
Developing a Framework of a Multi-objective and Multi-criteria Based Approach for Integration of LCA-LCC and Dynamic Analysis in Industrialized Multi-storey Timber Construction

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Abstract

To improve organizational decision-making process in construction industry, a framework of a multi-objective and multi-criteria based approach has been developed to integrate results from Life-Cycle Analysis (LCA), Life-Cycle Cost Analysis (LCC) and dynamic analysis for multi-storey industrialized timber structure. Two Building Information Modelling (BIM)-based 3D structural models based on different horizontal stabilization and floor systems will be analyzed to reduce both climate impact, material and production costs and enhance structural dynamic response of the floor system. Moreover, sensitivity of the optimal design will also be analyzed to validate the design. The multi-objective and multi-criteria based LCA-LCC framework analyzing the environmental, economic, and dynamic performances will support decision making for different design in the early phases of a project, where various alternatives can be created and evaluated. The proposed integrated model may become a promising tool for the building designers and decision makers in industrialized timber construction.

Keywords

LCA • LCC • Dynamic response • Multi-criteria • Multi-objective • BIM • Decision making • Industrialized timber construction

53.1 Introduction

In recent years, the usage of prefabricated structural components of solid wood and engineered wood products (EWPs) has increased due to the recent developments towards an industrialized construction and manufacture within the timber building sector in Sweden [19]. Multi-storey timber frame housing was identified as a field for industrialized process development in Sweden [24].

Life Cycle Analysis (LCA) assesses the sustainability of general products throughout its lifetime in environmental, social and economic perspectives (ISO Standard 14040) [16]. Flanagan and Jewell [10] define Life Cycle Cost (LCC) as the total cost of a facility/asset over its operating life including initial acquisition costs and subsequent running costs. Some applications of LCA methodology to timber buildings with comparisons to three different structural materials (timber, concrete and light steel framing) for the same house, concluded that the timber accomplished finer results for all the categories analyzed. Coelho et al. [5] presented a LCA for a single-family house built in Kiruna (Sweden), comparing two structural systems: timber frame and light steel framing, and concluding that timber-frame solution is much more economic. Buchanan and Levin [4] and Sathre and O'Connor [32] state that timber buildings considering the whole life-cycle need lower energy processes for its manufacture, than on the carbon storage itself.

Cross Laminated Timber (CLT) opening new perspectives and possible applications to the whole industry are used as slabs, shear walls, non-load bearing walls, ceilings and roofs elements and can be combined with other construction

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materials. Higher demands from customers to have more open lay out with large-span floors, 8–10 m and economic construction practices have amplified sensitivity issues concerning dynamic performances of the floor systems. This has also resulted in unaccepted floor springiness as disturbing sensation due to deflection and vibration of the floor at the point of application of a foot step load by one and the same person [40].

Some of the previous studies present a new combined LCA and LCC method [11], framework [13, 28, 34], model [2, 9, 12, 33] or tool [1, 15, 28]. Kovacic et al. [18] pointed out that development of a tool for successfully integration of LCA and LCC especially at an early design stage is crucial. In this study, a multi-criteria and multi-objective based approach will be applied to link the process-based LCA and LCC for a four-storey timber structure with optimized dynamic performance of the floor systems.

53.2 Background

53.2.1 Life Cycle Assessment and Life Cycle Costing

LCA is an organized method to assess the environmental influences related with products, processes and/or services. The evaluation comprises the whole life cycle of the product, process or an activity starting from extraction (or excavation), processing, manufacturing, transportation, distribution, use, recycle, and final disposal [31, 39]. LCC analysis is a method enabling relative cost appraisals to be prepared throughout a specific phase, considering all applicable economic factors, mutually in terms of initial costs and future operational costs (ISO 15686) [3]. LCA is divided into two major methods concerning assessment: the process-based LCA [25, 22] and the Input-Output LCA (IO-LCA) [23, 38]. The process-based LCA is based on the certain information of the life cycle processes, which comprise raw material extraction, manufacturing, use, disposal and end-of-life treatment [27]. The significant drawbacks recognized in LCA were data, results and output [34].

53.2.2 Dynamic Analysis of Timber Floor System

Timber floor system with small-span up to 4 m has normally acceptable dynamic responses because of the fact that the floor has often adequate stiffness resulting the floors first natural eigenfrequency will be in the most cases above 8 Hz. This is recognized by Eurocode 5 as the lower limit of the first eigenfrequency for timber floors where the most sensitive area lies between 4 and 8 Hz which corresponds to the eigenfrequencies of some of the organs of the human body. But when the floors span length increases the stiffness become lower and the floors first eigenfrequency normally goes below 8 Hz. Effects of structural and non-structural modifications of floor systems on the dynamic performance of the case studies will be analyzed by parametric studies based on the design criteria and modal dynamic analysis together with both multi-objective optimization. Vibration levels and deflection of different floor systems as two objective functions will be optimized simultaneously to create a Pareto front.

53.2.3 Analytical Network Process

Analytic Network Process (ANP) proposed by Saaty [30], admits complex interrelationships among decision levels and attributes [21] and signifies a decision problem as a network of elements gathered into clusters [6]. Deniz [8] created an ANP model to examine LEED-certified buildings' operational performance. Promentilla et al. [29] developed an ANP technique to rank the potential CO₂ sources and sinks to identify sites for CO₂ capture and storage demonstration projects. Theißen and Spinler [37] developed an ANP model for collaborative CO₂ reduction management for strategic analysis of manufacturer-supplier partnerships. Senante et al. [35] proposed an ANP approach for assessment of wastewater treatment alternatives for small communities. Wudhikarn et al. [41] proposed a framework for new product selection decision using ANP and knowledge management involving LCC. Lam and Laib [20] developed an environmental sustainability by ANP-Quality Function Deployment approach for the case of shipping operations.

53.3 Developing a Multi-objective and Multi-criteria Based Integrated Framework of LCA-LCC for Industrialized Timber Structures

The model of framework for the multi-story industrialized timber structure residential building is presented in Fig. 53.1. A multistory industrialized timber structure residential building is identified in Jönköping, Sweden. A multi-objective optimization will be performed based on the design criteria and modal dynamic analysis to reduce both the vibration levels and deflection of floor systems. Then a ANP based multi-criteria analysis will be used to choose optimal designs on Pareto front. ANP based multi-criteria analysis will be even performed on the case study with enhanced dynamic performances using LCA and LCC results. A gradually multi-objective and multi-criteria based framework and its application for the multi-story industrialized timber structure residential building is presented in the following sections.

53.3.1 Structural Design and Finite Element Models

Two BIM-based 3D structural models as seen in Figs. 53.2 and 53.3 below based on different timber horizontal stabilization systems and several different floor systems will be analyzed to enhance both the dynamic performance of the floor systems and reduce life cycle impact in terms of CO₂ emissions and material and production costs of whole structure.

53.3.1.1 Model 1

The multi-story industrialized timber structure of residential building including basement, with the overall dimensions $L \times W \times H = 20.2 \times 13.2 \times 14.7$ m. The model consists of reinforced concrete walls and slab at basement, reinforced concrete shaft and stair-way along the height for horizontal stability of the structure and timber structural elements from height 2.6 m up to 14.7 m. Timber structural elements includes glulam columns with different dimensions and several different structural floor systems as seen in Fig. 53.2.

53.3.1.2 Model 2

The only difference between model 2 and model 1 is that in model 2 concrete shaft and stairway as horizontal stabilization of structure has been replaced by shear walls along all four facades as horizontal stabilization of structural system. Timber structural elements includes glulam columns with different dimensions and several different structural floor systems as seen in Fig. 53.3.

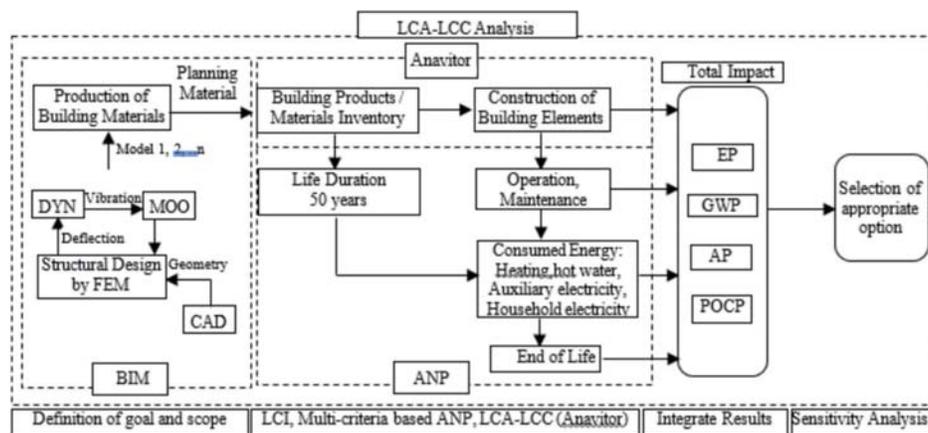


Fig. 53.1 Model of framework of a multi-objective and multi-criteria based LCA-LCC analysis for multi-storey in industrialized timber structure

Fig. 53.2 3D structural finite element model for the multi-storey industrialized timber structure with concrete shaft and stairway—model 1

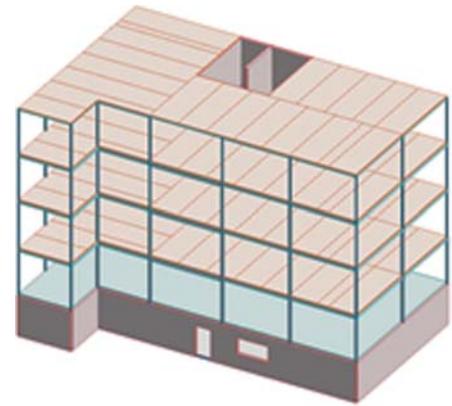
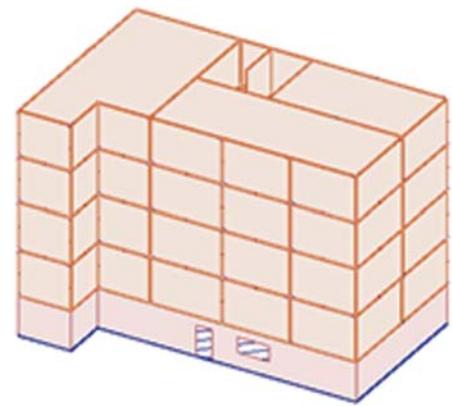


Fig. 53.3 3D structural finite element model for the multi-storey industrialized timber structure with CLT shear walls—model 2



53.3.2 Life Cycle Assessment

53.3.2.1 Definition of Goal and Scope

A four-storey industrialized timber structure residential building is identified for the case study. Accordingly, “The delivery of comfortable living area for its residents for the duration of 100 years, in a four-storey residential building with 8 apartments having an area of 1066 m² located in Jönköping” is defined as the functional unit. The number and size of structural members as per the design drawings and plans will be identified. Inventory will be detailed for the building shell and main construction options. Foundations will not be included in this study. The residential building will be analyzed for the 22 sustainability criteria that cover their environmental, structural safety, economical and serviceability footprints as shown in Fig. 53.4.

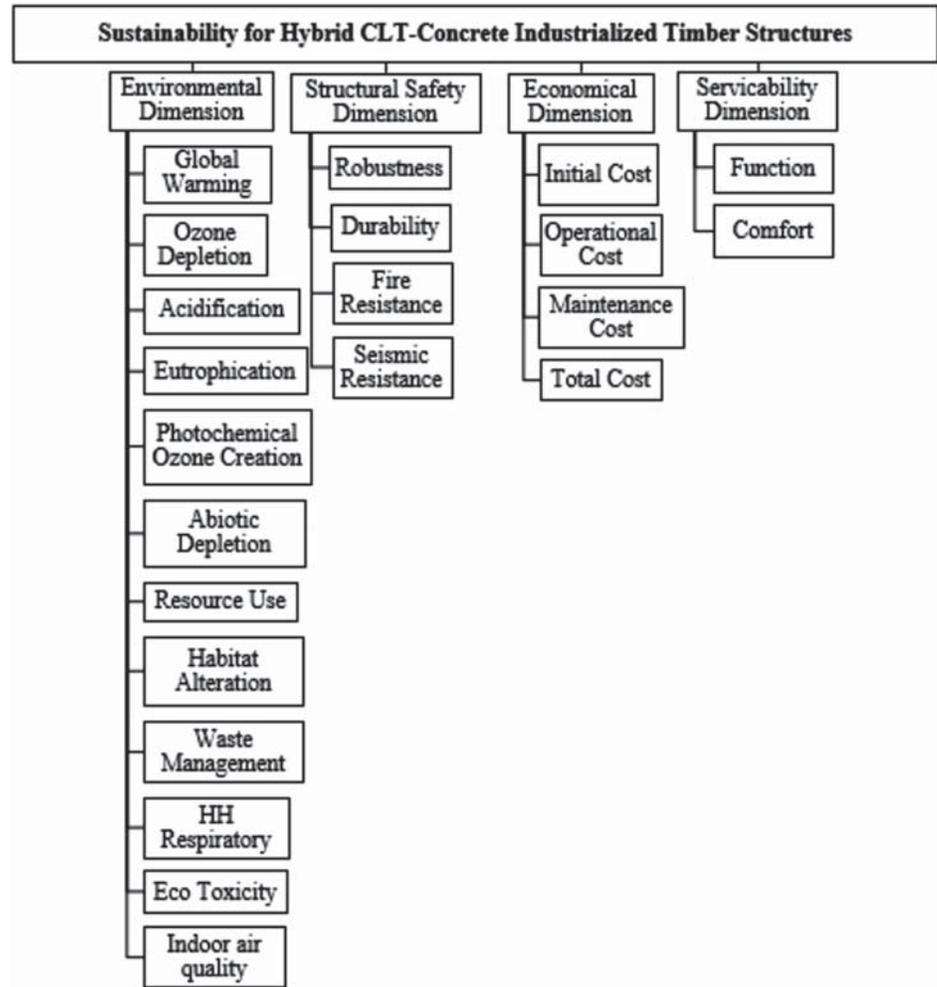
53.3.2.2 Life Cycle Inventory Analysis

LCI analysis is a record of input and output data of the examined system to evaluate the environmental significance of potential impacts [18]. The boundary of the system is defined, and a flow model of inputs and outputs is determined to develop the inventory. An LCI which will provide information about all inputs and outputs in the form of elementary flow to and from the environment from all the unit processes involved in the study will be the result of the inventory. IVL Svenska Miljöinstitutet (Swedish Environmental Institute)-Miljöstatus för Byggnader (Swedish system for environmental auditing and assessment of buildings) and Anavitor software will be used for environmental inventory analysis of the building in the city of Jönköping.

53.3.2.3 ANP Model for LCC in Industrialized Timber Construction

ANP can be applied to choose from options or rate a restrained number of factors by means of their relative importance values. In this study, ANP is used to find the relative importance weights of sustainability parameters in assessing the

Fig. 53.4 Sustainability factors for hybrid CLT-concrete industrialized timber structures



performance of industrialized timber construction. The procedure undertaken in this research study to form and implement the ANP model is as follows: (1) the identification and categorization of sustainability parameters: a systematic literature review and the formation of a “sustainability breakdown structure” by classifying and determining sustainability parameters based on expert views, (2) the formation of a limit super matrix by developing an ANP model using the Super Decisions software, making pair-wise comparisons of the sustainability parameters and sustainability categories followed by the estimation of eigen vectors and the consistency ratio to form the matrix to enable expert decision makers to make pair-wise comparisons using Saaty’s scale, and prioritizing sustainability parameters and their categories, (3) sustainability factors are identified according to a standard list of parameters based on relevant literature studies, documents and records as well as interviews and focus groups in which all possible parameters are discussed. In this study, the sustainability factors confronted in industrialized timber construction are obtained from an extensive literature analysis, as presented in Fig. 53.4.

53.3.2.4 Environmental Impact Assessment

The sustainability framework comprises twelve environmental impact groups as illustrated in Fig. 53.4. The life cycle environmental impact assessment is based on IVL Svenska Miljöinstitutet (Swedish Environmental Institute)-Miljöstatus för Byggnader (Swedish system for environmental auditing and assessment of buildings). All these criteria will be assessed by using the LCA performed by Anavitor Software. The flowchart of Anavitor LCA and LCC is presented in Fig. 53.5.

53.3.2.5 Economic Impact Assessment

LCC analysis considers the total cost of the building project by design and construction, operation and maintenance, and end of life costs of demolition and recycling/reuse of building materials. 5D BIM-LCC workflow starts from the process of

Fig. 53.5 Flowchart of Anavitor LCA and LCC

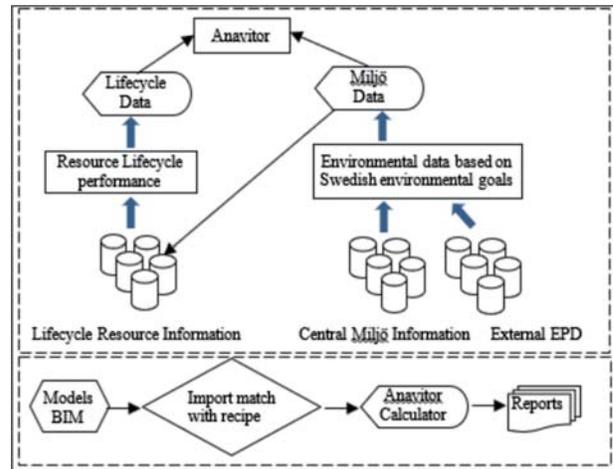
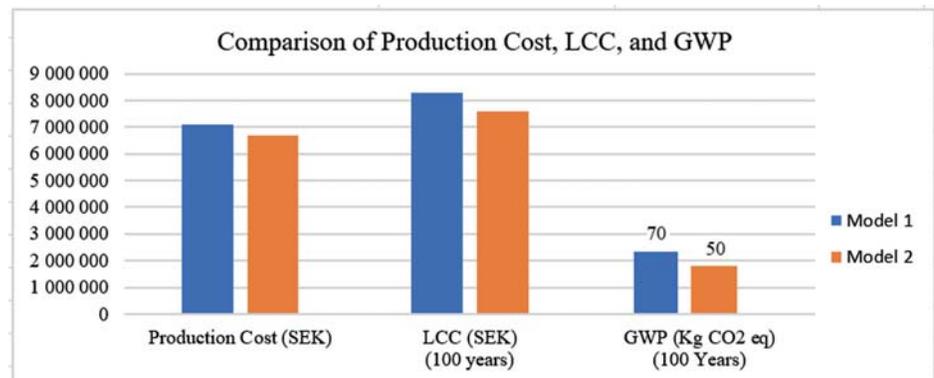


Fig. 53.6 Comparison of production costs, LCC, and GWP for model 1 and model 2



importing 3D BIM models. Based on the 3D models and related information, 5D simulation is conducted in the simulation program. Thereafter the simulation results are generated in excel spreadsheet as the available format. Then LCA applications import this excel spreadsheet, conducting LCA and generate assessment results. Cost drivers of a product is identified by Anavitor software to compare and evaluate alternatives related with a process or flow throughout the life cycle. The interpretation phase involves the integrated assessment of the LCA and LCC results to visualize the economic and environmental performances graphically presented in combined arrangement and the trade-offs between environmental and financial cost turns into clearer to the user for the decision-making process. Comparison of Production Costs (cost of land and foundation are excluded), LCC, and GWP for Model 1 and Model 2 is presented in Fig. 53.6. Afterwards, a sensitivity analysis is performed to test the validity of the ranking of the sustainability factors (i.e. Global Warming Potential-GWP, Eutrophication Potential-EP, Acidification Potential-AP, Photochemical Ozone Creation Potential-POCP) based on subjective judgements and to reduce the ambiguity related with changes in expert's experiences. The decision-making process is finalized by selecting the appropriate option.

53.4 Discussion

Increasing the use of EWPs and constructing industrialized timber structures can contribute to a more emission-efficient production of construction materials substituting for carbon and energy intensive concrete and steel-based building constructions and reducing the climate change impact [14, 36]. Currently, the LCA tool is used to calculate the environmental impact of manufactured products and systems from the “cradle to the grave”. LCC is the result of an economic analysis where total costs and revenues for a system or product are compiled over its useful life [17]. However, for both LCA and LCC, there is a need to develop more robust and standardized analyzes. One tool for this is a BIM based LCC solution where LCC is

integrated into the 5D BIM process by embedding an LCC calculation model structure within an existing 5D BIM technology [17]. The rapid development within BIM constantly offers new opportunities for analyzes and simulations, where more and more aspects can be analyzed and checked earlier in the construction projects. Another method that will be used is multi-objective optimization to enhance dynamic performance of the floor systems. Both weight and vibration levels used as objective functions for capturing pareto front and hence optimal design configurations regarding dynamic performances of the floor systems. ANP is a MCA to analyze complex decision-making problems using a systematic approach and make detailed analysis of priorities and interdependencies between clusters' elements. Currently, there are no (or limited) opportunities for the decision maker to ensure that the delivered building will meet both environmental and cost requirements. The reasons are that, in particular, there is need of (1) reliable and robust LCA and LCC during the design and (2) integration of various analysis and simulations during the design process. The integration of MCA with LCA-LCC could be a practical solution to facilitate interpretation of results and to aid decision-making for analyzing the environmental impact of products and costs throughout their life cycle [7]. MCA can enrich LCA-LCC outcomes by providing studied methods to assess trade-offs mainly because it allows a broader view of different aspects [26].

53.5 Conclusions

This paper outlines a framework of multi-criteria and multi-objective based approach for the integration of LCA and LCC in a multi-storey industrialized timber structure. Two Building Information Modelling (BIM)-based 3D structural models based on different horizontal stabilization and floor systems is analyzed to reduce both climate impact, material and production costs and enhance structural dynamic response of the floor system. Moreover, sensitivity of the optimal design is analyzed to validate the design. The multi-objective and multi-criteria based LCA-LCC framework analyzing the environmental, economic, and dynamic performances will support decision making for different design in the early phases of a project, where various alternatives can be created and evaluated. The proposed integrated model may become a promising tool for the building designers and decision makers in industrialized timber construction.

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References

1. Anastaselos, D., Giama, E., Papadopoulos, A.M.: An assessment tool for the energy, economic and environmental evaluation of thermal insulation solutions. *Energy Build.* **41**(11), 1165–1171 (2009)
2. Bierer, A., Götze, U., Meynerts, L., Sygulla, R.: Integrating life cycle costing and life cycle assessment using extended material flow cost accounting. *J. Clean. Prod.* **108**, 1289–1301 (2015)
3. British Standards Institute: Standardized Method of Life Cycle Costing for Construction Procurement BS EN ISO 15686-5, United Kingdom (2008)
4. Buchanan, A.H., Levine, S.B.: Wood-based building materials and atmospheric carbon emissions. *Environ. Sci. Policy* **2**(6), 427–437 (1999)
5. Coelho, A.C., Lopes, A., Branco, J.M., Gervásio, H.: Comparative Life-Cycle Assessment of a Single-Family House: Light Steel Frame and Timber Frame, https://repositorium.sdum.uminho.pt/bitstream/1822/20801/2/Ecowood_paper.pdf
6. De Felice, F., Petrillo, A.: Multicriteria approach for process modelling in strategic environmental management planning. *Int. J. Simul. Process Model.* **8**(1), 6–16 (2013)
7. De Souza, R.G., Climaco, J.C.N., Sant’Anna, A.P. Rocha, T.B., do Valle, R.A., Quelhas O.L.G.: Sustainability assessment and prioritization of e-waste management options in Brazil. *Waste Manage.* **57**, 46–56 (2016)
8. Deniz, G.O.: An analytic network process (ANP) model to examine LEED-certified buildings’ operational performance. *Built Environ. Proj. Asset Manage.* **7**(4), 366–376 (2017)
9. Ding, G.K.C.: Developing a multi-criteria approach for the measurement of sustainable performance. *Building Res. Inf.* **33**(1), 3–16 (2005)
10. Flanagan, R., Jewell, C.: *Whole Life Appraisal for Construction*. Blackwell, Oxford (2005)
11. Gu, L., Lin, B., Zhu, Y., Gu, D., Huang, M., Gai, J.: Integrated assessment method for building life cycle environmental and economic performance. *Build. Simul.* **1**(2), 169–77 (2008)
12. 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 Build.* **56**, 189–203 (2013)
13. Heijungs, R., Settnani, E., Guinée, J.: Toward a computational structure for life cycle sustainability analysis: unifying LCA and LCC. *Int. J. Life Cycle Assess.* **18**(9), 1722–1733 (2013)
14. Hildebrandt, J., Hagemann N., Thranac, D.: The contribution of wood-based construction materials for leveraging a low carbon building sector in Europe. *Sustain. Cities Soc.* **34**, 405–418 (2017)

15. Hoogmartens, R., Van Passel, S., Van Acker, K., Dubois, M.: Bridging the gap between LCA, LCC and CBA as sustainability assessment tools. *Environ. Impact Assess. Rev.* **48**, 27–33 (2014)
16. International Organization for Standardization, Standard 14040: Environmental management—Life cycle assessment: Principles and Framework (2006)
17. Kehily, D., Underwood, J.: Embedding life cycle costing in 5D BIM. *J. Inf. Technol. Constr.* **22**, 145–167 (2017)
18. Kovacic, I., Reisinger, J., Honic, M.: Life cycle assessment of embodied and operational energy for a passive housing block in Austria. *Renew. Sustain. Energy Rev.* **82**, 1774–1786 (2018)
19. Kuzman, K.M., Sandberg, D.: Comparison of timber-house technologies and initiatives supporting use of timber in Slovenia and in Sweden—the state of the art. *iForest* **10**, 930–938 (2017)
20. Lam, J.S.L., Laib, K.H.: Developing environmental sustainability by ANP-QFD approach: the case of shipping operations. *J. Clean. Prod.* **105**, 275–284 (2015)
21. Lee, J.W., Kim, S.H.: Using analytic network process and goal programming for interdependent information system project selection. *Comput. Oper. Res.* **27**(4), 367–382 (2000)
22. Lenzen, M.: Errors in conventional and input-output-based life-cycle inventories. *Ind. Ecol.* **4**(4), 127–148 (2000)
23. Leontief, W.: Environmental repercussions and the economic structure: an input-output approach. *Rev. Econ. Stat.* **52**, 262–271 (1970)
24. Levander, E., Stehn, L.: Addressing uncertainties about timber housing by whole life costing. In: *Proceedings of 4th Nordic Conference on Construction Economics and Organisation: Development Processes in Construction Management*, pp. 249–258 (2007)
25. Lotteau, M., Loubet, P., Pousse, M., Dufresnes, E., Sonnemann, G.: Critical review of life cycle assessment (LCA) for the built environment at the neighbourhood scale. *Build. Environ.* **93**, 165–178 (2015)
26. Manzardo, A., Ren, J., Piantella, A., Mazzi, A., Fedele, A., Scipioni, A.: Integration of water footprint accounting and costs for optimal chemical pulp supply mix in paper industry. *J. Clean. Prod.* **72**, 167–173 (2014)
27. Menzies, G.F., Turan, S., Banfill, P.F.: Life-cycle assessment and embodied energy: a review. *Proc. Inst. Civ. Eng. Constr.* **160**(4), 135–144 (2007)
28. Petrillo, A., De Felice, F., Jannelli, E., Autorino, C., Minutillo, M., Lavadera, A.L.: Life cycle assessment (LCA) and life cycle cost (LCC) analysis model for a stand-alone hybrid renewable energy system. *Renew. Energy* **95**, 337–355 (2016)
29. Promentilla, M.A.B., Tapia, J.F.D., Arcilla, C.A., Dugosa, N.P., Gaspillo, P.D., Roces, S., Tan, R.R.: Interdependent ranking of sources and sinks in CCS systems using the analytic network process. *Environ. Model Softw.* **50**, 21–24 (2013)
30. Saaty, T.L.: *Decision Making with Dependence and Feedback: The Analytic Network Process*. RWS Publications, Pittsburgh (2001)
31. Sadiq, R., Khan, F.I.: An integrated approach for risk-based life cycle assessment and multi-criteria decision-making: selection, design and evaluation of cleaner and greener processes. *Bus. Process Manage. J.* **12**(6), 770–792 (2006)
32. Sathre, R., O'Connor, J.: Meta-analysis of greenhouse gas displacement factors of wood product substitution. *Environ. Sci. Policy* **13**(2), 104–114 (2010)
33. Savino, M.M., Manzini, R., Della, S.V., Accorsi, R.: A new model for environmental and economic evaluation of renewable energy systems: the case of wind turbines. *Appl. Energy* **189**, 739–752 (2017)
34. Schmidt, M., Crawford, R.H.: Developing an integrated framework for assessing the life cycle greenhouse gas emissions and life cycle cost of buildings. *Procedia Eng.* **196**(988–995), 1877–7058 (2017)
35. Senante, M., Gómez, T., Caballero, R., Hernández-Sancho, F., Ramón Sala-Garrido, R.: Assessment of wastewater treatment alternatives for small communities: an analytic network process approach. *Sci. Total Environ.* **532**, 676–687 (2015)
36. Skullestad, J.L., Bohne, R.A., Lohne, J.: High-rise timber buildings as a climate change mitigation measure - a comparative lca of structural system alternatives. *Energy Procedia* **96**, 112–123 (2016)
37. Theißen, S., Spinler, S.: Strategic analysis of manufacturer-supplier partnerships: an ANP model for collaborative CO₂ reduction management. *Eur. J. Oper. Res.* **233**, 383–397 (2014)
38. Treloar, G.J., Love, P.E., Holt, G.D.: Using national input/output data for embodied energy analysis of individual residential buildings. *Constr. Manage. Econ.* **19**(1), 49–61 (2001)
39. Tukker, A.: Life cycle assessment as a tool in environmental impact assessment. *Environ. Impact Assess. Rev.* **20**, 435–456 (2000)
40. Weckendorf, J., Zhang, B., Kermani, A., Reid, D.: Dynamic Response of Timber Floors. In: *2nd PRoBE 2005 Conference, Postgraduate Researchers of the Built and Natural Environment*, Glasgow, UK, 1617 November 2005
41. Wudhikarn, R., Chakpitak, N., Neubert, G.: A framework for new product selection decision using analytic network process and knowledge management. *Adv. Mater. Res.* **538–541**, 3098–3105 (2012)