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Lessons Learned from Life Cycle Assessment and Life Cycle Costing of Two Residential Towers at the University of British Columbia

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Abstract

The University of British Columbia has an interest in incorporating life cycle environmental impacts and financial information into project planning, as well as research and teaching. As part of a tall wood building research program with the UBC Sustainability Initiative and Dept. of Civil Engineering, a comprehensive life cycle assessment (LCA) and life cycle costing (LCC) study was done of two student high-rise residential buildings, based on the result of whole building LCA done by Athena Sustainable Materials Institute and whole building LCC done by Sensible Building Science. These buildings are of similar design but Brock Commons Tallwood House has a hybrid mass-timber structure and Ponderosa Commons Cedar House has a more traditional concrete structure. This paper will include a brief overview of the research process, data collection, analysis, and key results. The paper will then focus on the main opportunities, challenges, and lessons learned from both the results of the LCA/LCC projects and the process of conducting the study.

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Keywords: Whole Building Life Cycle Assessment; Building Life Cycle Costing; Tall Wood Building; LCA and LCC Education

1. Introduction

Nomenclature

UBC	University of British Columbia
CLL	Campus as a Living Laboratory, UBC initiative
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCC	Life Cycle Costing
GWP	Global Warming Potential
BOM	Bill of Material
TCO	Total Cost of Ownership
NPV	Net Present Value
UBC	University of British Columbia
USI	UBC Sustainability Initiative
LEED	Leadership in Energy and Environmental Design
Athena	Athena Sustainable Materials Institute
SBS	Sensible Building Science
FII	BC Forestry Innovation Investment

With four million square meters of space and about 20,000 residents, the Vancouver campus of the University of British Columbia (UBC) is the size of a small North American city. This gives the university an opportunity to combine its teaching and research interests with its operational needs to demonstrate and advance innovative and sustainable solutions—an opportunity it has actively pursued through initiatives such as

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Campus as a Living Laboratory (CLL) program, which combines the planning, design, construction and operation of the built environment with opportunities for applied research, teaching and learning [1].

One of the research areas that UBC has explored in the past few years is the potential benefits of incorporating life cycle assessment (LCA) and life cycle costing (LCC) methodologies to make informed decisions regarding capital projects and to incorporate these in policy and guidelines for future projects.

Currently, UBC's LEED v4 Implementation Guide demands all new institutional buildings achieve the credits for the building life cycle impact reduction [2]. UBC is also developing a 20-year Green Building Plan for its Vancouver Campus, which will incorporate life cycle method and tools to achieve net-positive environmental impacts in buildings through material selection and management [3].

Over the past decade, students and consultants have conducted Life Cycle Assessment (LCA) and Life Cycle Costing (LCC) studies on the existing buildings or major capital projects on campus. For example, a technical elective course was offered from 2008 within the Civil Engineering program in which students conducted LCA of campus buildings, eventually covering almost all of the campus buildings. However, the scope of these studies were somewhat limited in the elements or life cycle stages they studied.

This paper focuses on the major challenges and opportunities associated with the process of conducting a comparative LCA and LCC study on a hybrid mass-timber residential tower and a high-rise of similar design but with a concrete structure. The study was conducted by the UBC Sustainability Initiative (USI), based on LCA and LCC analyses done by Athena Sustainable Materials Institute (Athena) and Sensible Building Science (SBS) respectively, with the support of BC Forestry Innovation Investment (FII).

Brock Commons Tallwood House (Tallwood House) is an 18-storey, 15,115 m^2, residential building, which was completed in the summer of 2017 as the first building in a mixed-use student hub. Tallwood House has 404 student beds and provides study and social spaces on the ground floor and a student lounge on level 18 (Fig. 1.a).

Tallwood House has an innovative hybrid structure: the foundation, ground floor, second-floor slab, and stair/elevator cores are cast-in-place concrete, while the superstructure is composed of prefabricated cross-laminated timber (CLT) panel floor assemblies supported on glue-laminated timber (GLT) and parallel strand lumber (PSL) columns with steel connections, and a steel roof deck. The mass timber is encapsulated with 3-4 layers of type-X gypsum boards for fire protection (see [4] for further information regarding Tallwood House).

Ponderosa Commons Cedar House (Cedar House) served as the baseline building for comparison in this study. It is an 18-storey plus basement, 12,838 m^2, residential tower forming part of the mixed-use Ponderosa Commons complex. Completed in 2015, it provides accommodations for 310. The basement through Level 2 have a mixed-use program, including student communal areas, research and administrative offices and building services and storage facilities (Fig. 1.b).

Cedar House has a conventional structure for a high-rise building. The foundation and basement are reinforced concrete, as are the two stair/elevator cores. The superstructure consists of two-way reinforced concrete suspended slabs supported by concrete columns and a concrete roof structure.

2. A summary of the comparative LCA-LCC study

Since the focus of this paper is on the lessons learned from the process of conducting such a life cycle analysis, rather than the findings of the research per se, a summary of the research objectives, scopes, project team, data collection process, and main findings are presented in this section.

2.1. The LCA-LCC study goal and objectives

The goal of the LCA-LCC study was to understand the benefits and trade-off of utilizing mass-timber products in the high-rise applications through a comparative analysis of two case study projects. The objectives of the study were to:

- Compare the environmental impacts for both projects, including environmental impacts, energy flows and resource flows.
- Compare the total cost of ownership (TCO) for both projects.
- Identify potential correlations between life cycle environmental impacts and costs.

2.2. The scope of the LCA-LCC study

A cradle-to-grave LCA of each building was conducted by Athena, according to a North American interpretation of EN 15978, a European standard that specifies the LCA method to assess the environmental performance of a building [5]. The scope of the LCA studies is as follow:

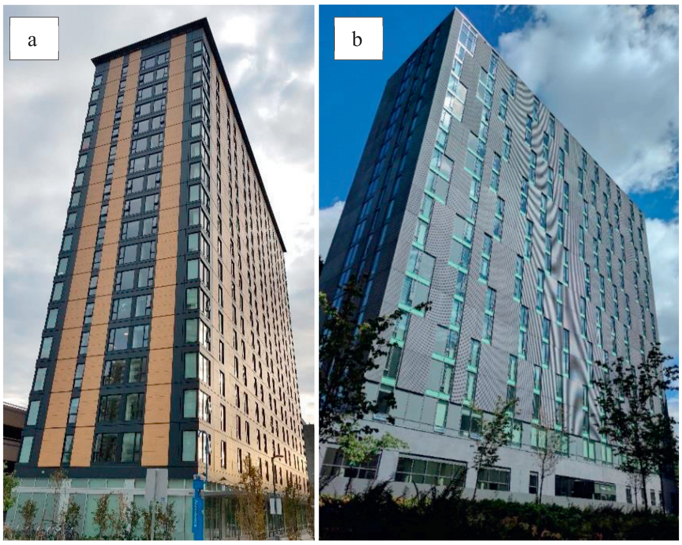

Fig. 1 Studied student residential tower at UBC (a) Brock Commons Tallwood House: Mass-timber hybrid structure (b) Ponderosa Commons Cedar House: concrete structure (photos by: Zahra Teshnizi)

- building elements: the structure, envelope, interior partition, and finishes.
- study period: 100 years (the buildings' full design life)
- life cycle stages: product and construction, operation (water and energy), maintenance, renewal, end of life;
- impacts beyond building's lifetime: potential benefits or burdens from the recovery of materials or the energy recovered from materials at the end of building's lifetime;
- carbon sequestration: potential carbon that is stored in the wood (from photosynthesis during the tree's life) and in the concrete (from a chemical process when concrete is exposed to air and moisture).

The TCO for both buildings were estimated through an LCC study that was conducted according to ISO 15686-5 standard by SBS. The scope of the LCC study was as follow:

- study period: 100-year period (to match the LCA model);
- costs included (Net Present Value (NPV) in 2017 Canadian dollar):
  - first costs: the actual construction, project management, and design costs;
  - annual operating costs to run the building: examples include custodial, ongoing maintenance, municipal service, and utility costs;
  - building systems renewal and replacement costs;
  - end-of-life costs.

2.3. The data collection and analysis process

In this study, the USI acted as the research project manager and as a link between the LCA and LCC consultants and the building project stakeholders. The USI collected and organized data from the project teams and UBC stakeholders and asked for their expert input wherever needed. They extracted the input data from project documents and drawings, models, and other UBC-specific data sources.

The primary input for the LCAs were the projects' bill of materials (BOM), operational energy and potable water use, and construction waste quantities. The USI team collected the BOM from the digital models of the project. Materials and elements that were missing in the models were calculated from the Issued-for-Construction architectural and structural drawings using quantity-take-off software. The operational energy and potable water data were derived from estimates created for relevant LEED credits. The operation energy was then recalibrated using the actual energy use of a few recent UBC residential towers.

Athena reviewed and completed the input data provided by the USI and prepared the Life Cycle Inventory (LCI), primarily drawing on data from the Athena's ISO 14040/44-conforming databases. Life cycle impacts were evaluated for one square meter of gross floor area over 100 year lifetime of each project according to TRACI v2.1 category mid-point characterization methodology [6].

For the LCC study, the USI team attained the latest construction costs in MasterFormat from the projects' construction managers and the design and project management costs from UBC project managers. The USI team attained the estimates for annual operating costs, building systems lifetime, and renewal costs from UBC internal operational departments with some input from the project team members.

SBS used the data provided by the USI with additional industry average data (where UBC-specific information was unavailable) to estimate the TCO for the buildings' full design life (100 years). The LCC model is based on the National Institute on Standards in Technology (NIST). Following ISO 15686 (section 5.4.4 and 5.4.5), SBS calculated the NPV using a discount rate of 7.75% to represent the interest cost of the loan for the project investments. The 7.75% discount rate is formed by 2% inflation rate established by UBC based on Statistic Canada's Construction price index for the Vancouver area [7], and 5.75% interest rate set by UBC Treasury for long term (>10 years) capital project financing. SBS considered a 3% social interest rate for the sensitivity analysis.

Since the discount rate for the study is high which and from a sustainability point of view, a lower rate would be preferable.

The USI later received the primary life cycle analyses results from Athena and SBS and broke them into categories such as life cycle phases, project activities (e.g. manufacturing, construction, and transportation), building elements, and building materials. Such breakdowns allowed the research team to identify the main reasons behind the environmental and cost performance differences and similarities between the two projects. The research team's awareness of the design and construction processes was significant in enabling them to interpret the LCA and LCC results.

2.4. The key findings of the LCA-LCC study

The key findings of the LCA-LCC study are as follow:

- The full life cycle results show that the TCO of Tallwood House is more than Cedar House by 7% per square meter and it does not necessarily perform better in terms of reducing the total negative environmental impacts. However, the materials and especially the structure are not the primary contributors to the increased negative impacts in either the LCC or LCA. Rather, it is a more complex and nuanced interaction of different building elements and operations that influence the overall impacts.
- With 7.75 discount rate, the operation and capital renewal costs each comprised about 15% of the TCO for both projects (Fig. 2.a)). Whereas if 5% discount rate is assumed the proportions change to 20% for operation and 30% for capital renewal costs (Fig. 2.b). This is in contrast to the environmental impacts, where the operational energy and water constitute more than 65% of the impacts of both projects in five out of the six environmental impact categories. This highlights a significant methodological difference between LCA and LCC studies. High discount rate in LCC results in assigning less value to costs and savings that occur further in the future, whereas LCA indicators implicitly use a 0% discount rate.
- When operational impacts are excluded from the results and the building materials life cycle impacts are compared, per square meter, Tallwood House has smaller negative impacts in five out of six impact categories. The differences in these categories are equal or more than 9%. Tallwood House has

Fig. 2 Comparison of TCO of 100 years in 2017 CDN $ for Tallwood House vs. Cedar House, by life cycle phase, per m²
(Based on the LCC study conducted by SBS)

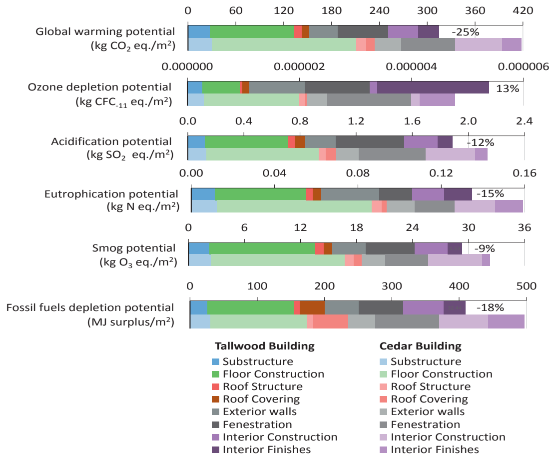

Fig. 3 Comparison of environmental impacts of building materials in Tallwood House vs. Cedar House, by building element per m²
(Based on the LCA studies conducted by Athena)

25% less Global Warming Potential (GWP) and 18% less Fossil Fuel Depletion Potential impacts respectively (Fig. 3).

- The structure of Tallwood House (including substructure, mass-timber floor construction, and roof structure), performs considerably better than the concrete structure of Cedar House across all the environmental impact categories. This includes GWP where Tallwood House has 36% less negative impacts (Fig. 3). This is despite the fact that the extra layers of type-X gypsum boards are included in the mass-timber structure of Tallwood House.
- First costs, in particular construction costs, are where the most significant cost differences are between the two buildings. The construction cost for Tallwood House is 11% higher than Cedar House. However, an innovation premium was part of the higher costs of Tallwood House. The construction manager reported that they expect this premium to go down significantly within the next few projects [7]. Moreover, the structure itself is not the source for the differences in the construction cost. In fact, structural costs of the buildings are similar at about 18% of the total cost for Tallwood House and about 20% of the total cost for Cedar House.

3. Discussion of the opportunities and challenges

This section looks at the conducted comparative LCA-LCC study through the lens of the challenges and educational opportunities it provided. These opportunities and challenges are categorized and discussed in three major categories: data collection, applicability of the results, and educational opportunities for students.

3.1. Data collection

The involvement of the USI as an insider UBC organization, gave the research team a unique opportunity to identify and access project and UBC-specific data that otherwise would have been difficult or considerably more time consuming to collect. For instance the USI was aware that the actual energy use of UBC buildings is typically higher than the modeled energy. Therefore, they attained modeled and actual energy use data from three recent UBC high-rise residences to recalibrate the modeled operational energy of both Tallwood house and Cedar House.

Despite this unique access, most of the barriers that arose throughout this study were related to the availability, accessibility, or quality of relevant data. Such data gaps can be discussed in three groups:

- Insufficient project or context specific data: an instance is the maintenance and operation costs, where not all the costs are tracked in a building specific level for the UBC student residences. UBC rather plans and distribute the budget across all the student residence portfolio. Other examples include the distance between the manufacturing and construction sites, energy use on the construction sites, or recycling and reuse rates in the manufacturing facilities. While this information might have been available, they were not accessible to the research team within a reasonable investment of time and effort.
- Insufficient life cycle data: the mechanical and electrical systems were excluded from the LCA study. This is due to the lack of North American LCI data for these systems. Even for the elements that are available in LCI databases, the information might reflect an average number for the region, rather than specific data for the elements and technologies used in the studied buildings. Moreover, the long timeframe of a whole building life cycle study, make it difficult to predict some future factors such as the durability of building systems or the functional, technological and regulatory evolution. This is especially challenging when an innovative project like Tallwood House is studied, where there is little to no precedent data available.
- Defining a comparable baseline: Having a baseline to compare the results of the Tallwood House LCA and LCC study was crucial. Cedar House was the most similar building to Tallwood House, among the existing UBC

residential towers, based on criteria such as: size, layout, function, and year of construction. Despite all these similarities, various factors made it challenging to accurately compare the two buildings. For instance, Cedar House is an integrated part of a larger academic and residential complex (Ponderosa Commons) and has some academic and other non-residential functions in its lower levels. Therefore, in various input categories, the research team was challenged to identify an appropriate allocation method to separate the quantities of Cedar House from the overall Ponderosa Commons complex. For LCA, the tower was isolated in the digital model (Revit) and the lower floors, which were originally connected to the complex, were enclosed with materials similar to the adjacent walls. To identify the best allocation methods for the major LCC items, different project team members and UBC stakeholders were consulted. In most cases the original measurement units were used to allocate the cost items. Examples of these measurement units include gross floor area, gross surface area, volume, construction time, and number of beds.

3.2. Applicability of the results

The results of such an in-depth life cycle analysis on an innovative project can help UBC decision makers to assess the success of this project more comprehensively. However, as discussed in the previous section, in the absence of various project and context-specific life cycle environmental and cost information, the data were replaced with UBC, regional, or North American averages. In a few cases, where no average data were available, the research team had to rely on the estimates of the industry experts. These data replacements may result in practical limitations on the accuracy and applicability of the results and may limit the ability of decision-makers to rely on these results to support their decisions in future projects.

The comparative LCA-LCC study confirmed another major concern regarding the current tools and methods available for conducting whole-building life cycle analysis. The study required a significant amount of time and resources to collect accurate and detailed input data [8, 9, 10]. This creates doubt on whether the project team would have had the time and resources to conduct such an analysis during the design phase, when major project decisions had to be made. Moreover, many of the data that were collected during or after the construction phase would have not been available during the design phase.

Choosing an effective communication method was crucial in the research team's ability to communicate the results with the stakeholders. Therefore, another major challenge was simplifying and interpreting the results in a meaningful way while still keeping the scientific nuances. This supports previous discussions in the literature regarding the choice between communicating the results through the mid-point impact indicators, such as global warming potential and eutrophication potential, versus end-point damage categories such as human health and ecosystem services [11].

Moreover, although the current output methods for the LCA and LCC results might help project teams and policy makers to see a more comprehensive picture of the buildings' environmental and cost impacts and identify the major contributors to the impacts, these output breakdowns might not be sufficient to help them identify the exact contributors or ways of reducing these impacts. Therefore, major environmental and cost impact categories must be further broken down to show the main contributors among various building materials, components, systems, and life cycle activities. If these results be accompanied with supporting guideline and information on the alternative design solutions, they possibly could be more useful to support the design decision-making process.

Finally, LCA and LCC analyses are purely quantitative methods, which fail in capturing some of the qualitative and strategic motivations of certain decisions. For instance, the Tallwood House project team decided to choose a more expensive wood-fiber cladding instead of the proposed metal alternative. This decision was made not because of the environmental or cost advantages, but rather for the cladding's aesthetic value and its potential to communicate the project's innovative mass-timber structure to the community.

3.3. Educational opportunities for students

This study was conducted as part of the larger CLL initiative at UBC, which utilizes key campus projects to provide case studies for advancing sustainability practice through the demonstration of innovation and assessment of lessons learned.

To this end, the Tallwood House project achieved a much higher degree of integration between industry, campus operations, and academic teaching and research than is common. The project was the subject of a cluster of research projects, in which UBC graduate research students studied the design, pre-construction, construction, commissioning, handover, and operation of the building. UBC students were engaged with the comparative LCA-LCC study through internship opportunities at the USI. The project was the focus of graduate class research projects, including a project in which a student accessed the educational and research materials from this research project to conduct their own preliminary comparative LCA analysis [12]. Presentations about the project were given in large undergraduate courses. For all of these engagement activities, the USI acted as a hub for students and faculty to access research materials and connect to the project stakeholders and share the research findings with the industry professionals [4].

Given the extent and positive outcomes of this collaborative engagement, the Tallwood project can be considered to be a substantial success and a model for achieving high degrees of industry/operations/academic integration, particularly involving graduate students. Yet it also serves as a case study of how difficult it is to achieve and maintain this level of engagement. It required a significant level of time and effort by the USI and many of the stakeholders from all sides to coordinate these activities. The significant sponsorship of FII provided a major driver for this commitment of resources, which would otherwise have been difficult.

Although a high degree of engagement with graduate research students was achieved, there was limited engagement with large groups of undergraduate students. While the program did not focus on undergraduates, the educational materials created by the USI can be used in the development of undergraduate curriculum. However, none of these engagement activities evolved into activities that can be maintained as ongoing engagement with new groups of students without the influx of new projects and resources.

In summary, the project provided valuable lessons about how to successfully achieve high levels of engagement opportunities for students and co-learning on campus projects, but it also highlighted the many difficulties in achieving and maintaining this engagement.

4. Conclusion

The CLL initiative at the UBC campus provides a unique opportunity for conducting further research on how life cycle approaches can be used to help decision makers contribute to the development and management of future sustainable cities. This paper discussed the major opportunities and challenges that were experienced in the process of conducting a comparative LCA-LCC study on two UBC residential towers, one with a hybrid mass-timber structure and the other with conventional concrete structure.

The research team was able to access key data through internal connection with various UBC operational departments. However, availability and access to data were still major barriers to this study. This was partially due to the lack of useful project or context specific data, and partially due to the insufficient data in the current life cycle databases and tools. The inherent uncertainty regarding possible future scenarios in the long lifetime of the buildings was another contributor to the data challenges.

These challenges not only affect the quality and applicability of the final results, but also affect the time and financial resources required to conduct such an analysis. This will consequently affect the feasibility and interest of the decision and policy makers in considering a life cycle approach in supporting their decisions. This highlights the necessity and value of future research on improving and expanding context specific life cycle databases.

To make life cycle analysis more useful for the construction industry and policy makers, there is a need for guidelines and tools to interpret the LCA results and identify major contributors to the life cycle impacts as well as tools to help identifying alternative solutions that can improve the buildings' life cycle performance.

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- UBC departments: UBC Infrastructure Development, Properties Trust, Student Housing and Hospitality Services, Building Operations, Energy and Water Services, and Campus and Community Planning.

References

[1] P. Save and T. M. Froese, "UBC Living Lab: Innovation In Accelerating The Adoption Of Sustainable Technologies For Campus Infrastructure," in *2nd Int. Conf. On Urban Sustainability & Resilience*, London, 2014.

[2] UBC Campus and Community Planning, "UBC LEED Implementation Guide for Building Design and Construction V4," University of British Columbia, Vancouver, 2016.

[3] UBC Campus and Community Planning, "Green Building Plan," University of British Columbia, 2017. [Online]. Available: https://planning.ubc.ca/vancouver/projects-consultations/consultations-engagement/green-building-plan. [Accessed 28 09 2017].

[4] naturally:wood, "Brock Commons Tallwood House," Forestry Innovation Investment, [Online]. Available: https://www.naturallywood.com/emerging-trends/tall-wood/brock-commons-tallwood-house. [Accessed 29 09 2017].

[5] European Committee for Standardization, "CSN EN 15978: Sustainability of construction works - Assessment of environmental performance of buildings - Calculation method," 2011.

[6] J. Bare, "TRACI 2.0: the tool for the reduction and assessment of chemical and other environmental impacts 2.0," *Clean Techn Environ Policy,* vol. 13, p. 687–696, 2011.

[7] Statistics Canada, "Table 327-0044 - Price indexes of apartment and non-residential building construction, by type of building and major sub-trade group, quarterly (index, 2002=100), CANSIM (database)," [Online]. Available: http://www5.statcan.gc.ca/cansim/a26?lang=eng&id=3270044. [Accessed 15 09 2017].

[8] T. M. Froese, Interviewee, *Interview with Construction Management Personel on UBC Tallwood House.*. [Interview]. 2017.

[9] I. Bribián, A. Capilla and A. Usón, "Life cycle assessment of building materials: Comparative analysis of energy and environmental impacts and evaluation of the eco-efficiency improvement potential," *Building and Environment,* vol. 46, no. 5, pp. 1133-1140, 2011.

[10] A. Säynäjoki, J. Heinonen, S. Junnila and A. Horvath, "Can life-cycle assessment produce reliable policy guidelines in the building sector?," *Environmental Research Letters,* vol. 12, no. 1, p. 013001, 2017.

[11] S. Hellweg and L. Milà i Canals, "Emerging approaches, challenges and opportunities in life cycle assessment," *Science,* vol. 344, no. 6188, pp. 1109-1113, 2014.

[12] J. Bare, P. Hofstetter, D. Pennington and H. De Haes, "Midpoints versus endpoints: the sacrifices and benefits," *The International Journal of Life Cycle Assessment,* vol. 5, no. 6, pp. 319-326, 2000.

[13] M. A. Tehrani and T. Froese, "A Comparative Life Cycle Assessment of Tall Buildings with Alternative Structural Systems: Wood vs. Concrete," in *Book of Abstracts for CSCE 2017 Annual Conference*, Vancouver, 2017.

[14] G. Rebitzer, T. Ekvall, R. Frischknecht, D. Hunkeler, G. Norris, T. Rydberg, W. Schmidt, S. Suh, B. Weidema and D. Pennington, "Life cycle assessment: Part 1: Framework, goal and scope definition, inventory analysis, and applications," *Environment international,* vol. 30, no. 5, pp. 701-720, 2004.