Author/s:
Schmidt, M;Crawford, RH

Title:
Developing an integrated framework for assessing the life cycle greenhouse gas emissions and life cycle cost of buildings

Date:
2017

Citation:
Schmidt, M. & Crawford, R. H. (2017). Developing an integrated framework for assessing the life cycle greenhouse gas emissions and life cycle cost of buildings. Procedia Engineering Special Issue: Creative Construction Conference 2017, 196, pp.988-995. https://doi.org/10.1016/j.proeng.2017.08.040.

Persistent Link:
https://hdl.handle.net/11343/297341

Available online at www.sciencedirect.com

ScienceDirect

Procedia Engineering 196 (2017) 988 – 995

Procedia Engineering

www.elsevier.com/locate/procedia

Creative Construction Conference 2017, CCC 2017, 19-22 June 2017, Primosten, Croatia

Developing an integrated framework for assessing the life cycle greenhouse gas emissions and life cycle cost of buildings

Monique Schmidt[a*], Robert H. Crawford[a]

[a] *Faculty of Architecture, Building and Planning, The University of Melbourne, Parkville, VIC, 3010, Australia*

Abstract

With building-related greenhouse gas emissions(GHGE) having more than doubled since 1970, they represent one of the largest and most attractive opportunities for climate change mitigation. However, current focus has mainly been on reducing operational GHGE leaving building embodied GHGE (i.e. the GHG emissions associated with the extraction, manufacture and transportation of materials, and the building construction process itself) largely ignored. These embodied emissions have been estimated to represent between 10% to 97% of a buildings total life cycle GHGE. It is thus critical that decision-making in relation to buildings is based on a life cycle perspective. One of the main barriers to this approach is the uncertainty surrounding the financial implications of life cycle GHGE reduction strategies. Despite project cost being a key driver for decision-making, building developers, designers and owners have insufficient knowledge or appropriate tools to adequately consider these life cycle costs and balance them against GHGE savings. Several methods exist for quantifying the costs of a building, such as life cycle costing (LCC). However, LCC and life cycle GHGE assessments are often used in isolation. This study will address the urgent need to move towards integrating these assessments by developing a framework that can be used to ascertain the important relationships and trade-offs between financial and GHGE performance of various building-related GHGE reduction strategies. This framework can be used as part of the building decision-making process and help create a low carbon, affordable built environment.

Peer-review under responsibility of the scientific committee of the Creative Construction Conference 2017

Keywords: low carbon building; greenhouse gas emissions; life cycle assessment; life cycle cost

* mfouche@student.unimelb.edu.au.

1. Introduction

There is a growing concern about the poor environmental performance of buildings. In 2010, based on the most recent Intergovernmental Panel on Climate Change (IPCC) ‘Climate Change Report’, buildings accounted for 19% of energy-related global greenhouse gas emissions (GHGE) (which have more than doubled since 1970) (1). These

GHG emissions are one of the most significant contributors to climate change and are extremely likely to have been the dominant cause of the observed global warming since the mid-20th Century (1). Conversely, buildings represent one of the largest and most attractive opportunities to reduce GHGE (2). This GHGE mitigation has mainly focussed on reducing the operational GHGE, leaving the embodied GHGE largely ignored. These embodied emissions have been estimated to equate to between 10-97% of whole life cycle emissions for buildings (depending on building location, function, material use and assumptions about service life and energy supply) (3). Thus it has become critical to look at GHGE mitigation from a life cycle perspective. However, there are several barriers hindering the uptake of this. One such barrier not widely explored yet is the uncertainty towards the financial cost of this life cycle GHGE (LCGHGE) reduction. By having both the LCGHGE and life cycle cost (LCC) information available, the trade-offs between both these aspects can be used in the decision-making process. This paper will first provide a brief overview of the LCGHGE and LCC methods. The next section will discuss in more detail the previous studies that have combined both LCA and LCC, including the key weaknesses and gaps. The next section will then discuss how these weaknesses can be further developed into an improved integrated framework.

1.1. Life cycle greenhouse gas emissions assessment

A method commonly used to assess the GHGE of buildings from a life cycle perspective is called 'Life Cycle Analysis' (LCA). LCA helps analyse the relevant inputs (such as water, energy and raw materials) a product or building may require over its multiple life cycle stages in relation to its outputs (such as atmospheric emissions, waterborne and/or solid waste). LCA can be used to assess one product or building, which is referred to as a conventional LCA, or multiple products of building options, which is referred to as a comparative LCA. To further help narrow the scope of the assessment a streamlined LCA can be used which may only look at one environmental impact. An example of such an LCA is a LCGHGE assessment, which only looks at GHGE over the life cycle of the building. There is no mandatory legislation calling upon an LCA of buildings or standardised method, however voluntary standards, such as the International Organisation for Standardisation's 'Environmental Management – Life Cycle Assessment – Requirements and Guidelines' (ISO 14044, 2006), provides a suggested framework to be followed. This framework includes four key LCA steps, namely goal and scope definition (step 1); inventory analysis (step 2); impact assessment (step 3) and interpretation (step 4). There have been several studies discussing the shortcoming of these standards such as (4). What is also apparent from this framework is the lack of a sensitivity analysis step after Step 4. Life cycle studies are very subjective and include a range of assumptions that can significantly impact the final result, making the need for a sensitivity analysis critical (5, 6). LCA also tends to be completed towards the end of the design phase, thus having less potential to influence design choices, and are seen as quite complex and data intensive (7).

1.2. Life cycle cost assessment

A method used to assess the expected financial performance of a product or building from a life cycle perspective is 'Life Cycle Costing' (LCC). LCC analysis is 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 operational costs, as defined by ISO 15686 (2008) (8). Similar to LCA, LCC is not mandatory for building assessment and have no universally agreed upon method, however voluntary standards such as ISO 15686 suggest the following framework: define alternative strategies to be evaluated (step 1); identify economic criteria (step 2); obtain and group significant costs (step 3) and lastly perform a risk assessment (often referred to upon as a sensitivity analysis) (step 4). Similar to LCA, several studies have highlighted the amount of uncertainty involved with LCC studies as the future is being forecast on the basis of current data and knowledge (9, 10). What is also apparent from this suggested framework is that step 1 should ideally be preceded with defining the goal and scope of the study (similar to LCA) and should also involve a step of defining the base case strategy against which the alternative strategies should be compared. Thus it is evident that LCA and LCC, usually performed in isolation of each other, require further development in order to harness their true potential. There has also been a move towards combining both LCA and LCC building assessments, as discussed in the next section.

2. Previous studies that include both life cycle greenhouse gas and life cycle cost assessment

LCA and LCC have been predominantly used in isolation of each other, but there has been an increase in academic studies and commercial tools that have started combining both these functionalities in their analysis of a buildings performance. The next section will describe the previous academic studies that have used both LCA and LCC to either suggest a new framework, tool or method. The following section summarises the key weaknesses and gaps that need to be addressed in order to evolve the LCA and LCC integration process.

2.1. Previous studies

Previous studies that include both LCA and LCC can be broadly classified in to two groups. The first group have used the methods and data already associated with LCA and LCC in order to provide a building or product evaluation. These evaluations tend to conduct an LCA first to be followed by an LCC analysis and include examples such as (11), (12), (13) and (14). This group tends to not integrate the results or methodology but rather reports the LCA and LCC findings separately. In contract to this, the second group sets out to either provide a new combined LCA and LCC method (15), framework (16-18), model (19-22) or tool (18, 23, 24). The provision of a framework is a common theme in most of the second group's studies (whether the aim of the study was to create a new framework or whether a new tool/model was the aim of the study but required a framework to base its development on). A framework can be broadly defined as a real or conceptual structure intended to serve as a support or guide for the building of something that expands the structure into something useful (25). These frameworks, often diagrammatically illustrated, provide a road map for the suggested building or product assessment.

An example of a framework is provided by the Italian study completed by Petrillo et al (18), who's aim was to aid the systematic sustainability assessment based on both LCA and LCC. They performed their analysis in three different phases. Phase 1, 'Analytical', provided the initial analysis and characterisation which included scenario definition and choice of indicators. The second phase, 'Modelling', carried out LCC, LCA and social LCA separately resulting in a large collection of data. The last phase, 'Assessment', provided a means to integrate the results from the previous phase thorough methods such as multi-criteria analysis, and concluding in ranking assessed options with what they termed as a 'sustainability ranking'. This framework demonstrates an example of how LCA and LCC can be performed separately at first (as per Phase 2) and then aim to integrate both results in the last phase of the assessment. Even though this study provides a clear framework, they did not provide a full life cycle energy assessment with the exclusion of recurrent embodied energy (which can represent up to 32% of the initial embodied energy of a building (26) and did not provide a clear explanation of the weighting and scaling factors used when creating the sustainability rankings. Another example is the Chinese study completed by Deng et al (16). Their aim was to develop a framework for the integration of LCA and LCC in order to 'eco-balance' mechanical product design. In the interpretation phase the economic and environmental performance is assessed separately and then integrated to establish the trade-off relationships. Their study resulted in a table that lists the assessed options according to 'improvement degree' and 'integrated benefit matrix'. However the weighting and scaling factors used to get to these ranked results are not explained and lack of graphical output makes it harder for the user to grasp the assessment results.

Several studies did succeed in providing a form of graphical output, such as a graph, that integrates the LCA and LCC results. These graphs can potentially make it easier for the user to interpret the findings and visualise the environmental and economic trade-offs. An example is the recent Italian study completed by Savino et al (22) that aimed to create a new model for environmental and economic evaluation of renewable energy systems. They created a colour-coded matrix with the GHG impact on the Y-axis (kgCO_2e). The matrix is divided in to 'optimal region' (which is a low carbon footprint per unit costs) to 'intolerable region' (high carbon footprint per unit costs). The integrated LCA and LCC results are placed within the matrix allowing the user to clearly see which options are more optimal. However some allowance should be made for users personal parameters, as what might be optimal to one user might be intolerable to another. Also, the weighting needs to be more transparent especially with regards to how the options were placed on the X-axis and how that came to correspond to the values on the Y-axis (i.e. what scaling factor was used). Other graphical LCA and LCC examples include (12, 14, 27).

2.2. Key weaknesses and gaps in previous studies

The key weakness categories identified were data, results, life cycle stages, output and other, as illustrated in Fig.1. Under the data category, there is a lack of the use of comprehensive environmental data in studies. Almost all of the studies, except (28), (29) and (12), use process data, which has a much narrower system boundary when compared to other data types such as input-output data or hybrid data, thus many upstream impacts are ignored (7). There is also a severe lack of transparency regarding data inputs and calculation methods used. The next key item is that most of these studies set about claiming to integrate LCC and LCA data but fail to actually provide this integration either graphically or within the text. Some of the studies that do in fact succeed in this integration through graphic means are discussed above but this is quite a small number in comparison to the overall 22 studies that were found. Most studies provide their LCA and LCC results separately either in graphs or tables, such as (30) and (11) and still continue to separate the environmental results from the economic results in their discussion and conclusion sections. There is also a general lack of graphical output, such as (19) and (17). Life cycle studies can be quite complex and data intensive (31) and providing a form of graphical interpretation can better help the reader to interpret the results and emphasise the trade-offs between environmental and economical impacts. Another common aspect is the fact that several studies rank results into terms such as 'integrated benefit' or 'sustainability index' for example, such as (16) and (22). However the method behind the weighting of these results is not provided. For the studies that integrate both LCA and LCC results into one graph (as discussed above), the scaling factor (i.e. how to get two quite dissimilar datasets, such as cost and GHG, onto one graph and scale) is not provided.

The next key weakness to note is that several studies either neglect or don't explicitly state that recurrent embodied energy was not considered, such as (11), (17) and (24). Thus failing to actually carry out a full LCA as this life cycle stage can represent up to 32% of the initial embodied energy of the building (26). From a LCC perspective replacement and maintenance costs are also often excluded such as in (23) and (22). Another life cycle stage often not clarified is the operational stage. Both from an LCA perspective, such as in Langston and Langston (28) and (27), and a LCC perspective such as (24) and (32). In order to understand the true life cycle impacts of a building or product, all life cycle stages need to be considered. What can also be noted is a trend to carry out LCA and LCC on either products (16) or energy efficient technologies (11, 12). There is a lack of studies that combine LCA and LCC on typical buildings, especially residential buildings, which tend to make up a significant proportion of the total building fabric. Some of these studies present quite complex and data intensive framework and methods, such as (17), (18) and (19), that are not suitable to early stage design. Implementing life cycle economic and environmental optimisation at the early design stage is critical as the potential for change decreases rapidly throughout the building life cycle (33). Lastly, some of the studies are quite inflexible to personal parameters. What might seem tolerable to one user will not be tolerable (either in terms is economical cost or environmental cost) to another user. There should be allowance for the user of such frameworks to tailor it according to their personal needs.

There has been an increase in LCA tools starting to include LCC analysis within their capabilities, and visa versa, as discussed by (18, 24, 31, 34-36). Many of the studies consulted above have made use of one or more of these tools to either perform an LCA or LCC assessment. Kovacic et al (33) confirmed there is a gap in developing tools that successfully integrate both LCA and LCC, especially at an early design stage. Petrillo et al (18) also states that since so many tools currently exist, there is more a need to highlight complementarities or possibilities for integration rather than generating more new tools. These key weaknesses provide the road map to future integrated LCA and LCC development.

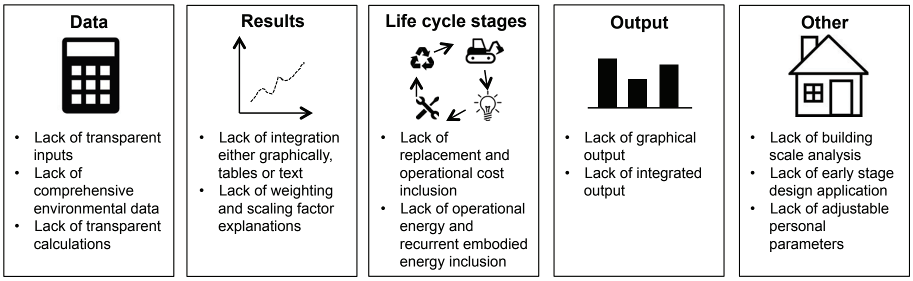

Fig. 1. Key weaknesses of previous LCA and LCC studies

3. Developing an integrated framework for life cycle analysis and life cycle costing

The next step was to address the key weaknesses identified in the previous section and translate them into an improved integrated framework. The aim of the framework is to aid building-related decision making at an early stage in the design process and to help the user balance financial cost and GHGE reduction, from a life cycle perspective. In order to develop the framework, a diagram was created that helps illustrate the various steps involved in carrying out such an integrated assessment, as illustrated in Fig.2. A brief overview of the assessment steps is then provided concluding in the framework's future development and summary of how it addresses the gaps identified in Fig.1.

3.1. Framework steps

The first step (similar to an LCA) is to define the goal, scope and aim of the assessment. The second step is to define the base case building to be assessed (and includes defining any key building characteristics such as size, materials, location etc.). The next step (similar to LCC step 1) is to define the alternative building options to be assessed. This could include, for example, building options with improved insulation or glazing strategies. The relevant economic and environmental data will be determined in Step 4 and refers to the data required to calculate the initial, recurrent and operational life cycle stages. Step 5, which will tie in with the aim of the study, will be to select the environmental impact category to be used in the assessment. The next step is to use this data and perform both the LCA and LCC assessments. These assessments will be carried out separately using the data and methods already inherent in each assessment, as described above. The seventh step is the critical step of integrating the results followed by interpretation and reflection of these results (more detail on both these steps are provided in the

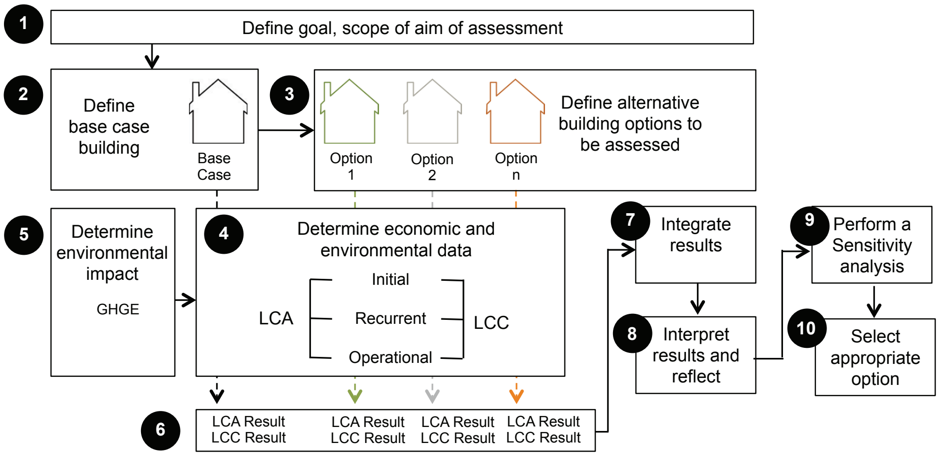

Fig.2 Integrated life cycle greenhouse gas and life cycle cost framework diagram

next section). The second last step borrows from LCC's final step by performing a sensitivity analysis in order to determine how key inputs might affect the results. The final step requires the user to select the appropriate option, based on their own personal preference (for example, some users will want to select a building option with the lowest LCGHGE with no major concern for cost, others will possibly want to select a less costly option).

3.2. Integration and interpretation of results

Two options are illustrated in Fig.3 as a means of integrating LCA and LCC results. Output A is an example of the four-quadrant approach (as used by (37)). The base case is plotted in the middle of the four quadrants with LCC on the y-axis and LCGHGE on the x-axis. The other building options results are then plotted on the graph. A graph such as this can aid the users' interpretation of results (as is required for Step 8 of the framework). For example if a building option appears in the top right quadrant, it is actually performing worse than the base case on both a financial and GHGE level and thus should probably not be selected. If an option is in the top left quadrant, it is performing better than the base case on a GHGE level but costs more than the base case. This option will be more suitable for a user with a priority of decreasing LCGHGE with no major concern to increased cost. This approach supports the selection of options based on the users personal parameters. The graph in output B is a stacked bar chart and provides the user with a more detailed understanding as to how each option impacts each life cycle stage. For example, based on the illustration in Fig.3, option 1 has an increased initial GHGE result when compared with the base case but in fact a lower LCGHG total. It can also be seen that the capital cost of Option 1 is higher than the base case but the total LCC is in fact lower than the base case LCC. By providing graphical outputs such as these (a major weakness noted in the previous studies consulted above) the users interpretation of results can be aided and the integration of LCA and LCC more seamlessly reached.

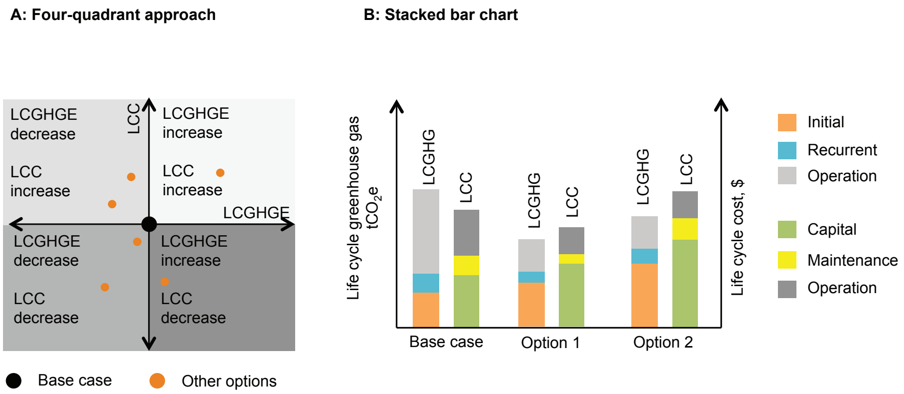

Fig 3. Possible graphical outputs of integrated framework

3.3. Summary of framework

First of all the framework addresses the critical lack of integrated LCA and LCC results, especially graphical outputs. By providing graphical outputs such as the examples above, the trade-offs between environmental and financial cost becomes more apparent to the user and has a greater potential to become a more integrated factor in early stage building decision-making. The graphical examples above do not make use of any weighting factors or using terms such as 'eco-points' or 'sustainability rating'. Instead the results are transparent. LCA and LCC results are presented along side each other allowing the user instead to rate the options based on their own personal preference. This framework also addresses the need to base embodied GHGE calculations on a more comprehensive approach of input-output hybrid approach (in contrast to the narrower system boundary of a process approach in previous frameworks). The framework is intended for building scale application and based on typical information available at an early stage in the design process (unlike the other more complex frameworks more appropriate for product related assessments).

The next step in the frameworks development is to identify the key parameters. The key parameters are divided into 'user defined inputs' and 'embedded inputs'. These inputs are based on the data requirements for the calculation methods used. The LCA data requirements are based on the Path Exchange hybrid approach as defined by (7). The LCC data requirements were defined by the calculations presented in (29) and (14). After this, the framework can be applied to a range of case study building projects. Through this application the framework potential can be further explored and any limitations and potential for future development can be identified. This next Step form part of an ongoing project at The University of Melbourne in partnership with the CRC for Low Carbon Living.

3.4. Conclusion

The described framework builds upon the existing frameworks already associated with the LCA and LCC methods (as discussed in Section 1), and the previous frameworks from similar studies (as discussed in Section 2). By identifying the key weaknesses and gaps, the foundation was set upon which to further develop an improved integrated environmental and financial framework for building scale assessment. A suggested framework approach (including the various steps involved and graphical output) has been provided which will be used in the next development process of identifying the key parameters, case study application and identification of framework potential and limitations. This framework aims to address the urgent need for integrating LCC and LCGHGE considerations, so that both the environmental and economic value of potential building strategies can be included in the decision making process contributing to the creation of a low carbon built environment.

Acknowledgements

This research is funded by the CRC for Low Carbon Living Ltd supported by the Cooperative Research Centres program, an Australian Government initiative, under the RP2007 Integrated Carbon Metrics Project.

References

1. IPCC. Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change Cambridge, United Kingdom and New York: 2014.
2. Climate Council. New report reveals that Australia is among the worst emitters in the world Australia Climate Council 2015 [06/06/2016]. Available from: https://http://www.climatecouncil.org.au/new-report-reveals-that-australia-is-among-the-worst-emitters-in-the-world.
3. Chastas P, Theodosiou DB. Embodied energy in residential buildings-towards the nearly zero energy building: A literature review. Building and Environment. 2016;105:267-82.
4. Dixit MK, Fernández-Solís JL, Lavy S, Culp CH. Need for an embodied energy measurement protocol for-buildings: A review paper. Renewable and Sustainable Energy Reviews. 2012;16:3730-43.
5. Menzies GF, Banfill PFG, Turan S. Life-cycle assessment and embodied energy: a review. Proceedings of the ICE - Construction Materials. 2007;160(4):135-43.
6. Dixit MK, Fernández-Solís JL, Culp CH. Identification of parameters for embodied energy measurement: A literature review. Energy Build. 2010;42(8):1238-47.
7. Crawford RH. Life Cycle Assessment in the Built Environment London: Taylor and Francis; 2011.
8. British Standards Institute. Standardized Method of Life Cycle Costing for Construction Procurement BS EN ISO 15686-5. United Kingdom 2008.
9. Flanagan R, Norman G, Meadows J, Robinson G. Life Cycle Costing: Theory and Practice. Oxford: BSP Professional books; 1989.
10. Islam H, Jollands M, Setunge S, Haque N, Bhuiyan MA. Life cycle assessment and life cycle cost implications for roofing and floor designs in residential buildings. Energy and Buildings. 2015;104:250-63.
11. Leckner M, Zmeureanu R. Life cycle cost and energy analysis of a Net Zero Energy House with solar combisystem. Applied Energy. 2011;88(1):232-41.
12. Ristimäki M, Säynäjoki A, Heinonen J, Junnila S. Combining life cycle costing and life cycle assessment for an analysis of a new residential district energy system design. Energy. 2013;63:168-79.
13. Bull J, Gupta A, Mumovic D, Kimpian J. Life cycle cost and carbon footprint of energy efficient refurbishments to 20th century UK school buildings. International Journal of Sustainable Built Environment. 2014;3(1):1-17.
14. Schwartz Y, Raslan R, Mumovic D. Implementing multi objective genetic algorithm for life cycle carbon footprint and life cycle cost minimisation: A building refurbishment case study. Energy. 2016;97:58-68.

15. Gu L, Lin B, Zhu Y, Gu D, Huang M, Gai J. Integrated assessment method for building life cycle environmental and economic performance. Building Simulation. 2008;1(2):169-77.
16. Deng C, Li Z, Shao X, Zhang C. Integration and Optimization of LCA and LCC to Eco-balance for Mechanical Product Design. Proceedings of the 7th World Congress on Intelligent Control and Automation June 25 - 27, 2008,; China: IEEE; 2008.
17. Heijungs R, Settanni E, Guinée J. Toward a computational structure for life cycle sustainability analysis: unifying LCA and LCC. The International Journal of Life Cycle Assessment. 2013;18(9):1722-33.
18. Petrillo A, De Felice F, Jannelli E, Autorino C, Minutillo M, Lavadera AL. Life cycle assessment (LCA) and life cycle cost (LCC) analysis model for a stand-alone hybrid renewable energy system. Renewable Energy. 2016;95:337-55.
19. Bierer A, Götze U, Meynerts L, Sygulla R. Integrating life cycle costing and life cycle assessment using extended material flow cost accounting. Journal of Cleaner Production. 2015;108:1289-301.
20. Ding GKC. Developing a multicriteria approach for the measurement of sustainable performance. Building Research & Information. 2005;33(1):3-16.
21. Hamdy M, Hasan A, Siren K. A multi-stage optimization method for cost-optimal and nearly-zero-energy building solutions in line with the EPBD-recast 2010. Energy and Buildings. 2013;56:189-203.
22. Savino MM, Manzini R, Della Selva V, Accorsi R. A new model for environmental and economic evaluation of renewable energy systems: The case of wind turbines. Applied Energy. 2017;189:739-52.
23. Anastaselos D, Giama E, Papadopoulos AM. An assessment tool for the energy, economic and environmental evaluation of thermal insulation solutions. Energy and Buildings. 2009;41(11):1165-71.
24. Hoogmartens R, Van Passel S, Van Acker K, Dubois M. Bridging the gap between LCA, LCC and CBA as sustainability assessment tools. Environmental Impact Assessment Review. 2014;48:27-33.
25. TechTarget. Framework Massachusetts: TechTarget; 2017 [23/01/2017]. Available from: http://whatis.techtarget.com/definition/framework.
26. Treloar GJ, Love PED, Holt GD. Using national input–output data for embodied energy analysis of individual residential buildings. Construction Management and Economics. 2000;19:49-61.
27. Huppes G, Ishikawa M. A Framework for Quantified Eco-efficiency Analysis. Journal of Industrial Ecology. 2005;9(3):25-41.
28. Langston YL, Langston CA. Reliability of building embodied energy modelling: an analysis of 30 Melbourne case studies. Construction Management and Economics. 2008;26(2):147-60.
29. Stephan A, Stephan L. Life cycle energy and cost analysis of embodied, operational and user-transport energy reduction measures for residential buildings. Applied Energy. 2016;161:445-64.
30. Menzies GF. Carbon energy and monetary investment model for low carbon building design. International Renewable Energy Congress; Tunisia2010.
31. Zuo J, Pullen S, Rameezdeen R, Bennetts H, Wang Y, Mao G, et al. Green building evaluation from a life-cycle perspective in Australia: A critical review. Renewable and Sustainable Energy Reviews. 2017;70:358-68.
32. Bovea MD, Vidal R. Increasing product value by integrating environmental impact, costs and customer valuation. Resources, Conservation and Recycling. 2004;41(2):133-45.
33. Kovacic I, Zoller V. Building life cycle optimization tools for early design phases. Energy. 2015.
34. Gluch P, Baumann H. The life cycle costing (LCC) approach: a conceptual discussion of its usefulness for environmental decision-making. Building and Environment. 2004;39(5):571-80.
35. Haapio A, Viitaniemi P. A critical review of building environmental assessment tools. Environmental Impact Assessment Review. 2008;28(7):469-82.
36. Heijungs R, Huppes G, Guinée JB. Life cycle assessment and sustainability analysis of products, materials and technologies. Toward a scientific framework for sustainability life cycle analysis. Polymer Degradation and Stability. 2010;95(3):422-8.
37. Torcellini P, Pless S, Leach M. A pathway for net-zero energy buildings: creating a case for zero cost increase. Building Research & Information. 2014;43(1):25-33.
38. Stephan A, Crawford RH. House size and future building energy efficiency regulations in Australia. Living and learning: Research for a better built environment: 49th International Conference of the Architectural Science Association 2015; Melbourne: The Architectural Science Association and The University of Melbourne; 2015. p. 342-51.