: workers, local communities, electricity consumers, and society at large. This study demonstrated that SLCA framework for assessing energy justice was workable for evaluating new energy installations and potential substitutions of energy systems. SLCA in this study also needed to emphasize life cycle management and corporate social responsibility goals. The research found that SLCA had a responsible role in informing energy transition by categorizing, qualifying, and quantifying justice considerations. It supported the plan of developing energy efficient projects as well as implementing low-carbon energy sources, while also demonstrating new technologies has a place in understanding energy transitions.

Besides SLCA for social evaluation, there were many other different tools to measure the contribution of sustainability towards society. These tools emphasize the considerations of human health and well-being, including:

- Quality Adjusted Life Years (QALY) for assessing human health and well-being under sustainable conditions (Weidema 2006).
- Life Cycle Attribute Assessment (LCAA) for considering human health through the summary of attributes (Norris 2006). LCAA could be the socio-economic pathway to health, reflecting life cycle environmental impacts on health.

However, these two tools were often implemented in the supply chain industry rather than in the construction industry (Weidema 2006; Norris 2006).

As a new approach to life cycle cost (LCC), Sloan et al. (2014) examined the interrelationship among the cost component in different stages of a project. This new approach explored the co-efficiency on the combination of the use of binominal theorem and LCC. The binomial theorem was used as an efficient tool to discover the combination numbers of variables that should be estimated in life cycle cost (Hoffman and Frankel 2001). The new approach was known as the Continuous Whole Life Cycle (CWLC) with a broadened development of the standard WLC:

$$WLC = \sum_{t=0}^{T} \frac{C_t^i}{(1+d)^t} \tag{5}$$

and a new generation whole-life costing (NWLC) in train.

Based on these, the continuous whole-life cycle can be presented as below:

$$CWLC = C_0 + \int_{t=0}^{n=25} C_k(t)dt \tag{6}$$

This approach explained that the relationship between cost parameters caused the increase of life cycle cost in a sustainable project compared with a traditional project. This model expressed the linkages among project stages from initial design decisions to operational efficiency. Therefore, the combination improved the accuracy of estimating life cycle cost during the project period. However, the challenge of this model is obtaining realistic data for implementation.

From the lifecycle-based approach, various models can be summarized as shown in Fig. 2:

To select a better design under given conditions, Wang et al. (2005) integrated the life cycle assessment with the multiobjective optimization model. This model solved the problem of the having to trade-off the relationship between economic and environmental performances for generating cost-effective decisions. In this model, the selected objectives were to minimize lifecycle cost (LCC) and life cycle environmental impact (LCEI) by using optimization models. These models may be expressed as the following Eq. (7):

$$\mathrm{LCC(x) = IC(x) + OC(x)}$$

and

$$\mathrm{LCEI(x) = EE(x) + OE(x)} \tag{7}$$

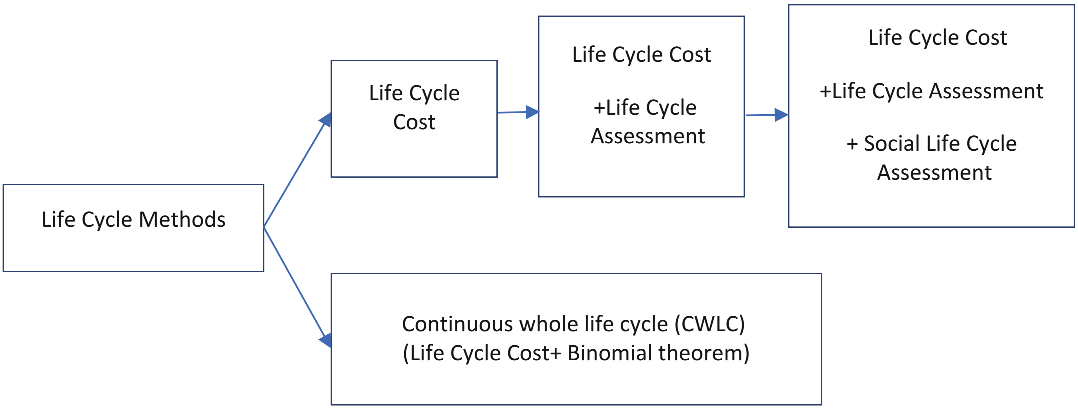
In these, x is denoted as a variable vector, IC is the initial cost, OC is the life cycle operating cost, EE is the environmental impact due to the pre-operational phase, and OE is the environmental impact due to the operation phase.

Based on these models, a genetic algorithm was implemented with multiple Pareto solutions to resolve the trade-off relationships and find optimal solutions. This method of multiobjective optimization and modeling was suitable for the objective optimization of environmental and economic performances in a sustainable project. The challenge of this method is the selection of parameters that are optimized to suit the assessment scope.

Specifically regarding the energy assessment Chau et al. (2015) illustrated that LCC assessment has been developed to include life cycle assessment (LCA), life cycle energy assessment (LCEA), and life cycle carbon emissions assessment (LCCO$_2$A) for evaluating environmental impacts and supporting decision making of building projects. Of these tools, LCA was used for assessing all environmental impacts of inputs and outputs of building materials during different stages of these projects. It was calculated by using the Eqs. 8 and 9:

$$\begin{aligned} \mathrm{I} = {} & \mathrm{I_{Extraction} + I_{Manufacture} + I_{On\ site} + I_{Operation}} \\ & \mathrm{+ I_{Demolition} + I_{Recycling} + I_{Disposal}} \end{aligned} \tag{8}$$

Also, LCEA aimed to evaluate energy inputs for different stages and was calculated by:



Life Cycle Costing: Evaluate Sustainability Outcomes for Building and Construction Sector, Fig. 2 Lifecycle-based methods. (Source: Authors)

$$\begin{aligned} E = {} & E_{\mathrm{Extraction}} + E_{\mathrm{Manufacture}} + E_{\mathrm{On\ site}} + E_{\mathrm{Operation}} \\ & + E_{\mathrm{Demolition}} + E_{\mathrm{Recycling}} + E_{\mathrm{Disposal}} \end{aligned} \tag{9}$$

LCEA was able to use for either primary energy (energy directly extracted from nature) or secondary energy (energy was actually consumed). Further, $LCCO_2A$ was developed for assessing CO_2 emission outputs of these projects. Similarly, $LCCO_2A$ was calculated from the following Eq. (10):

$$\begin{aligned} CO_2 = {} & CO_{2\mathrm{extraction}} + CO_{2\mathrm{manufacture}} + CO_{2\mathrm{on\ site}} \\ & + CO_{2\mathrm{operation}} + CO_{2\mathrm{Demolition}} \\ & + CO_{2\mathrm{Recycling}} + CO_{2\mathrm{Disposal}} \end{aligned} \tag{10}$$

Based on the extensive literature review, this study showed that these three tools supported the assessment of environmental impacts throughout different stages of a project. Implemented in some case studies, the research also noted that the largest life cycle environmental impacts were from the use phase of a building project and the impact depended on the types and compositions of materials used. This study also mentioned that LCA would be potentially enhanced in the construction industry as this tool enabled the assessment of both indoor and outdoor environmental impacts for building projects. Further, this study recommended LCA should be applied in the early stages of a project for optimizing any design options although it was very hard to be undertaken during the early design stage of a project life cycle.

Conclusion and Way Forward

For evaluating sustainability contributions of and for building projects, LCC has been implemented for assessing energy efficiency or determining energy impacts in such projects. This is because the primary focus of sustainability has traditionally been in the category of energy efficiency. LCC may be used to assess the economic underpinnings during a project life cycle. However, LCC solely works with monetized contributable elements, which becomes a restriction for the smooth implementation in projects seeking sustainability outcomes. LCC is unable to or has limitations to assess intangible and nonmonetized contributions of sustainability, such as productivity and health improvement. LCC has been extended for evaluating environmental and social contributions beyond traditional economics or fiscal perspectives. Life cycle assessment (LCA) is used as a tool for evaluating environmental contribution. However, it is worth noting that social life cycle assessment (SLCA) has been developed for social assessment. These tools, when integrated to LCC, support to capture holistic contributions of sustainability in building and construction projects and satisfy TBL requirements for sustainability achievement.

LCC provides greater value-add with the integration of the Binomial theorem. This integration focuses on the inter-links and inter-relationships between the various cost parameters or elements. For instance, initial cost and operational cost are inter-linked in projects seeking sustainability outcomes. The higher the initial cost is, the lower the operational cost should result as presented in the research by Sloan et al. (2014), as already stated. The links between initial and operational costs can be considered as the new approach of LCC with the view of total costs in project life cycle.

The contributions of LCC to sustainability assessment can be summarized below:

- Use for life cycle consideration during building projects. As reviewed and presented in a wide range of literature, LCC is technically included as initial/capital costs, operational costs, maintenance costs, and demolition or removal costs. With current thinking around circularity issues or circular economy, the demolition needs to be replaced with deconstruction. LCC applies present value with the selection of life cycle and discount rates for its calculations so the fiscal alternatives provided are in real time.
- Implementation for a dynamic evaluation of sustainability contributions on three different pillars of economics, environment, and society is also supported through understanding LCC. LCC has been extended to other nontraditional areas with support of LCA and SLCA for assessing environmental and societal contributions.
- Modifications or development of additional functions for covering the considerations of a life cycle approach for a project from different perspectives of sustainability provides a more holistic approach.

However, LCC has some limitations. The first limitation is the scope among LCC, LCA, SLCA, and other extensions. The scope needs to be defined clearly for avoiding double counting of one or more sustainability contributions, which leads to inaccurate assessment as already flagged by Sala et al. (2013). Indeed, some contributions of sustainability (such as energy savings) can be assessed by economic contributions and can also be considered from an environmental perspective, which is even more reason to ensure there is no double counting. Therefore, a contribution should be carefully considered for evaluation only once in sustainability assessments and the scope should be clearly defined.

Another limitation is the availability of cost data. Often, data is too hard to be published or made available because of the nature of the construction business, which does not provide information openly due to copyright issues and competition as flagged by several authors such as Meng and Harshaw (2013), Fawcett et al. (2012), and Olubodun et al. (2010). Without the data, LCC cannot be undertaken and hence, unable to demonstrate relevant contributions to project stakeholders as well as to convince developers and investors to develop projects with sustainability outcomes.

Despite its limitations, LCC is an effective approach for assessing sustainability outcomes. From the perspective of the SDGs, SDGs of 9.4 and indicator 9.4.1 relevant to the building and construction sector have impacted to this sector in terms of resources, energy, and CO2 emissions. Human well-being can be achieved with economic growth as long as it is decoupled with environmental impacts. Sustainability integrated into this sector is essential and the role of LCC in this sector is crucial. LCC needs to become mainstream rather than remain in its current place at the fringes of the broader sector. Supporting this process is urgently needed now than ever before.

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