UNIVERSITÉ DE SHERBROOKE
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# **Development of consequential approach in life cycle sustainability assessment**: the case of hybrid multistory building

# Développement de l'approche conséquentielle pour l'analyse de la durabilité du cycle de vie: cas d'un bâtiment hybride multiétages

Thèse de doctorat - spécialité : génie civil

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Sherbrooke (Québec) Canada
May 2022

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*Allah will elevate those of you who are faithful, and ⌜raise⌝ those gifted* ***with knowledge*** *in rank. And Allah is All-Aware of what you do. Quran 58-11.*

*This work is dedicated to my family.*

# ACKNOWLEDGEMENTS

Alhamdulillah, praise be to God, without Him who has sent individuals that have helped me during my PhD journey. First innumerable thank is to my family; my beloved wife Winda and my son Ibrahim who always and always support and cherish me during tough moments; thanks to your patience. I also thank to my parents (Arif and Titik) and my parents-in-law (Waridi and Sulistyowati) for their constant love and prayers. Thanks also to my sister, Evif, my brother-in-law, Reifki, my other brother-in-law and my sister-in-law who also give encouragements and prayers all the way from hometown.

I would like to thank my supervisor, Professor Ben Amor, for your guidance, patience, empowerment, and compassion throughout my graduate study while keeping me challenged to become a better researcher. I feel very fortunate to have you not only as my mentor but also a good friend. Thank you for never stop believing in me and always have my back. I would like to thank Professor Audrey for your inspiration, patience, and valuable feedback on my work and dissertation. Thank you to Mr Patrick for the good and valuable mentorship, great research insights and for giving me new perspectives in the civil engineering practice. I want to thank Professor Dahai and Dr Aline for the positive vibes and valuable feedback on my dissertation.

My heartfelt thanks go to the entire LIRIDE family. I am grateful for the warm welcome, team spirit, cheerful personalities, and kind support that I will never forget, especially to Sylvain, JM, Xavier, Marianne, and Kikki.

My sincere gratitude also goes to Amus family. I am also grateful for the team work we had during all social, fund-rising, donating and philanthropic events we had during two years I served as treasurer and general assistant. Special thanks to Mohamed Eldakamawy, Ahmed Ayari, Boubacar, and Marwan.

Last, I want to say thanks to the financial supports of this research project. I am grateful to the Natural Sciences and Engineering Research Council of Canada for financial support, through its ICP and CRD programs (grants IRCPJ 461745-12 and RDCPJ 445200-12), and to the industrial partners of the NSERC industrial chair on eco-responsible wood construction (CIRCERB), and the Quebec's Economy, Science and Innovation Ministry. Last, I am also grateful to LIRIDE Scholarship that help me in the last year of my research.

# Résumé

Il est indéniable que l'industrie du bâtiment doit évoluer vers des bâtiments plus durables à l'avenir. Les décideurs dans le secteur du bâtiment doivent prendre en compte les aspects sociaux et économiques dans leur prise de décision, en plus de l'aspect environnemental. Ces évaluations doivent également inclure la perspective du cycle de vie. L'approche conséquentielle est nécessaire pour évaluer les conséquences à long terme par rapport à l'approche attributionnelle qui se concentre sur l'évaluation d'un profil donné. Ce projet de recherche montre comment l'approche conséquentielle est intégrée dans l'analyse du cycle de vie (ACV), l'analyse du coût du cycle de vie (ACCV) et l'analyse sociale du cycle de vie (AsCV) dans le cadre de l'analyse de la durabilité du cycle de vie (ADCV).

Ce mémoire de thèse contient huit chapitres pour atteindre les objectifs de recherche susmentionnés. Le chapitre 1 décrit le contexte de l'étude et l'organisation de la thèse. Le chapitre 2 présente les défis et les opportunités actuels de l'évaluation de la durabilité du cycle de vie qui a été publié et auquel il est fait référence comme premier article de cette thèse. Le premier article présentait les lacunes identifiées dans l'harmonisation des trois méthodes discutées (ACV, ACCV et AsCV). Dans l'intégration de l'ACV et du ACCV, la question de la temporalité est toujours absente dans l'ACV, en plus de la perspective conséquentielle dans l'ACV et l'ACCV. Dans l'intégration de ACCV et AsCV, deux lacunes de recherche sont également trouvées : la différence de perspective lors de l'utilisation à la fois de la méthode, en plus du manque de la perspective conséquentielle. Dans l'intégration de l'AsCV et de l'ACV, les problèmes qui se posent sont : la présence d'impact négatif et positif dans l' AsCV, par rapport à l'ACV (dont les impacts sont presque toujours négatifs), sans oublier l'absence de l'approche conséquentielle dans l'AsCV. Lors de l'application de l'ADCV dans un contexte politique, nous avons suggéré que le cadre a besoin d'une perspective conséquentielle pour faciliter la capture non seulement des impacts directs, mais aussi des conséquences indirectes.

Le chapitre 4 présente l'énoncé du problème et les questions de recherche, le but et les objectifs de la recherche, ainsi que la définition du projet. Le chapitre 5 décrit l'ACV et le CCV d'un bâtiment hybride à plusieurs étages avec une étude de cas au Québec, Canada. Il a également été publié et fait référence au deuxième article de cette thèse. Le deuxième article a démontré la pertinence de l'utilisation complémentaire d'approches attributionnelle et conséquentielle avec l'étude de cas d'un bâtiment hybride à plusieurs étages, et ce du point de vue environnemental et économique. Les résultats de l'ensemble du cycle de vie indiquent des différences potentielles entre les deux approches de modélisation sous-jacentes. Par exemple, la production de matériaux est l'étape la plus impactante sur le plan environnemental (avec une contribution de 86 à 98 %) et économique (72 %) dans l'approche attributionnelle. Cependant, dans l'approche conséquentielle, la production de matériaux est moins responsable sur le plan environnemental (46 à 94 %) et pourtant plus responsable sur le plan économique (59 %). Cela démontre que l'ACV et l'ACCV conséquentielle peuvent révéler des informations complémentaires (non disponible d'un point de vue attributionnelle). Même si l'étude est soumise à des limitations et des incertitudes notables, telle que la disponibilité et la qualité des données, la réalisation d'une ACV-ACCV attributionnelle et conséquentielle d'un produit pourrait donner plus d'informations pertinentes pour une prise de décision plus robuste.

Le chapitre 6 présente l'ACVS du même bâtiment en utilisant l'analyse multiniveau et constitue le troisième article publié dans cette thèse. Dans le troisième article, l'analyse sociale du cycle de vie (ASCV) a été réalisée en évaluant l'impact social potentiel et les bénéfices du cycle de vie du bâtiment. L'utilisation d'une analyse à plusieurs niveaux (résolutions), qui est appliquée à l'ACV sociale conséquentielle et attributionnelle, pourrait aider à combler les lacunes dans

les données. Bien que davantage de données ne soient pas toujours meilleures, cela peut aider à comprendre les points chauds possibles de l'impact/bénéfice social et le champ d'influence de l'impact/bénéfice social pour les parties prenantes. Combler les lacunes dans les données est important de deux manières : 1) combler les lacunes des données sur les indicateurs et 2) combler les lacunes des données sur le cycle de vie du système de produits (du berceau à la tombe). En utilisant une analyse à plusieurs niveaux dans une ACV sociale conséquentielle, il a été observé que l'importation d'acier et/ou d'aluminium de Chine est potentiellement associée à certains impacts sociaux négatifs (restrictions à l'association des travailleurs, risque pour la santé et la sécurité et travail des enfants), mais aussi des contributions bénéfiques (emploi). En fin de compte, révéler ces types d'indicateurs peut aider les décideurs politiques à prévoir et à planifier les conséquences négatives avant qu'elles ne surviennent, et vice versa à promouvoir des avantages positifs. Plus important encore, comme pour l'ACV, la nécessité d'inclure une perspective du cycle de vie complet existe, car l'impact tout au long de la phase du cycle de vie du produit est souvent négligé en raison de données manquantes.

Enfin, le chapitre 7 présente la discussion de la recherche tandis que le chapitre 8 montre les conclusions, les contributions, les limites et fournit des recommandations pour les recherches futures. En conclusion, l'utilisation de trois outils ADCV (ACV, CCV et AsCV) dans l'approche conséquente signifie que le LCSA conséquent a également été réalisé. L'optique prospective de l'approche conséquentielle permet d'améliorer les performances de durabilité de manière causale. Les impacts du processus, de l'activité ou de la technologie évalués sont ceux du processus, de l'activité ou de la technologie qui vont répondre à la demande accrue. Ainsi, l'évaluation a pour logique de répondre aux conséquences futures. Cela inclut éventuellement l'implication des fournisseurs de matériaux mondiaux de l'étranger, comme observé dans cette étude, où les conséquences sociales peuvent avoir différents résultats possibles. La situation sociale et les conditions de travail dans d'autres pays (en particulier dans les pays en développement) peuvent présenter de mauvaises pratiques. L'approche conséquentielle aide les décideurs politiques à anticiper l'impact des différents résultats possibles et à identifier les faiblesses. Par exemple, les décideurs peuvent découvrir qu'il faut réduire l'acier et les importations de l'étranger et se concentrer davantage sur l'utilisation de produits locaux. Un plan de transformation peut être élaboré à l'avance pour faire face à d'éventuels problèmes techniques et opérationnels liés au passage de l'étranger au local et offrir une valeur future plus mesurable.

# Summary

It is undeniable that building industry needs to move to more sustainable buildings in the future. Building policy-makers need to include social and economic aspect into consideration, beside environmental one. These assessments also need to include a life cycle perspective. Consequential life cycle approach is suitable for assessing long-term consequences ,as compared to attributional approach that only focus on the impact accounting itself. This research project aims to demonstrate  how the consequential approach when applied to life cycle assessment (LCA), life cycle costing (LCC) and social life cycle assessment (S-LCA) (under the life cycle sustainability assessment umbrella) can shed light on important insights that can't be identified when using the attributional one.

This thesis dissertation contains eight chapters to achieve the aforementioned research objectives. Chapter 1 describes the context of the study and dissertation organization. Chapter 2 presents the current challenges and opportunities of life cycle sustainability assessment that has been published and referred as first paper in this thesis. The first paper presented the identified gaps shown in the harmonization of the three presented methods (LCA, LCC, and S-LCA). In the integration of LCA and LCC, temporality issue is still missing in LCA (issue, here it is called research gap [RG 1]), in addition to the missing consequential perspective in LCA and LCC (RG 2). In the integration of LCC and S-LCA, two research gaps are also found: the difference in stakeholder perspective when using both method (RG 3), in addition to the missing consequential perspective (RG 4). In the integration of S-LCA and LCA, the identified issues are (not extensive list): the presence of negative and positive impact in S-LCA, as compared to LCA (RG 5), the scales of assessment applied in each method differs (RG 6), in addition to the absence of a consequential approach in S-LCA. When applying LCSA in a policy context, it is suggested that the framework needs a consequential perspective to facilitate capturing not only direct impacts but also indirect consequences. Chapter 3 presents the updated and recent literature review with the same topic as in Chapter 2.

Chapter 4 shows the problem statement and research questions, research goal and objectives, and project definition. Chapter 5 describes the LCA and LCC of hybrid multistory building with case study in Quebec, Canada. It is also has been published and referred as second paper in this thesis. The second paper showed the added value of using attributional and consequential approaches with the case study of hybrid multistory building, from environmental and economic perspectives. For example, material production is the most impactful stage environmentally (with 86–98% contribution) and economically (72%) in the attributional approach. However, in the consequential approach, material production is less environmentally responsible (46–94%), while from an economic perspective the contribution reached 59%. By implementing consequential LCA-LCC, additional insights are gained from the consequential impacts of constructing hybrid wood multistory buildings. Even though the study is a subject to notable limitations and uncertainties, such as data availability and quality, conducting attributional and consequential LCA-LCC of a building can give a broader/more comprehensive spectrum of possible results for a robust decision-making.

Chapter 6 provides S-LCA of the same building using multilevel analysis and referred as third published paper in this thesis. In the third paper, the social life cycle assessment was carried out by evaluating the potential social impact and benefit from the product's life cycle. Using a multilevel analysis, applied to consequential and attributional social LCA, helped in filling data gaps, particularly for the consequential perspective. While more data is not always better, it

can help to understand the possible hotspots of social impact/benefit. Filling data gaps is important in two ways: 1) filling data gaps on indicators and 2) filling data gaps on the product system's life cycle (cradle to grave). As a matter of fact, when using multilevel analysis in consequential social LCA, it was noticed that importing steel and/or aluminum from China is potentially associated with negative social impacts (restrictions on worker association, risk on health and safety, and child labor) but also some beneficial contributions (employment). Ultimately, revealing these types of trade-offs may help policymakers predict and plan for negative consequences before they occur, and vice versa promote positive benefit. More importantly, as with LCA, the need to include a full life cycle perspective exists because the impact throughout the product's life cycle phase is frequently overlooked due to missing data.

Finally, Chapter 7 presents the research discussion while Chapter 8 shows conclusions, contributions, limitations, and provides recommendations for future research. In conclusion, having three tools of LCSA (LCA, LCC and S-LCA) performed in consequential approach mean that consequential LCSA also have been carried out. The forward-looking lens of consequential approach helps to improve sustainability performance in causal-effect manner. The impacts of the process or activity or technology assessed are the ones from process or activity or technology that are going to supply the increased demand. Thus, the assessment has logic on answering the future consequences. This possibly includes the involvement of global material suppliers from abroad such observed in this study where the social consequences can have different possible outcomes. The social working situation and labor condition in other countries (especially in developing countries) may have poor practices. Having consequential approach helps the policy makers anticipate the impact of different possible outcomes and identify weaknesses. For example, policy makers may discover that it needs to reduce the steel and import from abroad and more focus on using local products. A transformation plan can be made in advance to cope with possible technical and operational problems from shifting from abroad to local and deliver more measurable future value.

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# List of Symbols

- $s$ = scaling factors for job opportunity.
- $E_p$ = the technology matrix of the physical system
- $E_{p,\ scaled}$ = technology matrix transferred or scaled to the functional unit
- β = the employability vector
- Em = transformation of technology matrix Ep into employability
- $Em_{scaled}$ = employability matrix transferred or scaled to the functional unit
- $e = E_{m,\ scaled}^{T}$ the employability aggregation
- Pca: total production cost - attributional
- e: engineering design cost
- s: site work cost
- ci: construction cost of each material
- f: finishing cost
- pl: plumbing cost
- me: mechanical and electrical cost
- mci: material cost
- lci: bare labor cost
- eci: bare equipment cost
- oi: overheard cost
- Ci: city index
- Pcq: total production cost - consequential
- PV: present value
- mcfi: material costyear n in future
- lcfi: labor costyear n in future
- ecfi: equipment costyear n in future
- r: discounting rate
- t: time
- U: Total use cost
- ui: use cost
- el: electricity cost per kWhyear n

# List of Abbreviations

# Glossary

| | |
|---|---|
| Attributional modelling | A system modelling approach in which inputs and outputs are attributed to the functional unit of a product system by linking and/or partitioning the unit processes of the system according to a normative rule |
| Substitution | A replacement of one product or group of products with another product or group of products that are functionally equivalent |
| Consequential modelling | A system modelling approach in which activities in a product system are linked so that activities are included in the product system to the extent that they are expected to change as a consequence of a change in demand for the functional unit. |
| Environmental exchange | Environmental exchanges are environmental inputs to a product system (resources), environmental outputs from a product system (emissions to air, water and soil) as well as environmental relations of a product system, which are not directly connected to its inputs and outputs (e.g. land use, physical impacts, non-chemical aspects of occupational health, welfare of workers and domestic animals). |
| Functional unit | A quantified description of the performance of a product system, in terms of the obligatory product properties required by the market on which the product is traded. |
| Marginal technology | Technology that is going to supply the demand in the future based on the market change |
| Life cycle assessment | Compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product (system) throughout its life cycle. |
| Life cycle inventory analysis | Phase of life cycle assessment involving the compilation and quantification of exchanges for a product throughout its life cycle. |
| Reference flow | A reference flow is a quantified amount of product(s), including product parts, necessary for a specific product system to deliver the performance described by the functional unit. |
| System expansion | A procedure for eliminating by-products as activity outputs by including them instead as negative inputs, thereby including the additional functions related to the by-products and modelling the resulting changes (substitutions) in the product system, especially by including the reduction in supply of the same product from the marginal supplier to the market for the by-product. |

This vocabulary is available in its entirety at:
https://consequential-lca.org/glossary/

# List of Research Communication

This research project has resulted in two scientific papers published in peer-reviewed journals and another one submitted. Three presentations were made in seminars and conferences in the form of oral (1) and poster (2). Details on all articles and communications are summarized in the following table.

| Type | Detail | Date |
|---|---|---|
| Submitted article | Rizal Taufiq Fauzi, Patrick Lavoie, Audrey Tanguy and Ben Amor. On the Advantages of Multilevel Analysis to Cover Data Gaps in Consequential S-LCA: Case Study of Hybrid Multistorey Building. **Journal of Cleaner Production.** | 2021 |
| Accepted article | Rizal Taufiq Fauzi, Patrick Lavoie, Audrey Tanguy and Ben Amor. Life Cycle Assessment and Life Cycle Costing of Multistorey Building: Attributional and Consequential Perspectives. **Building and Environment. Volume 197, 107836.** | 2021 |
| Accepted article | Rizal Taufiq Fauzi, Patrick Lavoie, Luca Sorelli, Mohammad Davoud Heidari and Ben Amor. Exploring the Current Challenges and Opportunities of Life Cycle Sustainability Assessment. **Sustainability. 11(3), 636**. | 2020 |
| Oral presentation | Rizal Taufiq Fauzi, Patrick Lavoie and Ben Amor. Assessing Sustainability Performance of Hybrid Wood Multi-Storey Building using Life Cycle Sustainability Assessment (LCSA). LCA for Wood Construction and the Circular Economy. **LIRIDE/NRCan Workshop. 24th July 2019, Ottawa, Canada.** | 2019 |
| Poster presentation | Increasing timber in hybrid multi-storey building: What are the environmental life cycle consequences? **Rendez-vous de l'économie circulaire. 9-10 Mai 2019, Sherbrooke, Canada.** | 2019 |
| Poster presentation | Rizal Taufiq Fauzi, Patrick Lavoie, Luca Sorelli and Ben Amor. Life Cycle Sustainability Assessment of Hybrid (Wood-Concrete) Multi Storey Building**. École d'été du CIRCERB. 15 Juin 2017. Québec, Canada**. | 2017 |

# Chapter 1 - Introduction

## 1.1. Context

### 1.1.1. Sustainability Assessment

Policymakers and corporate leaders have undertaken efforts to adapt to and address environmental challenges such as climate change, resource depletion, and ecosystem deterioration. One typical strategy is by examining a product's or service's environmental performance and ensuring that it has the least possible impact on the environment. Life cycle thinking (LCT) is critical for grasping the environmental impact in a broader context from cradle to grave (Finnveden, 2009). It is critical to avoid problem shifting.

Broadly conceived, the examination of a product's or service's environmental impact has been elevated to a greater level called sustainability by the addition of two features: "economics" and "social." The term "sustainability" was indeed coined in 1993 by the United Nations Conference on the Human Environment as "development that meets current demands without compromising future generations' ability to meet their own" (UN 1987). This word is translated and widely accepted as referring to three distinct categories of value, namely the environmental, social, and economic dimensions. Evaluating these three pillars within decision making is indeed a major challenge (Plevin *et al.*, 2014; Yang, 2016a; Yang and Heijungs, 2018).

The decision to produce or consume a sustainable product is not simply a matter of whether the product meets the requirements outlined in the sustainability pillars; it requires a thorough study. This is important since problem shifting may also occur here if we concentrate our efforts on minimizing the environmental impact, for example, on a single phase of the product's life cycle. However, we overlook the product's potential to cause not only more environmental problems elsewhere in other phases, but also economic and social problems for other stakeholders throughout the supply chain. Thus, improving an overall product's sustainability performance through LCT is a critical need.

LCT has been used for decades for assessing the product's impact in its entire life phase (Finnveden *et al.*, 2009; Hellweg and Canals, 2014; Jeroen B. Guinee; *et al.*, 2011). The first version is on economic side called Life Cycle Costing (LCC). Second adaptation is Life Cycle Assessment (LCA) to assess the environmental impact. Last, the social aspect is assessed by Social Life Cycle Assessment (S-LCA). These three methods have their own characteritics, but they have similar four iterative stages to perform: 1) goal and scope definition 2) inventory analysis 3) impact assessment and 4) interpretation (Benoit *et al.,* 2009; Hunkeler *et al*., 2008; ISO 14040, 2006; ISO 14044, 2006). Moreover, in terms of goal and scope definition and inventory modelling, LCA community can commonly agree on the establishment of two approaches: attributional and consequential.

Attributional approach, in environmental LCA, describes the environmentally relevant physical flows into and out of a life cycle of a product and its subsystems. The main question to ask within attributional approach is how much global environmental burden can be attributed or allocated to a product being assessed? While in consequential, it describes how environmentally relevant flows would alter as a result of potential decisions. To improve the future long-term environmental or sustainability profile of a decision, rather than looking at it as a retrospective way, one needs to look at the activities in the system that are likely to change as demand increases.

Thus, the unit process and suppliers that are included in the product system are the ones that are going to supply the market (Ekvall, 2020; Schaubroeck *et al.*, 2021a).

Even though consequential approach is aimed to assess indirect and future consequences from market change-oriented perspective, the application of it is still rare, and most importantly in the environmental side (Earles and Halog, 2011; Zamagni *et al.*, 2012). In LCA, it has been implemented for decades while in LCC, quite a few studies have been found (Pedinotti-Castelle *et al.*, 2019). The latest to implement is S-LCA. Only one study so far have implemented it (Tsalidis and Korevaar, 2019).

Speaking about the methodology, it is clear that consequential approach is not broadly applied compared to attributional ones. This calls for more development and applications in transition pathways for sustainability assessment and ensure the consequential approach well documented and more accessible to decision-makers.

### 1.1.2. Sustainability Issue in Building Sector

Building is one of the fundamental requirements of all human beings. The industry, on the other hand, has significant environmental consequences. Approximately one-third of the landfill waste stream (Kibert *et al.*, 2002), 25%–40% of energy consumption (Pérez-Lombarda *et al.*, 2008), and around 30% of greenhouse gas emissions are attributed to the building construction industry (USGBC, 2009).

In parallel with the growing population of human beings, the demand for buildings for residential and other commercial activities also increases around the world, with high-rise buildings in particular becoming increasingly popular. According to the data and prediction of The Council on Tall Buildings and Urban Habitat, multi-storey buildings will be massively constructed over time (Gabel *et al.*, 2016). The number of buildings that has a height more than 200 meters significantly increased since 1980 to 1990. This implies that the construction of multi-storey buildings will play part to face those challenges in time.

Not only should the degradation of environmental quality be taken into consideration while considering the activities of the building sector, but also the socio-economic aspect. Despite the fact that the building construction industry has contributed significantly to the growth of the Gross Domestic Product (GDP) in many countries (Alaloul *et al.*, 2021; Anaman and Osei-Amponsah, 2007; Taylor, 2010). Buildings have a social impact as well. For example, in some nations, the building construction industry has been responsible for fatalities and injuries on the job (El-menyar *et al.*, 2016; Jeong, 1998). The construction industry topped the first rank on the list of industries with the highest risk of occupational injury. Building construction projects deal with some safety and health problems of the workers due to the high risk of dangerous work environments (Jaafar *et al.*, 2018; Khosravi *et al.*, 2014; Sousa *et al.*, 2014; Swuste *et al.*, 2012; Zhang *et al.*, 2015). In the use phase, the quality of building materials and indoor atmosphere also impacts the occupant's health (Geng *et al.*, 2017; Kang *et al.*, 2017; Mujan *et al.*, 2019; Zuo and Zhao, 2014). As a result of the discussion above, it is clear that a comprehensive sustainability assessment that considers three sustainability pillars is required, particularly in the building sector and even for multi-storey building.

### 1.1.3. Life cycle sustainability assessment in building sector

As presented in section 1.1.1 and 1.1.2, it is clear that the construction industry should strive to become more sustainable and analyzing its sustainability performance should be done while keeping problem shifting in mind. But then the question arises on how to assess an action that aims to improve sustainability comprehensively? How did a consequential approach apply in LCSA might help in more comprehensively assessing sustainability profile of multistory[1] building?

In 2012, United Nations Environment Programme (UNEP) and Society of Environmental Toxicology and Chemistry (SETAC) published a guidance document to introduce the new concept or technique called Life Cycle Sustainability Assessment. It is basically consisting of three concepts: LCA, LCC and S-LCA.

The growing importance of Life Cycle Sustainability Assessment (LCSA) as a scientific tool to evaluate environmental burdens is a positive trend; however there are still many research opportunities and areas to improve current practice. The construction sector causes unwanted environmental and social effects and anticipating what might happen in the future become important. To improve a decision's long-term environmental or sustainability profile, rather than looking at it retrospectively, one needs to consider the activities in the system that are likely to alter as demand increases. Thus, future improvement can be easily measured since what can we do for future has more interest. Consequential approach can be used to assess these. However, the application of consequential perspective to life cycle sustainability assessment is little to none despite its importance on avoiding problem shifting in its three dimensions.

The purpose of this research project is to advance and conduct consequential LCSA on hybrid multistory building and identify and address methodological issues that arise. The account of consequential approach is for assessing the direct and indirect impact and benefit in ecological, economic and social aspect for facilitating long-term decision-making and policy.

## 1.2.Dissertation Organization

This thesis dissertation contains eight chapters to achieve the aforementioned research objectives. Figure 1.1 illustrates the organization of the thesis chapters and their interconnections with the research objectives. Chapter 1 describes the context of the study and dissertation organization. Chapter 2 presents the current challenges and opportunities of life cycle sustainability assessment. Chapter 3 presents the updated and recent literature review with the same topic as in Chapter 2. Chapter 3 shows the Chapter 4 shows the problem statement and research questions, research goal and objectives, and project definition. Chapter 5 describes the LCA and LCC of hybrid multistory building with case study in Quebec, Canada. Chapter 6 provides S-LCA of the same building using multilevel analysis. Finally, Chapter 7 presents the research discussion while Chapter 8 shows the conclusions, contributions, limitations, and provides recommendations for future research as explained in figure 1.1.

[1] The term of multistory building is used in this thesis instead of high-rise building. According to the U.S. The National Fire Protection Association definition, a high-rise building is building that is higher than 75 feet (23 meters), or about 7 stories. While multistory building has not been defined in any guideline but generally it is defined as building that has more than a structure that has multiple floors above ground in the building. Both contain similar meaning.

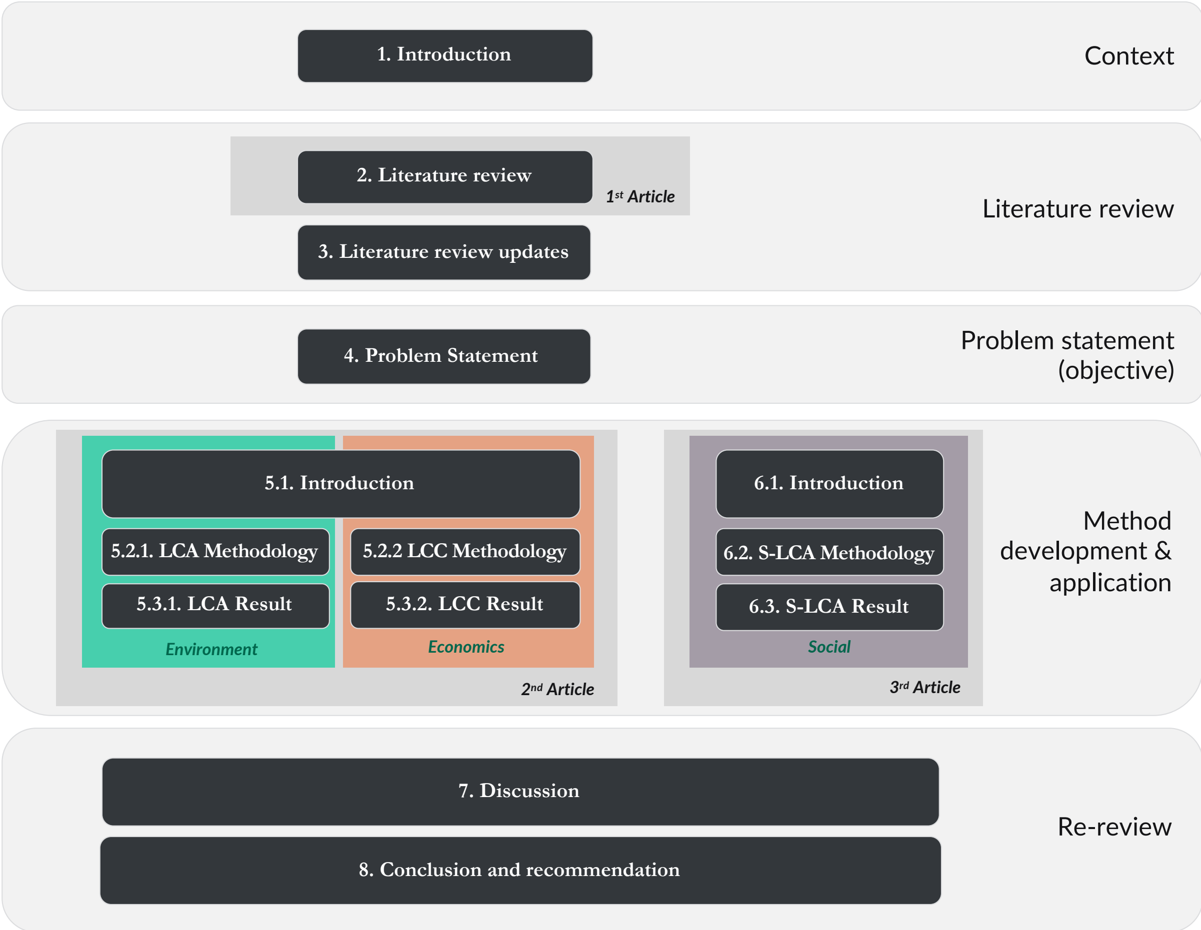


Figure 1.1. Dissertation Organization

# Chapter 2 - Exploring the Current Challenges and Opportunities of Life Cycle Sustainability Assessment

Avant-propos

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Date d'acceptation : 18 January 2019

État de l'acceptation : *Accepted and published*

Référence : Fauzi, R.T.; Lavoie, P.; Sorelli, L.; Heidari, M.D.; Amor, B. *Exploring the Current Challenges and Opportunities of Life Cycle Sustainability Assessment*. Sustainability 2019, 11, 636. https://doi.org/10.3390/su11030636

Titre en français : Explorer les défis et les opportunités actuels de l'évaluation de la durabilité du cycle de vie

Contribution au document: This paper contributes as a critical literature review for starting point to carry out the research.

Abstract

Sustainability decision making is a complex task for policy makers, considering the possible unseen consequences it may entail. With a broader scope covering environmental, economic, and social aspects, Life Cycle Sustainability Assessment (LCSA) is a promising holistic method to deal with that complexity. However, to date, this method is limited to the hotspot analysis of a product, service, or system, and hence only assesses direct impacts and overlooks the indirect ones (or consequences). This critical literature review aims to explore the challenges and the research gaps related to the integration of three methods in LCSA representing three pillars of sustainability: (Environmental) Life Cycle Assessment (LCA), Life Cycle Costing (LCC), and Social Life Cycle Assessment (S-LCA). The challenges and

the research gaps that appear when pairing two of these tools with each other are identified and discussed, i.e., the temporal issues, different perspectives, the indirect consequences, etc. Although this study does not aim to remove the shadows in LCSA methods, critical research gaps are identified in order to be addressed in future works. More case studies are also recommended for a deeper understanding of methodological trade-offs that might happen, especially when dealing with the consequential perspective.

Keywords: sustainability; life cycle assessment; life cycle costing; social life cycle assessment; consequential; research gaps

## 2.1. Introduction

In 2015, an international agenda was agreed upon in an attempt to move society towards improved wellbeing and surroundings, through a collective plan called the Sustainable Development Goals (SDGs) (Costanza *et al.*, 2016; United Nations, 2015). SDGs were marked as a progressive move to achieve sustainable development involving various stakeholders in many regions. In comparison to their predecessor, Millennium Development Goals, new fields were added, addressing issues such as climate change, economic inequality, innovation, sustainable consumption, peace, and justice, among other priorities (United Nations, 2015; Weidema, 2017).

Sustainability challenges have attracted increasing attention over the last few decades. However, the sustainability challenges we face today are frequently seen solely in terms of environmental threats, and thus the assessment emphasizes only on this aspect (Catherine; Benoît and Mazijn, 2009; Johnston *et al.*, 2007; Onat *et al.*, 2017). Many tentative efforts for expanding the scope of assessment away from exclusively looking at the environmental space have been made, incorporating both economic and social aspects (Finkbeiner *et al.*, 2010; Kloepffer, 2008; Onat *et al.*, 2017). Life Cycle Assessment (LCA) is a powerful method for examining potential environmental impacts from the entire life cycle of a product system (ISO 14040, 2006). Now, the ideas of life-cycle thinking from LCA are being extended to other pillars, such as the economic pillar (Life Cycle Costing—LCC), the social pillar (Social Life Cycle Assessment—S-LCA), and sustainability as an entire concept (Life Cycle Sustainability Assessment—LCSA).

### 2.1.1. Life Cycle Assessment (LCA)

LCA seeks to quantify the potential environmental impacts of a product system based on physical energy and material flows (ISO 14044, 2006). It is believed that the first LCA study was conducted in 1969 by the Midwest Research Institute in the US for the Coca-Cola Company, for decision making on bottles packaging (Bauman and Tillman, 2004). In 1990, the Society of Environmental Toxicology and Chemistry (SETAC) started to hold an annual conference on LCA to formulate the methodology. Three years later in 1993, the first guideline was published (Consoli *et al.*, 1993). Since then, LCA has been in increasing development in terms of standards, methodologies, and applications.

LCA has been internationally standardized over time, from the first International Organization for Standardization (ISO) version 14040-43 (1997–2000) to the revised version ISO 14040/44 (2006) (ISO 14040, 2006; Kloepffer, 2008). The United Nations Environment Program and the Society of Environmental Toxicology and Chemistry (UNEP/SETAC) Life Cycle Initiative works on the harmonization of LCA through the four stages of goal and scope definition, inventory analysis, impact assessment, and interpretation (LCI, 2017). In addition to that, there exists two distinct types of LCA modeling, i.e., attributional and consequential ones. In attributional LCA (ALCA), the assessment focuses on the environmental impacts produced by the processes directly used in the assessed product system (Zamagni *et al.*, 2012). In consequential LCA (CLCA), the assessment aims to model the consequences of the changes of physical flows caused by an increasing or decreasing demand in the processes of the product system (Curran, 2013; Earles and Halog, 2011)

Between attributional and consequential models, there have been several proposals to suggest the differences in terms of approaches and techniques (Bjørn *et al.*, 2018; Brando *et al.*, 2017). However, no general consensus heads to some points of agreement. The consequential model was developed around the year 2000 as an attempt to incorporate market mechanisms (economic principles) into LCA frameworks, that the attributional model was not focusing on (Bjørn *et al.*, 2018). The main goal of the consequential model is to answer this type of question: "What are the environmental consequences of consuming X?", instead of attributional ones (such as: "What environmental impact can be attributed to product X?") (Bjørn *et al.*, 2018). This is, among other characteristics, reflected in the way CLCA address multifunctionality through system expansion, allowing the fate of the coproducts in other markets (i.e., displacements) to be included (Brando *et al.*, 2017). The choice of attributional and consequential method depends on the goal and scope of the study, and will influence the definition of the system boundary and its modelling (Curran, 2013; Earles and Halog, 2011; Zamagni *et al.*, 2012). This will potentially cause certain methodological challenges when dealing with LCSA that will be discussed in Section 2.

### 2.1.2. Life Cycle Costing (LCC)

LCC is a method that summarizes all the costs in the life cycle of a product that are directly assumed by one or more participants in the product system (Thomas E Swarr *et al.*, 2011). LCC was first carried out by the U.S. Department of Defense in the 1960s, for the procurement of items of military equipment that were considered to be high-cost products (Jolliet *et al.*, 2016). It emerged from the need for a comprehensive understanding of the monetary flows within the whole life cycle of a product, so that the decision making could include not merely the initial cost, but also the operation, maintenance, and end-of-life treatment costs. The general LCC concept was first defined by Blanchard (Blanchard, 1978), and later other modifications and examples were produced by organizations such as the International Organization for Standardization (ISO), the International Electrotechnical Commission (IEC), and the Australian and New Zealand National Standards (AS/NZS), which also conceptualized the total cost of the investigated product (Blanchard, B.; Fabrycky, 1998; Jolliet *et al.*, 2016). LCC has been frequently used as a cost calculation and comparison tool from a product perspective, rather than from a life cycle viewpoint, or from use of an explicitly developed methodology.

In 2008, the European arm of the Society of Environmental Toxicology and Chemistry (SETAC-Europe) published a book (T.E. Swarr *et al.*, 2011) which was the result of its working group, in which three different categories of LCC were described: Conventional LCC, environmental LCC, and social LCC. If conventional LCC disregarded the post-production phase, while social LCC focused on indirect social costs, the environmental LCC was different. It was a mirror of LCA, which has the same definition as the assessment of entire product life cycle costs that are directly borne by one or more participants in its life cycle, with the inclusion of environmental externality costs (T.E. Swarr *et al.*, 2011). It has generally been agreed that, among those three LCC types, environmental LCC was appropriate to be used in parallel with LCA, to support the sustainability pillars (Kloepffer, 2008; T.E. Swarr *et al.*, 2011). For the sake of simplicity, it will be referred in this article to environmental LCC.

### 2.1.3. Social Life Cycle Assessment (S-LCA)

S-LCA assesses the real (site-specific) and potential, positive and negative, socio-economic impacts of a product system through its life cycle. Unlike its counterparts introduced earlier, S-LCA has a predecessor, namely Social Impact Assessment (SIA), which aimed to evaluate the social impacts of activities (Freudenburg, 1986).

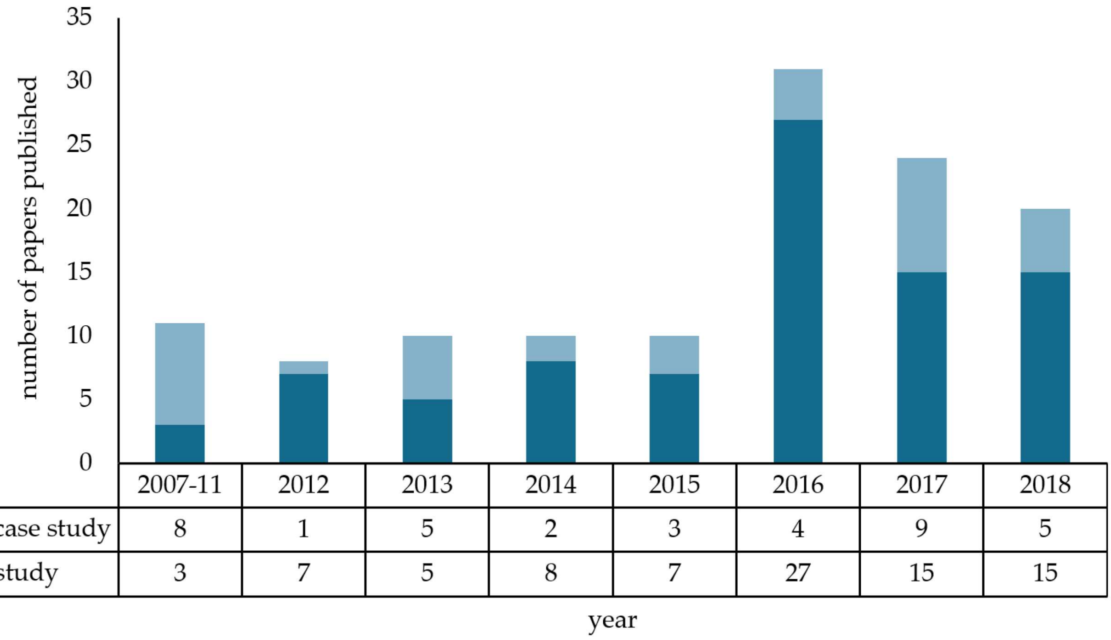
S-LCA does not have a long history, compared to the other two methods. Indeed, the first S-LCA guidelines from UNEP/SETAC (Catherine Benoît and Mazijn, 2009) were published in 2009, in order to provide guidance to stakeholders involved in the evaluation of the social impacts of products through their lifespan. S-LCA has four phases: Goal and scope definition, inventory analysis, impact assessment, and interpretation. Some noticeable differences to environmental LCA include the high level of stakeholder involvement in the goal and scope definition, data collection, and interpretation steps, as well as the high level of sensitivity to varying geographical locations for each stage (Catherine Benoît and Mazijn, 2009).

Recently, S-LCA is gaining much attention in the scientific community. It can be seen from the efforts proposed to advance the method (i.e., revisions on the current guideline, linking life cycle thinking to SDGs) and the different contexts of its application, including cutting-edge topics such as circular economy (Neugebauer *et al.*, 2018; Santos *et al.*, 2019), renewable energy (Corona *et al.*, 2017; Tseng *et al.*, 2017), and bio-based economy (Falcone and Imbert, 2018; Rafiaani *et al.*, 2016). However, the gaps still exist when it is combined with other tools and it will be elaborated on more in Section 2.

### 2.1.4. Life Cycle Sustainability Assessment (LCSA)

The development of the LCSA framework originated from the need to incorporate the three pillars of sustainable development (environmental, economic, and social impacts) into one formulation, while retaining a life cycle perspective. There are two main formulations of LCSA. The first one is the LCSA model suggested by Kloepffer (Kloepffer, 2008), which consists of LCA + LCC + S-LCA, where LCA is an ISO-conforming, environmental life cycle assessment; LCC is an LCA-type environmental life cycle costing; and S-LCA is a social life cycle assessment (Kloepffer, 2008). Second, LCSA acts as a framework, rather than a model, with a similar definition as first formulated, but with a broader and deeper scope (Jeroen B. Guinee; *et al.*, 2011). LCSA, as proposed by Guinee *et al.* (Jeroen B. Guinee; *et al.*, 2011), then broadened the scope from primarily product-related subjects (product level) to subjects related to a sector (sector level) or to a whole economy. It broadened the scope of the present LCA to go beyond predominantly technological (or physical) interdependences (involving resource limitations) to cover economic and behavioral ones, thus making it possible for it to be combined with other methods, such as Material Flow Analysis, Cost–Benefit Analysis, etc. What makes it different is that, as part of broadening the scope, rather normative aspects such as discounting, weighting, and the notion of weak versus strong sustainability could be easily incorporated (Guinee, 2016). Both types of LCSA models (or frameworks) are included in this review.

The number of publications related to LCSA is steadily increasing, as can be seen in Figure 1. From 2007 to October 2018, 124 papers were published on the topic, as determined by the authors, by putting the keywords “Life Cycle Sustainability Assessment” and/or “LCSA”, into both the Scopus database and Google Scholar (see Annex A for details on the methodology). In total, 83 publications describing case studies and 31 publications covering other things, such as discussions of the theoretical or methodological frameworks, were found.




| | 2007-11 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 |
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| non-case study | 8 | 1 | 5 | 2 | 3 | 4 | 9 | 5 |
| case study | 3 | 7 | 5 | 8 | 7 | 27 | 15 | 15 |

Figure 2.1. Life Cycle Sustainability Assessment (LCSA)-related paper published from 2007 to October 2018

LCSA has been applied in many sectors, including transportation (Cihat *et al.*, 2016c, 2016b; Onat *et al.*, 2016), building (Gencturk *et al.*, 2016; Hossaini *et al.*, 2015; Onat *et al.*, 2014), energy (Manzardo *et al.*, 2012; Ren *et al.*, 2015; Stamford and Azapagic, 2012), agriculture (Aziz *et al.*, 2016; Martínez-Blanco *et al.*, 2014), manufacturing (Huang and Mauerhofer, 2016; Peukert *et al.*, 2015), and waste treatment (Lu *et al.*, 2014; Menikpura *et al.*, 2012; Vinyes *et al.*, 2013). The increasing number of publications on this topic, and the diverse applications of case studies, shows that LCSA is now accepted as an assessment method to support decision making on sustainability.

With the growing numbers of publications on LCSA, UNEP/SETAC (UNEP, 2011)published a document as an introduction to the LCSA concept, and to provide guidance on putting LCSA into practice. In the guideline, the focus lays on the integration of three methods (LCA, LCC, and S-LCA) within an LCSA framework, through the presentation of various case studies. However, these three methods still have their distinctions, so they cannot be simply integrated and dovetailed with each other without some adaptation. This paper’s primary objective, then, is to investigate the research challenges brought about by the integration of LCA, LCC, and S-LCA under the umbrella of an LCSA framework, and to consider these when dealing with direct and indirect impacts (i.e., consequences). This review paper, to the best knowledge of the authors, gives a novel and different angle on looking the intersecting challenges than previous review studies.

## 2.2. Current Research Challenges in LCSA

### 2.2.1. The Integration of LCA and LCC

This section focuses on the integration of LCA and LCC, and addresses pinch points caused by their integration into LCSA.

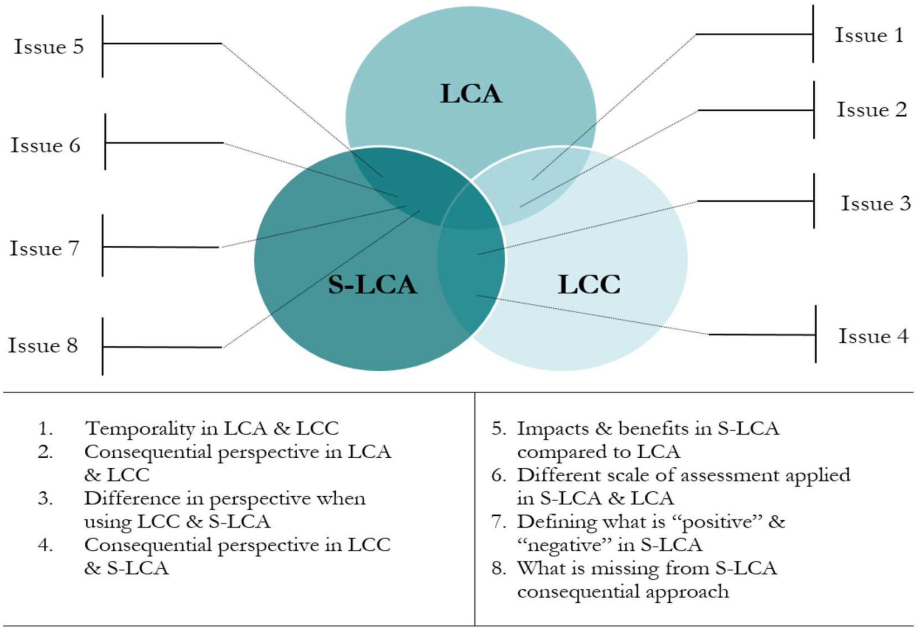



Figure 2.2. The methodology crossover research challenges identified in LCSA

#### *2.2.1.1. Temporality in LCA and LCC (Issue 1)*

The lack of temporality is an issue in the LCA methodology that has been increasingly discussed by the scientific community (Amor *et al.*, 2014; Mcmanus and Taylor, 2015; Montre, 2010; Yuan *et al.*, 2015; Zhai *et al.*, 2011). LCA, by origin, is a steady-state framework where the temporality of the life cycle impacts is not entirely integrated into the inventory analysis or the impact assessment (Amor *et al.*, 2014; Zhai *et al.*, 2011). For example, when the life cycle environmental impact of a 75-year old building is assessed, certain significant hypotheses are always applied, which suggest that the electricity composition used for the construction, the operational use, and the end-of-life stage of that building does not change over time, throughout its life cycle (Anand and Amor, 2017). In contrast, the temporal aspect of monetary value is embedded in LCC. With its monetary flow and the involvement of discounted monetary value, LCC is temporal by default. Hence, the cost assessment of a product system over the years should use the discounted rate to apply the temporal aspect of the changed monetary flow [23](Hunkeler *et al.*, 2008). This discrepancy may cause an issue in LCSA case studies when LCA and LCC are combined. For example, an LCSA of a building, by Ostermeyer *et al.* (Ostermeyer *et al.*, 2013), showed that the calculation used for the energy mix and the inventory data in their LCC study incorporated the discount rate for their cost flow. This meant that the future worth of a present sum of money, or a current stream of cash flow, was discounted at the considered discount rate across the given period. Ideally, this temporal integration should also be considered when dealing with current physical flows between the processes, as well as their emissions and resource use, from and to the environment. This is, however, not the case in standard LCA methodology, in which inventory results are aggregated values. By adding a temporal aspect to LCA, however, inventory results could be a function of time, where different characterization factors could consider a dynamic profile of the environmental impact.

Some effort has been made to identify the treatment of temporality in LCA and LCC, especially when a prospective change is assessed (Beloin-saint-pierre *et al.*, 2014; Field *et al.*, 2001; Shah and Ries, 2009). Heijungs *et al.* (Heijungs *et al.*, 2010) argued critically on this, noting that even when LCA and LCC have identical system boundaries, they have two different ways of extracting indicators, so that any inclusion of time in these two methods must be carefully done.

For now, the temporality issue in LCA remains an open discussion in the scientific community, and is deemed to be only slightly resolved, while in LCC, it has been well implemented.

#### *2.2.1.2. Consequential Perspective in LCA and LCC (Issue 2)*

Before discussing the consequential perspective in LCSA, it is worth recapping on the main differences between consequential and attributional LCA. First, they differ in the definition of the system boundary, which was originally based on the process influenced by market change. Later, it was called affected technology or marginal technology (Earles and Halog, 2011). However, a proper and consistently systematic method for determining a system boundary has not yet been established, despite the growing body of research applying and developing CLCA (Zamagni *et al.*, 2012).

Unlike CLCA, LCC (environmental LCC) with the consequential perspective is not explicitly mentioned in any literature. The notion of Consequential Life Cycle Costing (CLCC) was first mentioned in a UNEP/SETAC book on Environmental Life Cycle Costing (Hunkeler *et al.*, 2008). The authors argued that, for certain reasons, discussions over attributional or consequential LCA could be transferred to LCC, with a consequential approach called “LCC planning”, due to its focus on supporting decision making (Hunkeler *et al.*, 2008). Another application of the consequential approach within the life cycle method has also been found in a study estimating electricity pricing (Wood and Hertwich, 2013). However, the authors reported difficulties in finding the marginal costs necessary to apply CLCC. Another argument in favor of CLCC is that the consequential model is able to incorporate indirect market mechanisms and equilibrium analyses of the market, which are aspects that are highly meaningful to the context, and yet are frequently avoided in analysis (Wood and Hertwich, 2013).

In the broader context, Sala *et al.* (Sala *et al.*, 2013a) pointed out a general research gap regarding the consequential approach in sustainability assessment. They argued that the notion of market resolution (i.e., region, country, etc.) also needed to be accounted for in sustainability assessments. However, they did not define the characteristics of the consequential approach in sustainability assessment, or its distinction from an attributional approach. Further examples of applications using CLCA and CLCC need to be documented.

### 2.2.2. The Integration of LCC and S-LCA

Concerning the integration of LCC and S-LCA, this literature review focuses on two key points: The different perspectives of the stakeholders involved and the consequential perspectives when using S-LCA. These points are discussed in the following sections.

#### *2.2.2.1. Differences in Perspective when Using Both Methods (Issue 3)*

One of the most important issues in applying S-LCA, particularly when integrated with LCC, is related to the perspective of the assessment depending on the participants concerned, within a given system boundary. Most LCC case studies in the literature primarily focused on the effect on one participant, for example, only the costs for the producer were represented in the model, and these were thus regarded as negative impacts which needed to be minimized (Akhtar *et al.*, 2015; Martínez-Blanco *et al.*, 2014). For other participants, such as consumers or end-of-life managers, the perspective would be different. From an employee’s standpoint, for example, hourly wages can be considered as a positive impact as, generally, higher unit labor cost in the production process would mean more income to the labor force (Valdivia *et al.*, 2013). Most LCCs that are conducted within LCSA do not consider the importance of the participant perspective (Huang and Mauerhofer, 2016; Vinyes *et al.*, 2013). Moreover, most S-LCA studies are carried out from perspectives different to those of the LCC. For example, in some S-LCA studies, the social impacts are seen from the perspective of the consumer, but at the same time, the costs from the consumer's viewpoint, related to the same product, do not seem to be accounted for in the LCC. This lack of consistency in perspectives makes interpretation of S-LCA and LCC results alongside each other difficult.

As an example, an LCSA study of photovoltaic modules by Traverso *et al.* (Traverso *et al.*, 2012a) shows the difficulty of comparing economic and social impact. Whether a product is beneficial or detrimental is subject to interpretation, based on a stakeholder's perspective, since a benefit for a company might not necessarily be a benefit for society, the company's workers, or local communities. Lu *et al.* (Lu *et al.*, 2014) used different perspectives to account for the economic and social impacts of electronic waste recycling. In this study, most of the monetary value of the recycling process was quantified from the viewpoint of the recycling company as a leading participant, while on the other hand, they included the workers and the local community when looking at social aspects. In another instance, Menikpura *et al.* (Menikpura *et al.*, 2012) applied an LCSA to assess municipal solid waste management systems, again using different participant perspectives when applying LCC and S-LCA. The participant considered in the LCC was the waste management company, while the S-LCA focused on the local community. To make a combined LCC and S-LCA assessment comprehensible and holistic for law enforcement, and to support policy initiatives, the participants in question should be the same for both methods.

#### *2.2.2.2. Consequential Perspectives in LCC and S-LCA (Issue 4)*

In Section 2.1.2, the lack of a consequential approach in LCC was partly discussed. To bring a consequential LCC into an LCSA framework, two primary considerations were suggested by Wood and Hertwich (Wood and Hertwich, 2013), reflecting on the contradictions that LCC may have and the exclusion of some relevant indicators that LCC may exhibit. Firstly, the authors argued that consequential effects in LCC must be captured in the modeling framework of LCSA to be able to understand the full dimensions of economic sustainability, by involving more pertinent indicators to avoid double-counting, i.e., the added value to the economy, through parameters that are linked to it, such as import dependency, capital and labor, and potential innovation. These parameters are the indirect effects of the added value of goods in global trade. Otherwise, the economic dimension cannot be captured holistically in LCSA. Second, it was recommended that consequential LCC was undertaken on a macro-scale, and not merely at the product level. This was because there is an inherent contradiction in that from an individual user's perspective, life cycle cost should be minimized, while from society's perspective, the sum of the components of added value should generally be maximized. On this basis, the indicators used in LCC must be carefully chosen. In addition, attempts to estimate how added value will change as a consequence of different potential decisions are not captured yet in LCC. In particular, capturing the market effect and indirect consequences in the supply chain, with different what-if scenarios, will potentially increase the knowledge gained from it.

On the other hand, consequential S-LCA has the same status as consequential LCC. Jorgensen *et al.* (Jørgensen *et al.*, 2010) and Sousa-Zomer *et al.* (Sousa-zomer and Miguel, 2015) were the only publications that this review could identify which touched upon this issue. Jorgensen *et al.* (Jørgensen *et al.*, 2010) argued that there were three types of S-LCA, i.e., consequential, educative, and lead firm, based on the practicality of the model. Consequential S-LCA aims to see the consequences of a product decision in terms of the social wellbeing of the stakeholders, in such a way that S-LCA creates its effect by merely influencing certain production levels in companies (Jørgensen *et al.*, 2010). They argued that social impacts can also occur indirectly, through the absence of action, such as a decision not to implement a specific product life cycle. This is, to some extent, different to the consequential approach in LCA, which is more focused on the incorporation of market mechanisms into the estimation of indirect consequences in its assessment. How the consequential setting was proposed to be applied in S-LCA will be reviewed in greater detail in Section 2.3.4.

Concerning the application of LCSA, the integration of a consequential perspective in both S-LCA and LCC, however, has never been proposed in the literature—only the attributional approach has. In the publications which have been reviewed, there was no evidence that the consequential concept suggested by Jorgensen *et al.* was followed up with any applications.

### 2.2.3. The Integration of S-LCA and LCA

The application and methodology of LCA and S-LCA have reached different levels of maturity. The observed difficulties that need to be considered when integrating S-LCA and LCA in the LCSA framework are discussed in the following sub-sections.

#### *2.2.3.1. Impacts and Benefits in S-LCA Compared with LCA (Issue 5)*

There is a major difference on how we frame, and thus view, S-LCA and LCA. In the context of delivering the message, LCA is framed to assess the environmental impacts (or the negative impacts) of the resource inputs and outputs which occurred in a functioning product system (Clift, 2014). On the contrary, S-LCA inherently considers any social impacts, both negative and positive (Catherine Benoît and Mazijn, 2009).

In the discussion on the sustainability theme, the definition of Area of Protection (AoP) is a central focus, being a group of safeguard subjects that must be maintained for current and future generations (Schaubroeck, 2017). In S-LCA, it is suggested that wellbeing is not only to be protected, but in fact promoted, while this is not the case for how AoP is defined in LCA(Dreyer *et al.*, 2006). Sustainability assessments should be assessing both the positive and negative effects of society's activities, but, as argued, this is usually not reflected, and so the positive benefits of a product are underestimated (Hacking and Guthrie, 2008; Sala *et al.*, 2013b). The focus of LCA is on assessing environmental performance through negative environmental indicators, while for S-LCA it is on evaluating social performance through indicators for both negative and positive impacts, making interpretation of a product system more challenging. For example, when Quyen and Halog (Quyen and Halog, 2016) studied the LCA and S-LCA of rice husk-based bioelectricity, they elaborated on the difficulty of choosing the most sustainable option, due to blurred trade-offs between potential negative and positive impacts (benefits). In their summary of endpoint impacts, the potential positive impacts considered were the impacts on social wellbeing and prosperity, through the total hours of employment and of knowledge-intensive jobs. On the other hand, impacts on the environment, i.e., the loss of ecosystem biodiversity and disability-adjusted life years of human health, were regarded as potential negative impacts. The authors calculated the overall weighted summary of the results by subtracting the potential positive impacts from the potential negative impacts, by assuming that the potential positive impacts (benefits) were compensated for by the potential negative impacts.

Cihat *et al.* (Cihat *et al.*, 2016a)also faced this trade-off while assessing the sustainability of vehicle technologies for the United States. The conflicting goal existed in the context of considering the positive impacts of the products' social aspects, as well as negative impacts from the environmental perspective. The negative environmental impacts were primarily covered in the environmental assessment methods, such as LCA, but this did not account for the potential positive environmental impacts (i.e., benefits). The latter is considered when dealing with consequential LCA. It is suggested that life cycle methods should be extended to, and enlarged from, the priority of avoiding negative impacts, and also from the intensive promotion of positive impacts (benefits) in a way that supports sustainable development .

This idea of elaborating a more positive assessment by assessing environmental benefits (in addition to environmental impacts) has been initiated. A study by Norris (Norris, 2015) used the term "handprint", as opposed to "footprint", to quantify potential environmental benefits from a product or process. Steen and Palander (Steen and Palander, 2016), and Rugani (Rugani *et al.*, 2015) argued that this could be used as part of sustainability assessment. We conclude that both benefits and impacts could be part of the assessment, since improving sustainability performance is not merely a matter of reducing the risks of negative consequences, but also entails the promotion of positive benefits (Ekener *et al.*, 2018a; Rugani *et al.*, 2015; Steen and Palander, 2016).

#### *2.2.3.2. Different Scales of Assessment Applied (Issue 6)*

S-LCA data could be collected through site-specific assessment or desktop screening. However, when site-specific data are not available or accessible, the use of statistical data from databases may not reflect the real situation adequately (Traverso *et al.*, 2012b). This is because most available databases reflect the country or sector level, which is generally contrary to LCA, where various databases are available and have been developed at a process level. For S-LCA, databases are still in their developmental stage, and this creates an important obstacle for the application of LCSA to real-life case studies (Sala *et al.*, 2013b).

This issue of data availability was noted in an LCSA study of fertilizers (Martínez-Blanco *et al.*, 2014), and to cope with this difficulty, the authors collected data on three geographical scales: Country, sector, and company, for foreground processes. For background processes, only data on the sector scale were considered. They argued that country and sector data could be used as a baseline for company indicator selection, i.e., for the identification of hotspots. Consequently, the study at a company scale could then focus on these identified hotspots.

Another issue that needs to be considered in the integration of S-LCA and LCA is that not all the social indicators can be calculated as a function of the defined functional unit. A functional unit is a powerful reference to reflect the actual environmental performance of a product system (Heijungs and Sangwon, 2002) While this approach has been adopted by LCC (Heijungs *et al.*, 2013), S-LCA lacks this possibility, as it has both quantitative and qualitative indicators, and the latter cannot be tuned into the matrix formulation used for their calculation. It is also noted that, of the quantitative indicators, only a few could be assigned to functional units until now, for example, fair wages (Neugebauer *et al.*, 2017) and working hours (UNEP, 2011).

#### *2.2.3.3. Defining What is "Positive, or Right" and "Negative, or Wrong" in S-LCA Indicators (Issue 7)*

There is a distinctly different level of confidence in the methodologies between LCA and S-LCA. A problem for impact assessment in S-LCA, which does not exist in LCA, is the ambiguous interpretation of certain indicators. In LCA, we can distinguish what is right or good, and what is wrong or bad, based on the quantified environmental parameters which characterize the impacts. However, certain indicators in S-LCA are less clear-cut: For example, the low payment of workers. From a macro-perspective, as explained by Kloepffer (Kloepffer, 2008), cheap labor may be a significant advantage for developing countries, enabling them to survive in the global market, which means that cheap labor also provides job opportunities. But this macro-approach may not necessarily reflect the effects on the individual, and could be said to reflect more the short-term economic advantages of the individual worker, for instance, and then the conflict arises when one considers where the line lies between fair employment compensation and slavery .

Another example of the ambiguous valuation of indicators concerns the feedback mechanism. For example, consumer responses to a product could be seen to be reflected by their complaints

(Bo P. Weidema, 2006). However, a boycott of a specific product may not reflect the actual negative social performance related to its life cycle. For example, this social performance is not reflected in the case of Israeli products that have been boycotted by many countries due to the political situation with Palestine, or of Moroccan oranges because of the political situation in the Western Sahara. These examples reflect the influence of a conflict that is unrelated to the immediate life cycle of the product in question. Differing views on these site-specific circumstances make the assessment more difficult. Similar examples can be found in the broader context of bioenergy policy (Waldekker and Molnar, 2014). Questions arise, such as whether benefits stemming from jobs in sugar cane farming for bioenergy are positive enough for the local community, even if the industry might increase the dependency of the local economy to the global market price of sugar cane. In another example, is new job creation in a farm-based industry good or bad if it includes new occupational fatalities? These are examples of how valuations in some assessments become more challenging (Waldekker and Molnar, 2014).

Assessing social impacts is, furthermore, very context-specific and culturally dependent. Certain indicators are highly dependent on the location of the social impact. For example, absence from work can have different implications when applied to different economic or social situations . If absentee rates are low, generally we can make a judgment that this indicates a good thing. However, if it is applied to a highly competitive labor market, where unwell people would go to work rather than to stay at home because they are afraid to lose their jobs, then it would indicate the opposite. Another problematic trade-off on how to evaluate potential positive impacts is what smartphones could bring to (especially) younger generations in certain regions, as opposed to the negative effects linked to the increased stress levels they may cause (Waldekker and Molnar, 2014).

For LCA, the set of environmental indicators is well accepted by the LCA community. However, definitive targets for social performance in S-LCA are not generally agreed upon (Martínez-Blanco *et al.*, 2014). The analysis made by Finkbeiner *et al.* (Finkbeiner *et al.*, 2010) of 150 different societal objectives and indicators proposed in the scientific literature showed that many topics were not coherently addressed, and that a practical methodology for social indicators cannot be directly derived for products or processes, or if they can, only a few indicators could be directly assigned to products or processes. The majority of social indicators quantify the level to which societal objectives in certain areas of life can be attained, yet they are not easily quantifiable (Halog and Manik, 2011).

#### *2.2.3.4. What is Missing from the S-LCA Consequential Approach (Issue 8)*

While increasingly used, S-LCA methodology is not yet irredeemably fixed (Iofrida, 2017; Traverso, 2017). The application of S-LCA is increasing, in both academia and the industry (Arcese *et al.*, 2016; Wu *et al.*, 2014a). However, it has not yet incorporated a consequential approach. If CLCA aims to see the consequences of a decision on the environment, consequential S-LCA, or "C-S-LCA", is deemed capable of assessing the consequences of a decision, but not on the wellbeing of society, or in other words, on the social situation of the stakeholders involved in the product life cycle.

A suggestion was proposed for S-LCA to include quantification of the potential shifts or changes of social impacts (Jørgensen *et al.*, 2010; Macombe *et al.*, 2013a; Parent *et al.*, 2013). In essence, this could involve assessments of shifts in behaviors, affecting stakeholders' social conditions as the life cycle progresses towards a future (or prospective) setting (Parent *et al.*, 2013). Efforts to capture the interdependencies of social effects in the behaviors of the stakeholders are essential, yet difficult to conduct. Certain social effects are unpredictable over time, and social indicators are mostly unrelated to the product chain. Regarding the latter, some efforts have been made in relating social indicators to social impacts in the product system, through the impact assessment step.

When looking at the impact assessment step specified in the guideline published by UNEP/SETAC, two S-LCA impact categories were proposed, based on the two different treatments of the results for subcategories (Catherine Benoît and Mazijn, 2009; Macombe *et al.*, 2013a). Type 1 handled the resulting subcategories by aggregating them into similar topics, for which stakeholders could gain a better insight using performance reference points, while type 2 handled the resulting subcategories by incorporating causal interconnections of the social impact pathways to midpoint and end-point indicators, using a characterization factor (Catherine Benoît and Mazijn, 2009; Macombe *et al.*, 2013a).

## 2.3. Discussion

LCSA is an assessment method integrating LCA, LCC, and S-LCA. Before regarding the method as settled, however, there are some research gaps which we consider to have not yet been satisfactorily bridged across each pair of methods, and thus need more attention. Looking at the integration of the three methods into LCSA, using various case studies, the identified cross-method challenges have been presented, along with directions for future research (Table 2.1).

Table 0.1. Summary of the research challenges and opportunities associated with the integration of Life Cycle Assessment (LCA), Life Cycle Costing (LCC), and Social Life Cycle Assessment (S-LCA), within the LCSA framework.

| Focus area | Research challenges | Research opportunities |
|---|---|---|
| Integration of LCA and LCC | Temporal issue that is still missing in LCA | Developing a mechanism to discount the environmental (resource- and emission-) flow for comparison purposes and integrate them with discounted monetary value |
| | Consequential perspective in LCA and LCC | Identification on the consequences and indirect impact in the intersection of LCA and LCC |
| Integration of LCC and S-LCA | Different in perspective when using both methods | Proposal to exemplify economic and social assessment by incorporating various perspectives from different stakeholders |
| | Consequential perspective in LCC and S-LCA | Proposal to define and draw step-wise procedure for capturing consequential approach in LCC |
| | | Formulation of new and more relevant economic indicators (i.e. value-adding, capital and labor, import and export, taxes, etc.) that are more suitable for consequential method in LCC |
| Integration of S-LCA and LCA | The presence of impact and benefit in S-LCA as compared to LCA | Developing more positive indicators as a progressive way to positively |

| | | |
|---|---|---|
| | | promote sustainability especially in LCA |
| | | Formulation of “area of promotion” for positive indicators, as opposed to “area of protection” for both LCA and S-LCA |
| | Different scale of assessment applied in both methods | Proposal to develop code of conduct to apply LCSA in different layers of analysis, from product, sector, and country |
| | Unclear definition on what is good or bad in certain S-LCA indicators | Developing the guideline to make social indicators more applicable and definitive |
| | | Proposal for a new consensus or agreement for unclear social goals (or targets) in the regional or international context |
| | Missing of consequential approach in S-LCA | Incorporating the environmental and social consequences on the unit processes |
| | | Proposal to scheme of coherence system boundary in S-LCA and LCA by capturing beyond physical flow in the product/service but also corresponding interdependences flow of social impact in the product chain |

### 2.3.1. Filling the Gaps

The challenges identified need efforts directed towards their resolution. For the temporality issue (Issue 1), some progress has been made in its clarification, with the treatment of time in LCA addressed in recent studies, highlighting dynamic life cycle inventory (Kono *et al.*, 2017) and the characterization factor (Su *et al.*, 2017). More emerging approaches are under ongoing development within the LCA community (Cardellini *et al.*, 2018; Shimako *et al.*, 2018), and are ready to make progress. Having cost assessment that can be conducted by using different perspective (consumer, producer, etc.), similar issue with S-LCA (Issue 3) is expected. Some authors have realized this importance (Moreau and Weidema, 2015; Wood and Hertwich, 2013), noting that points of view from different stakeholders will give more meaningful platforms from which to approach sustainability-related issues and their decision making. Additional attempts at addressing this issue are necessary for better harmonization, using, as an example, the benefits of assessing the costs of a product from two or more perspectives.

In S-LCA, some approaches have been attempted to enhance positive assessment (Issue 5) in further studies, for example, by defining what are positive impacts (Indrane *et al.*, 2018), how to quantify them (Ekener *et al.*, 2018b), and even how to achieve net positive impacts (Benoit Norris *et al.*, 2018). This idea of focusing on positivism in sustainability is supported by other review studies (Sala *et al.*, 2013a, 2013b). How available databases reflect different scales of assessment (Issue 6) has been further addressed by some authors, by regionalizing the scope of assessment, be it in an LCA at the inventory level (Yang, 2016b), impact assessment level (Loiseau *et al.*, 2018), or S-LCA (Siebert *et al.*, 2018), and has also been confirmed by a recent review article (Martin *et al.*, 2018). In a recent LCA forum (Frischknecht *et al.*, 2019), during a discussion on regionalizing LCA, it was suggested that LCA practitioners should be more focused on rectifying spatially explicit datasets in order to have more reliable and accurate results. We hope such discussion will start for S-LCA databases as well in the future. Lastly, proposals for consensus on defining social goals are needed in regards to unclear definitions of what is good and bad in certain indicators (Issue 7), to help facilitate objectivity in the assessment.

### 2.3.2. Research Opportunities of Consequential Approaches in LCSA

Most research to date has focused on hotspot analyses of the sustainability performance of a product. During review of 114 published studies related to LCSA (see Annex A) consequential approaches being used. To formulate the consequences of environmental flow or of socio-economic value changes over the appointed decision made, more causal assessment is needed. This causal assessment should identify and capture direct and indirect impacts, evaluate the sustainability performance of a product system from an identical perspective, and provide feedback about what has been achieved. Causal assessment plays a vital role in the evaluation of the three sustainability pillars, as it allows us to scope out possible future developments and alternative actions. Furthermore, based on the SDGs, we believe that socio-economic factors and environmental concerns are the foci of stakeholder attention. That is, strategies such as how to alleviate poverty and how to reduce inequality have become global concerns among decision makers. However, are we ready for consequential LCSA? This question and possible answer needs further investigation.

## 2.4. Conclusions

The identified gaps show that the harmonization of the three discussed methods (LCA, LCC, and S-LCA) within LCSA is urgently required. Further formulation of technical recommendations to conduct LCSA is desirable. We suggest further research should be focused on these technical gaps in the intersecting challenges.

Second, when applying LCSA in a policy context, we suggested that the framework needs a consequential perspective to facilitate capturing not only direct impacts but also indirect consequences. Even though the consequential LCA is not standardized and bridging the gaps in LCSA is still very much a challenge, a stepping stone to paving the road of methodological and technical development of consequential LCSA should be placed first, reflecting how sophisticated the sustainability issue is.

Third, more application of case studies is recommended as lessons learned when integrating LCA, LCC, and S-LCA, for a deeper understanding of methodological trade-offs that may happen between the three methods of sustainability assessment, especially for the causal decision. This is important since the prospective policies made by stakeholders must contribute equally to the three bottom-lines of sustainability or, at least, avoid a biased decision that is, for example, economically viable, but environmentally and socially questionable.

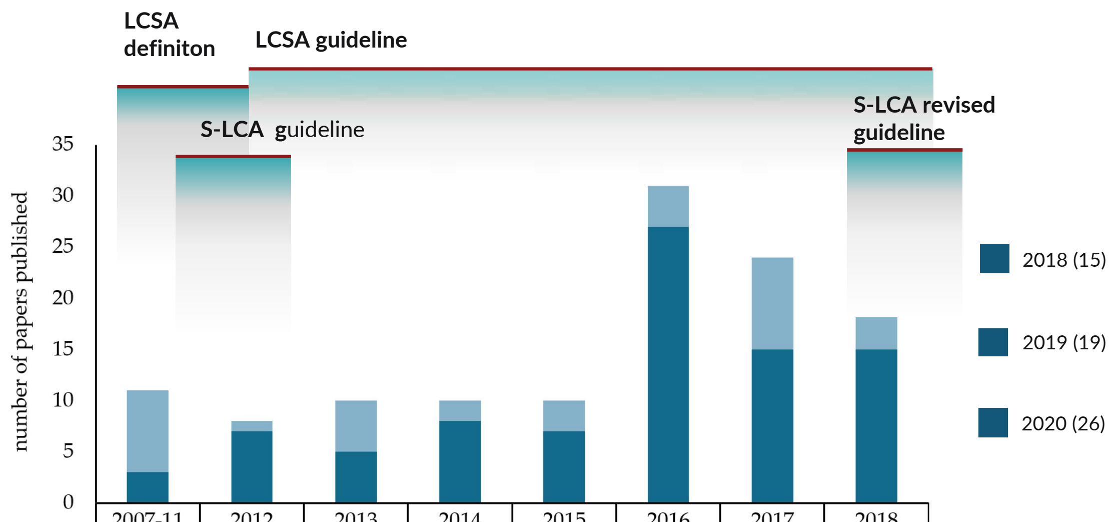
At the end, we alert that applying the suggested solutions on the research gaps (the research opportunities) on subsequent studies can come at the price of the increase of the time required due to the large amount of collected data. Further, it can possibly also increase the uncertainty that has to be anticipated because of possible simplification over trying to reach completeness of the study.

# Chapter 3 - Literature Review of LCSA (Revisited)

This chapter will update a literature review that was conducted few years ago up to 2018 and may be out of date. By revisiting the latest developments in LCSA research in the scientific community, this chapter discusses what is new and what needs to be considered within this research project.
This chapter is divided into two subsections. The first is an update on the literature review of LCSA studies in general, and the second is an update on the research prospects that arise from revisiting the scientific community's knowledge development. The former is more concerned with the general bibliography and meta-analysis of the papers discovered, whereas the latter is more concerned with the new research gap discovered and the new opportunity that follows.

## 3.1. Update of the Literature Review

The literature review presented in the previous chapter includes studies up to 2018. Afterwards research on LCSA intensified even more in various sectors. This is illustrated by a considerable increase in the number published peer-reviewed journal papers in recent years (Alejandrino *et al.*, 2021a). In this section an update will be presented focusing on recent research output (i.e., after 2018). The main objective is not to present a comprehensive literature review for this period, but to (1) assess to what extent previous observations are still valid and (2) to identify new research trends. In addition, given the general research questions of this project, special attention will be paid to studies that focus on the development of the consequential modelling approach.




| | 2007-11 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 |
|---|---|---|---|---|---|---|---|---|
| non-case study | 8 | 1 | 5 | 2 | 3 | 4 | 9 | 5 |
| case study | 3 | 7 | 5 | 8 | 7 | 27 | 15 | 15 |

year

Figure 3.1. Temporal evolution of case studies by sector (Alejandrino *et al.*, 2021a)

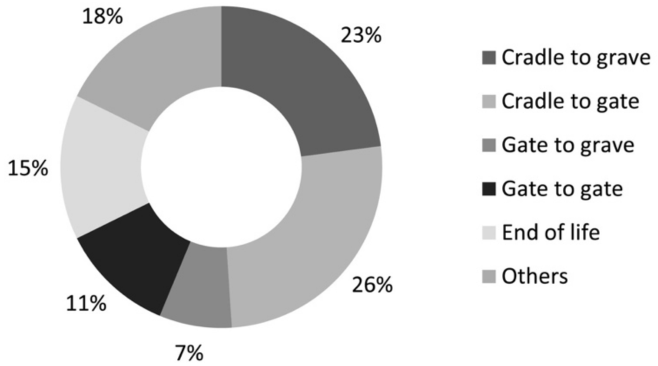



Figure 3.2. System boundary (Alejandrino *et al.*, 2021a)

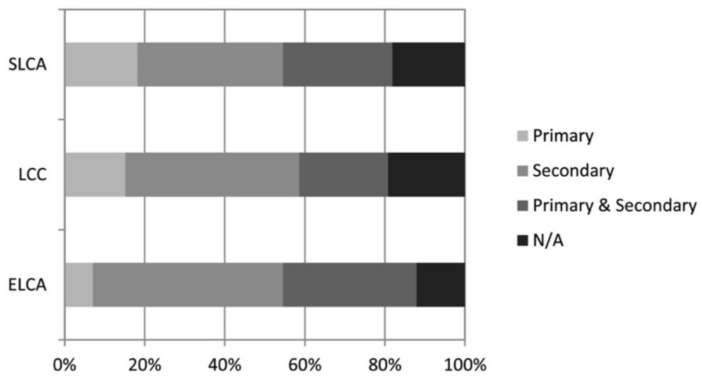



Figure 3.3. Data collection sources (Alejandrino *et al.*, 2021a)

Following 2018, LCSA publications have placed a strong emphasis on applications in a variety of areas, as illustrated in Figure 3.1. Due to the difficulties of obtaining data, the system boundary is often gate to gate. However, as illustrated in figure 3.2, cradle to gate and cradle to grave are becoming more popular. Additionally, data collecting is carried out at several levels of detail. The majority of LCSA research used secondary data, with LCA and LCC relying on primary data the least, as illustrated in Figure 3.3.

***S-LCA***

*General Revision of S-LCA guideline 2020*

According to the findings of a recent literature review, the S-LCA guideline has been revised to incorporate additional detail regarding data collecting. The new recommendations provide three alternative approaches to data collection prioritization (Achten *et al.*, 2020):

- The first strategy to prioritizing data collection is to ask if the literature assessment of the examined system identifies any critical social issues that should not be overlooked during the S-LCA process.
- A second way to prioritizing data collection is to determine which activities/unit processes in the examined system are the most active or intensive, for example, based on an activity variable.
- A third way to prioritizing data is by identifying the hotspots in the product's life cycle and how they might be avoided (Achten *et al.*, 2020).

*Children as new stakeholder*

The new guideline now includes children as a stakeholder (Achten *et al.*, 2020). Numerous additional indicators have been added, including education supplied in the local community, health problems faced by consumers' children, and children's concerns about marketing practices.

Children are introduced as a stakeholder group to represent the future generation since quantifying the social dimension of sustainability requires guaranteeing that the future generation enjoys the same degree of welfare and well-being as the current generation.

*The addition of new indicators*

There are three additional indicators for the worker stakeholder: the employment relationship, sexual harassment, and smallholders, which includes farmers, among others (Achten *et al.*, 2020). It was decided to integrate two new components in society: ethical treatment of animals and poverty reduction. There is only one addition to the category of "value chain actor," and it is focused on wealth distribution.

*Methodological Sheet of S-LCA guideline 2021*

Forty Methodological Sheets are provided and classified according to six stakeholder groups: employees, local communities, value chain players, consumers, society, and children (Traverso *et al.*, 2021). The Methodological Sheets define and contextualize each effect subcategory, establishing a link to the Sustainable Development Goals by specifying which target they can contribute to, defining generic and specific indicators, and offering examples of sources for collecting both types of indicators.

The sheets were created with the understanding that data collecting is the most time-consuming aspect of doing a social life cycle assessment (Traverso *et al.*, 2021). As a result, different indicators may be utilized based on the data available and the study's objective and scope.

***LCA and LCC***

In terms of LCA and LCC, little new information can be discussed here. The development of LCA has been centred on LCA as a standalone tool rather than as a component of the LCSA framework. While the update for LCC focuses on its utilization in conjunction with tools other than LCSA, such as BIM (Building Information Modeling) and TEA (Techno-Economic Assessment) (Alejandrino *et al.*, 2021b; Lu *et al.*, 2021; Mytilinou and Kolios, 2019).

## 3.2. Update of the Research Opportunity

### 3.2.1. Consequential Approach

When compared to our previous work on critical literature review, the current state of the application of the consequential approach in three tools within the LCSA framework presents no advancement. Similar small number of LCC and S-LCA studies are carried out using a consequential approach (Fauzi *et al.*, 2019). Even now, there is a significant gap in knowledge and a subject for further research and discussion.

### 3.2.2. Temporality Issue in LCA

This issue has been discussed by many studies through dynamic LCA (Levasseur *et al.,* 2010; Sohn *et al.*, 2020), especially in building (Su *et al.*, 2021). However, this can be further explored by integrating dynamic LCA with dynamic LCC that has never been performed in any study. Function of time in LCC is well documented while in LCA it remains an open discussion in the scientific community and is deemed to be only slightly resolved.

One step forward that can be explored is the possibility of creating dynamic databases that include dynamic inventory and impact assessment.

### 3.2.3. Impact and Benefit in S-LCA

When compensating for negative and positive impacts within a pillar or between the three pillars, it is a challenging task thus it needs a careful attention. Using this principle, it is possible to avoid misinterpretation. Therefore, at the very least, it is recommended to present negative and positive impacts separately, and, if weighting principles are used, reporting them transparently is needed. Consideration of the product's utility outside of the functional unit is essential (co-benefits). The challenge of this type of impact-benefit or negative-positive compensation and misinterpretation still exist and still be an open research opportunity.

### 3.2.4. Different Scale of Assessment in S-LCA and LCA

This point remains a challenge for the application of LCSA or S-LCA studies. All the assessment of LCA focuses on the unit process level while for S-LCA it can be in different multiple levels. To have comprehensive assessment, S-LCA should be performed with on-site assessment throughout its life cycle. However, with given long supply chain of products, S-LCA practitioners rely on databases that often lack of details with its aggregated data. Thus, this challenge still applies and lead to difficulty in the interpretation of the result. Having a picture of the social impact through entire life cycle is important but if the picture is too generic it will not give much overview of the result. This is still a call for further research area.

### 3.2.5. Refinement of What Is Positive and Negative in S-LCA

For some indicators, what is positive and negative in S-LCA or LCSA may be still blurred. This can be done through making clearer the area of protection and promotion in LCSA. Understanding of the areas of protection and impact pathways including the cause-effect mechanisms connecting inventory results to mid- and endpoints of an area of protection (AoP) is important. If cause-effect chains and mechanisms are not sufficiently known nor advanced for implementing an LCSA, it is recommended to indicate the shortcomings which should be further enhanced by methods developers. If available, mid- and endpoint indicators shall be identified. These challenges need a further research.

### 3.2.6. Consensus Building and Dialogue Are Needed

In recent years, consensus building and dialogue have been made in the LCA or LCSA community focusing on multiple parts and this must be often carried out. First, dialogue on what is needed to enhance the application of LCSA and the three tools inside. Second, how to communicate the LCSA result in a way that is easy to understand still needs improvement.

# Chapter 4 - Problem Statement and Project Definition

## 4.1. Problem Statement and Research Questions

The importance of considering a consequential perspective was prompted by the critical review. Critical review of the LCSA studies showed that when applying LCSA in a policy context, a consequential approach is needed to facilitate capturing not only direct impacts but also indirect consequences. Recapping on what has been discussed in the context section, the purpose of this research project is to develop and model consequential LCSA with the case study on hybrid multistory building. The account of consequential approach is for assessing the direct and indirect impact and benefit in ecological, economic and social aspect for facilitating future decision-making and policy.

One main question is identified following the problem statement. The main question is as follows *how can a consequential LCSA help assess the environmental, economic and social sustainability more comprehensively?*

## 4.2. Research Objectives

The main objective of the Ph.D. research project is *to develop an integrated method to assess the direct and indirect consequences in environmental, economic and societal aspect using consequential LCSA framework*. The developed method is applied to a wood multi-storey building in Quebec as a case study.

The sub-objectives are:

1. *To assess the environmental consequences* resulting from constructing more hybrid multistory buildings from cradle to grave.

   This sub-objective is aimed to answer research gap on the missing of consequential approach on LCA when it is combined with LCC or S-LCA.

2. *To assess the economic consequences* from constructing more hybrid multistory buildings from cradle to grave.

   This sub-objective is also aimed to answer research gap on lack of consequential approach on LCC.

3. *To assess the social consequences* from constructing more hybrid multistory buildings.

   This sub-objective is aimed to answer the gap on the different level of assessment in S-LCA, and lack of consequential approach in S-LCA.

# Chapter 5 - Life Cycle Assessment and Life Cycle Costing of Multistorey Building: Attributional and Consequential Perspectives

Avant-propos

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Date d'acceptation : 22 March 2021
État de l'acceptation : *Accepted and published*

Référence : Fauzi, R.T.; Lavoie, P.; Tanguy, A..; Amor, B. Life cycle assessment and life cycle costing of multistorey building: Attributional and consequential perspectives. Building and Environment 2021, 197, 107836. https://doi.org/10.1016/j.buildenv.2021.107836

Titre en français : Analyse environnementale et du cout du cycle de vie d'un bâtiment multiétages : perspectives attributionnelle et conséquentielle

Contribution au document: Cet article contribue à répondre au premier et deuxième objectif de du projet de recherche sur l'évaluation environnementale et économique.

Abstract

Buildings are accountable for much of the resource consumption and CO2 emissions generated from human activities. Nonetheless, the focus of building life cycle assessment (LCA) studies to evaluate the environmental footprint are more commonly adopted in an attributional approach. Nevertheless, understanding a direct and indirect consequences in larger system using consequential approach is also needed for policy-making. Rather small body of existing literature has been found on the implementation of consequential LCA and life cycle costing (LCC) in the building sector. In this study, attributional and consequential approach are performed for hybrid wood multistorey building. The results showed that with attributional approach, the phase that contributed the environmental impacts the most in climate change category is the production phase yet it became the use phase if consequential approach is used. By performing consequential LCA-LCC the possible hidden impacts can be uncovered and

sufficient insights into the indirect impacts can be seen, thereby offering stakeholders the opportunity to avoid such future consequences.

## 5.1. Introduction

The construction sector is the largest polluter in the global economy, representing 23% of the CO2 emissions worldwide and being a dominant resource consumer (Huang *et al.*, 2018; OECD, 2019). It is therefore a keystone for climate change and environmental mitigation (Anand and Amor, 2017; Basbagill *et al.*, 2013; Buyle *et al.*, 2013; Cabeza *et al.*, 2014). A comprehensive assessment to meet mitigation targets is needed, and a life cycle approach is an appropriate framework to measure outputs by considering the environmental and economic impacts of a product or system in their whole life cycle [5,7](Anand and Amor, 2017; Nwodo and Anumba, 2019).

The most widely applied life cycle method is life cycle assessment (LCA), which assesses the potential environmental impacts over the life cycle of a product and its sub-systems (ISO 14040, 2006; ISO 14044, 2006). The most common approach to LCA is attributional, also called ALCA, which is useful when one aims to establish the environmental profile of a system and/or identify its hotspots (Earles and Halog, 2011; Weidema, 2003; Zamagni *et al.*, 2012). For example, in the case of the construction sector, the attributional approach is relevant when a company aims to mitigate and communicate the environmental impact of material products through specific strategies such as environmental product declarations (EPDs), reduction of greenhouse gas (GHG) pollution or eco-design. In recent years, consequential LCA (CLCA) has come to the fore in LCA research to respond different key question that is not addressed by ALCA. Indeed, while ALCA is a snapshot of a system's environmental profile at a certain point in time, CLCA accounts for indirect effects of market adjustments due to decisions to implement the studied system at a large scale. As such, a consequential perspective is more relevant when one aims to assess the environmental impact of future policies, by taking into account the economic cause-and-effect chains arising from changing production systems. For the construction sector, this could be the implementation of new material products or construction systems throughout the country (Bamber *et al.*, 2020; Frischknecht *et al.*, 2017; Lotteau *et al.*, 2015).

Because of their complementary perspectives, several authors argued for the necessity of both approaches (Brander *et al.*, 2019; Weidema *et al.*, 2019, 2018) For example, Brander *et al.* (2019) (Brander *et al.*, 2019) suggested to couple ALCA and CLCA in a two-steps assessment. The first step was to use ALCA to identify key impact categories and specify reduction targets while the second step involved CLCA to check the environmental consequences of meeting these targets at a bigger scale. Moreover, they warned of mixing attributional and consequential modelling in a single step that could result in "misleading interpretations" (Brander *et al.*, 2019). Other authors investigated the differences in the results obtained with both approaches for the same case study in order to better understand the implications of choosing one type of modelling for practitioners (Buyle, 2018). Buyle *et al.* (2018) (Buyle, 2018) compared different scenarios of a Belgian dwelling using ALCA and CLCA and showed different rankings depending on the chosen approach. For the construction sector, this conclusion stresses even more that a careful justification of choosing ALCA or CLCA is needed depending on the objectives of the study. Moreover, this paper also fills the limitation in the scientific literature on how to carry out consequential economic life cycle costing. The case study in this paper also sheds more light on the modeling performance of LCA and LCC applied in hybrid multistory building with both approaches. It also provides additional information on the implications of choosing consequential and attributional LCA/LCC for Canadian buildings.

In the economic side, life cycle thinking has also been adopted to accompany LCA study though life cycle costing (LCC). However, the consequential approach applied in LCC is still lacking. In the same line than the study done by Buyle (Buyle, 2018) and Dara *et al.* (Dara *et al.*, 2019), this paper aims to compare ACLA and CLCA to further demonstrate the added value of both approaches on the case study of a hybrid composite buildings. The additional contribution of this paper is to provide consistent attributional and consequential framework to perform environmental (LCA) and economic LCC assessments altogether, which is currently a gap in the literature to the author's knowledge, especially in the consequential LCC side. There is a crucial need to develop and illustrate the consequential approach for buildings since this perspective is useful when large-scale decisions have to be made like for urban planning policies. Since the attributional approach is the most common option, this study aims to further emphasize the differences in methods, outcomes and relevance for this sector in the case of one building.

The paper is structured as follows. In the next section, the methodology used to perform LCA and LCC according to the attributional and consequential approaches is described. The third section presents the results and discussion of comparing both approach for a hybrid wood multistory building. Finally, the conclusion and outlook from this study are presented in the fourth section.

## 5.2. Methodology

### 5.2.1. Life Cycle Assessment

ISO 14040 defines LCA methodological framework in four iterative phases starting with goal and scope definition, inventory analysis, the impact assessment and the interpretation (ISO 14040, 2006; ISO 14044, 2006). In the goal and scope definition, the LCA aim and the product system studied are defined and elaborated. Inventory analysis involves the entire input and output data of the entire elementary process of each unit process that are collected and compiled as resource extractions and emissions list associated to the functional unit. The third phase, impact assessment, is aiming at interpreting the environmental burdens from the inventory tables into environmental impacts such as global warming, acidification, ozone depletion, etc. The last phase, interpretation is the final step in LCA.

The differences between CLCA and ALCA in terms of inventory modeling are summarized in the following sections. In CLCA, the technological flows registered as inputs are related to marginal technologies. These technologies are able to respond to a change in demand through a change in supply, by either allowing this change to be manifested in the operational margin (i.e., short-term supplier) or through a production capacity change (i.e., long-term supplier). In other words, they are technologies that are affected by the market demand and are predicted to supply the future market. Another methodological aspect of CLCA is in the handling of multioutput processes and end of life scenarios. Allocation is always avoided in favor of the system expansion method (ISO 14040, 2006; ISO 14044, 2006). Indeed, the system in CLCA must be fully expanded to cover all affected processes driven by the decision. This will result in the inclusion of indirect consequences in addition to directly and physically connected flows. The inclusion of indirect consequences is essential because they can be as important as the physically connected flows, thus neutralizing or counterbalancing potential impacts in the case of negative feedback or exacerbating a problem when positive feedback occurs , (Curran *et al.*, 2005; Ekvall and Weidema, 2004).

To apply the marginal technology, it is mandated to use marginal data that reflects marginal environmental burden affected by the technology (Ekvall, 2020). In ALCA, average overall burden is calculated and represented by current average data used from national or regional level or called average technologies. Fig. 1 illustrates how average and marginal technologies are considered in attributional and consequential approaches respectively. Unit process in consequential approach mainly allow the marginal technologies that are going to supply the demand while in attributional approach they are from average technologies.

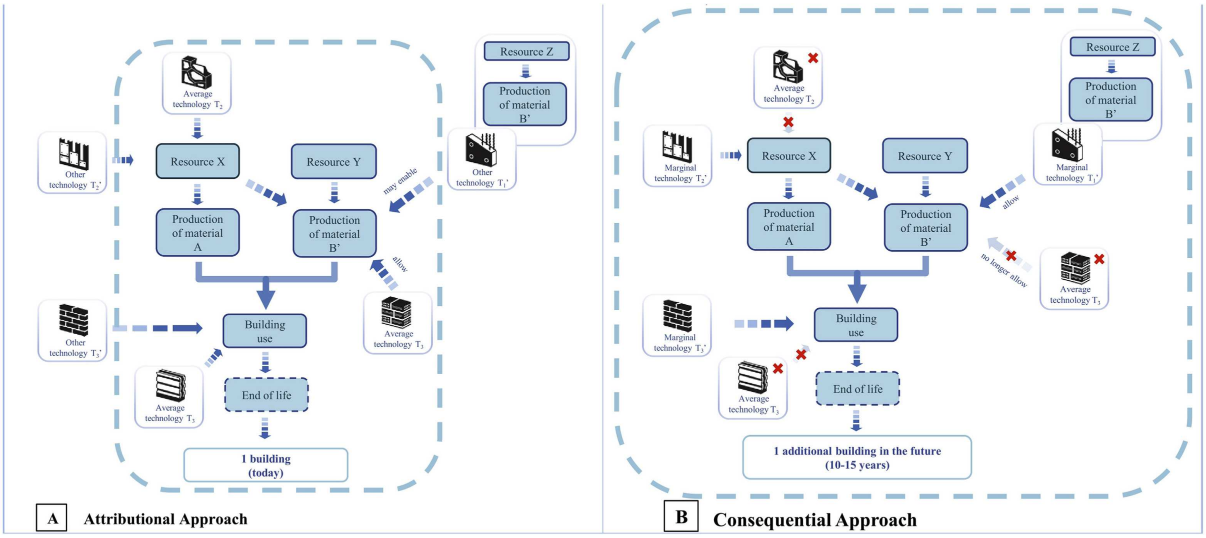


Figure 5.1. Illustration of scope analysis

Many different methods are available to identify the marginal technology depending on data availability, starting from complex models such as partial and general equilibrium model (Earles *et al.*, 2013), rectangular choice-of-technology model (Duchin and Levine, 2011), trade network analysis (Pizzol and Scotti, 2017), causal descriptive models (de Rosa *et al.*, 2016), gent modeling (Florent and Enrico, 2015), game theory (Alfaro *et al.*, 2010) and experience curves (Sandén and Karlström, 2007)(see Table 1). A variety of simpler techniques are also implemented by conducting statistical analyses on national trade data or market projections, relying on literature review, expert judgment (Brando *et al.*, 2017) or on the five-step procedure developed by (Weidema, 2003). By relying on the limited available data from regional and national statistics and reports, the five-step procedure is adopted in this case study.

Table 5.1. Summary of techniques to identify marginal technology

| Technique | Description |
|---|---|
| The partial and general equilibrium models (Earles *et al.*, 2013) | The models can capture the potential effects of policy decisions on supply, demand, price, and resulting product production for one or more economic markets (Earles *et al.*, 2013). |
| rectangular choice-of-technology model (Duchin and Levine, 2011) | It is a linear programming input–output model for analysis of the economy of a single region and of simultaneous, interdependent choices in multiple regions (Duchin and Levine, 2011). |
| trade network analysis (Pizzol and Scotti, 2017) | a trade network analysis is used for identifying clusters of countries historically linked in more intense exchanges of products with a regression analysis of historical production trends for product types across countries that ease marginal technology identification under the geographical constraints (Pizzol and Scotti, 2017). |
| causal descriptive models (de Rosa *et al.*, 2016) | causal descriptive models illustrate future condition of a system based on cause–effect relationships from a combination of biological and physical land characteristics, own and cross-price elasticities, statistical data, etc (de Rosa *et al.*, 2016). |
| agent based modeling (AGM) (Florent and Enrico, 2015) | AGM is a model from a collection of autonomous decision-making entities called agents. Each agent can evaluate its situation and makes decisions on the basis of a set of rules (Florent and Enrico, 2015). |
| game theory (Alfaro *et al.*, 2010) | Game theory (GT) is the study of human interaction formulated from an economic point of view that predicts presents situations as a game where several players take part and choose actions from a given set of strategies. Each strategy has an associated payoff or utility with the objective is to maximize his or her own utility by each player. In LCA, this represents stakeholder interest (Alfaro *et al.*, 2010). |
| experience curves (Sandén and Karlström, 2007) | This tool is used for estimating learning curve of a technology from empirical relationship between cumulative production and unit cost that has been observed for a number of technologies (Sandén and Karlström, 2007). |

CLCA follows causation logic where it interlinks activities that are not necessarily linked. Physical elements or value is added within the product system rather than activities that are consequently expected to change due to a product demand increase or decrease. In ALCA, only activities that intrinsically contribute to linking physical elements and adding value to a product system are considered. The mechanism logic is rather static in attributing value, mass or other allocated physical properties (Guinée *et al.*, 2018; Jeroen B. Guinee; *et al.*, 2011).

#### *5.2.1.1. LCA Goal and Scope*

The goal of this study is to determine the environmental impacts of constructing hybrid wood buildings. The function of the studied system is defined as follows: providing habitable floor area for residential use within the expected life span of 60 years and protecting its users and objects against harmful effects of external factors during that period. The product system of the study is the structure and envelope of the hybrid wood multistory building. This product system is selected because the focus of the study is to better understand the environmental impact of utilizing wood in high-rise buildings. Thus, the choice is limited to only the main building structure and envelope. The construction phase is not included neither the building exterior, interior parts and the transportation that is already included in material production phase. However, assumptions on the electrical and mechanical work during residential period (here electricity consumption) will be made and presented in subsequent sections. Considering the function stated above, the functional unit is defined as a 10,341.2 m2 habitable floor area in both attributional and consequential approaches. It is an eight-story hybrid wood-concrete structure with mix use (the first floor is for commercial and the rest is for residential purpose). Thus, it is appropriate to assume that the building is mostly used for residential purpose. The building consists of seven key building materials: wood, concrete, steel, gravel, aluminum, gypsum, and brick. Based on information from construction sites, these materials represent the major components by mass and size (see Table 2).

Table 5.2. Material composition of hybrid multistorey building

| Material | % by volume | % by mass |
|---|---|---|
| Wood | 23.27 | 2.53 |
| Concrete | 14.55 | 18.69 |
| Steel | 10.31 | 48.95 |
| Gravel | 8.47 | 5.60 |
| Gypsum | 17.82 | 6.59 |
| Aluminium | 4.28 | 4.55 |
| Brick | 6.76 | 1.33 |
| Others | 14.53 | 11.75 |

##### 5.2.1.1.1. Attributional LCA

Using the attributional approach, the aim is to determine what environmental impact can be attributed to a hybrid wood multistory building. In the attributional modeling, the cut-off approach is used, which means that impacts of the end of life phase are allocated to the life cycle that uses the recovered materials (see Fig. 2A).

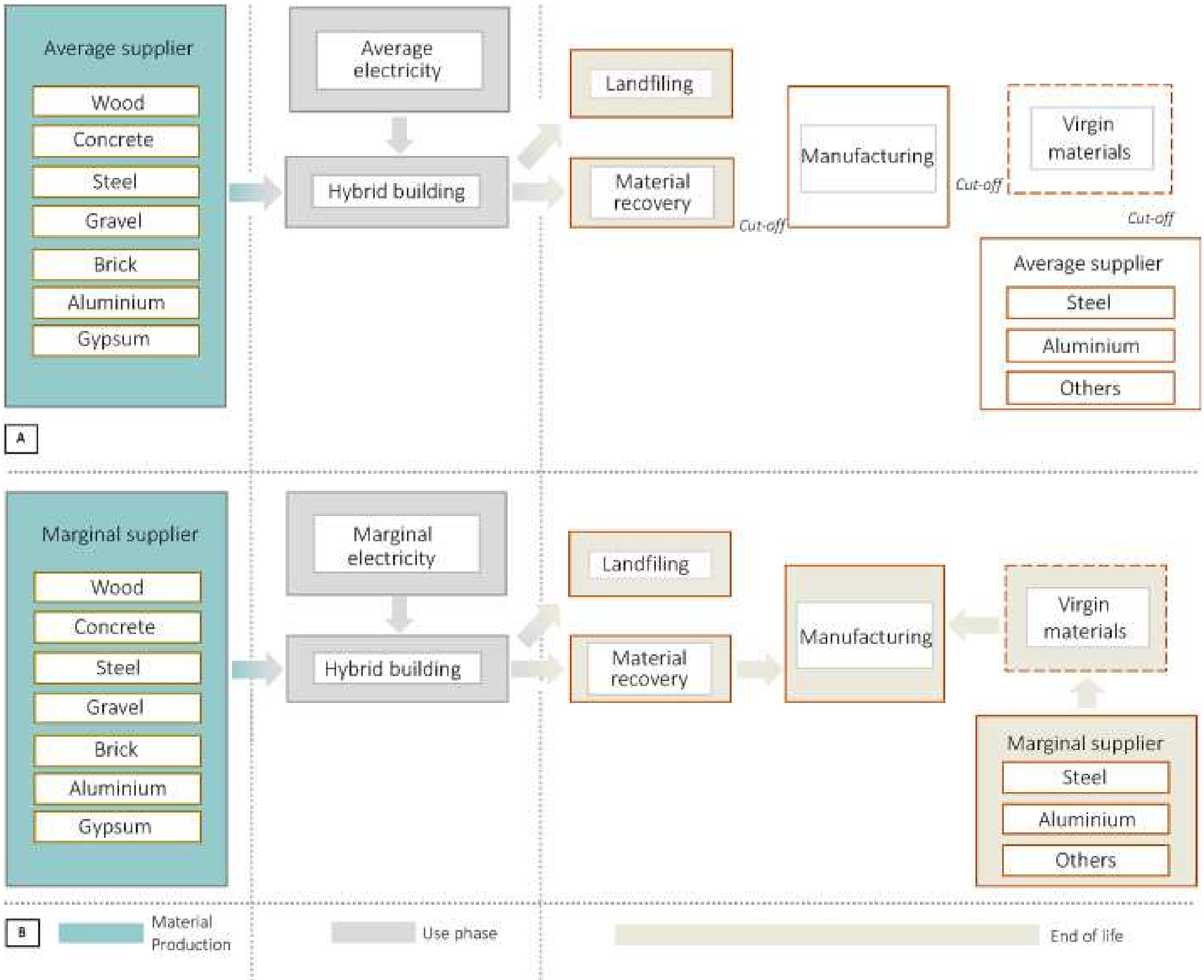


Figure 5.2. System boundary of hybrid multistory building in attributional (upper) and consequential assessment (lower) with the dash line means the avoided burdens

### 5.2.1.1.2. Consequential LCA

The second question that will be answered using the consequential approach is: what are the environmental consequences of constructing more hybrid wood multistory buildings in 10 years? This case study provides an example hybrid multistory building representing buildings that are likely to be constructed in large numbers by 2030–2045. In the consequential approach, system boundaries are expanded to include the avoided processes due to reuse and recycling at the end of life (see Fig. 5.2).

One of the main elements in the consequential approach is marginal technology identification. How to conduct marginal technology identification, however, remains unclear (Bamber *et al.*, 2020; Hildebrandt *et al.*, 2017; Majeau-Bettez *et al.*, 2018). The absence of consensus stems from the difficulty of the work conducted, which aims to capture all causal connections (Ekvall, 2020; Majeau-Bettez *et al.*, 2018). This cannot be perfectly done by any of the available models, thus requiring practitioners to introduce simplifications.

The most commonly used procedure to identify marginal technologies is the five-step framework developed by (Weidema, 2003)(see Fig. 5.3). In the five-step wise procedure, it is worth mentioning that the main interest in the market studied is the overall market trend, not the direction of a particular demand. The same suppliers of different materials will be affected by a demand increase or decrease. The only difference is the magnitude of the increase and the types of new technology that will be used in the system to meet the demand. For example, as wood is increasingly being used in multistory buildings, it is possible to compare this change with the concrete used in the same building market. Although it can be assumed that an increase in wood usage in multistory buildings will lead to a reduction in concrete demand, the same modern competitive technologies in both product systems will be affected. Increasing wood usage may not affect the overall market trends for wood and concrete, as both might still be increasing, even though with different growth rates. Therefore, an increase in the construction of hybrid wood multistory buildings will likely also increase the demand for intermediate products, such as wood, concrete, steel, gravel, aluminum, gypsum, and brick.

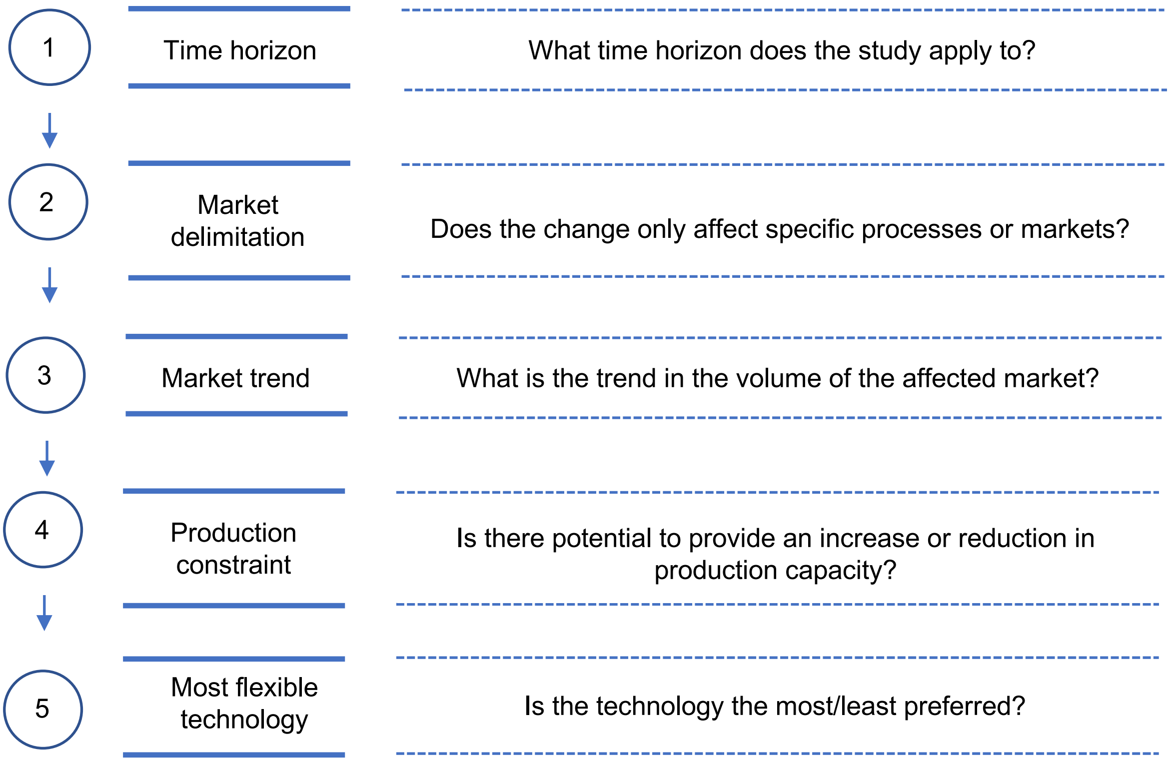


Figure 5.3. Identification of the marginal technologies (adapted and modified from Weidema)

In consequential settings, what happens in a single building in terms of the impact contribution will be similar to what happens in larger systems/building blocks if similar ones are also built. For example, if marginal technologies supply the future demand where the penetration of hybrid wood buildings will be extensive, e.g., 1000 buildings, the contribution impact of one building to the entire market in consequential approach will be similar. Thus, the results in this case study will be analyzed and discussed with contribution analysis.

4.2.1.1.2.1. Stepwise procedure

The first step of the procedure presented on Fig. 3 is identification of the time horizon. The time horizon considered here is the long term. It is predicted that large numbers of wooden multistory buildings will be constructed over the next 10 years. The choice of timeframe is chosen based on (Weidema, 2003).

The second step is market delimitation. When a change is introduced—in this case increasing wood usage in multistory buildings—it is important to determine whether the change only affects specific processes or markets. A change in materials in one building is considered small, as the additional demand is not expected to impact the overall market. If, in the future, more wooden multistory buildings are constructed, this will affect the demand for structural wood materials in the larger market. The increase in wooden multistory buildings will therefore alter the structural material market.

The third step is volume trend identification in the affected market, i.e., is the market increasing or decreasing over the long term? The demand for structural wood is expected to increase (Cordier *et al.*, 2020; Hildebrandt *et al.*, 2017), and there are four products that could supply the future structural wood demand: softwood glue laminated timber (glulam), softwood cross-laminated timber (CLT), hardwood glulam, and hardwood CLT. Currently, softwood is the main source of structural wood. According to various statistical sources, softwood production in Canada increased annually from 2009 to 2016 at a rate of 52% (NRCAN, 2018a, 2018b; Statistic Canada, 2018a). The Food and Agriculture Organization predicted that sawn wood production based on three different Intergovernmental Panel on Climate Change (IPCC) scenarios that also show increasing trends (FAO, 2006). The increasing markets are driven by the more widespread adoption of softwood in buildings, mainly in the form of glulam and CLT. These two technologies are fulfilling the needs of the current market that demand low-cost wood with good strength properties. Another technology that is likely to react to future market changes in high-rise buildings is CLT hardwood (Dara *et al.*, 2019; Espinoza *et al.*, 2016a, 2016b; Mallo and Espinoza, 2014). It is predicted that CLT will have better strength properties compared to glulam hardwood (Bogensperger *et al.*, 2011). However, no specific market data are available for these materials.

The fourth step considers production constraints and whether there is potential for a production capacity increase. Production constraints may change over time depending on location and scale. Timelines should be considered, as some constraints may only be applicable in the short term. At the ground level, softwood production is unconstrained or technically less constrained than other materials and could potentially meet future demands considering the vast forest area available for softwood harvesting in Canada; softwood also grows faster than hardwood (NRC, 2018).

The fifth step considers which of the unconstrained suppliers/technologies are the most flexible to a change in demand or are more competitive than others. Competitiveness is typically determined by the production cost or other externalities that may enter the decision-making process, i.e., the ability of a technology to respond to future concerns related to resource availability or political constraints such as regulations and policy amendments, as discussed in the previous steps. For example, compared to softwood glulam, softwood CLT is a newer technology with a structurally better perpendicular strength performance. It could, therefore, respond to the wood demand of higher buildings, which glulam could not due to its limited use for posts and beams. It is true that both CLT and glulam can be used together for different structural components; however, before CLT penetrated the market, glulam fulfilled the demand. CLT manufacturers in North America have experienced a steady growth since the product was first introduced, with no sign of a decline (Pei *et al.*, 2016). The general trend is driven by voluntary efforts in the construction industry to replace nonrenewables with more sustainable materials, the need to lower the carbon footprint and more speedy construction process (NRCAN, 2019). Considering the availability of softwood trees in Quebec, it is safe to assume that CLT softwood from Quebec near manufacturers can meet future demands. The summary of long-term marginal technologies is presented in Table 3.

Table 5.3. Summary of long-term marginal suppliers

| Material | Market trend | Affected long-term supplier |
|---|---|---|
| CLT | Increasing | CLT softwood from Québec manufacturer |
| Concrete | Increasing | Ready-mix concrete from Québec plant |
| Steel | Increasing | Blast furnace with carbon capture technology from Chinese supplier |
| Aggregate | Increasing | Crushed aggregate |
| Gypsum | Increasing | Gypsum produced with conical kettle technology from Ontario (Hagersville, Caledonia and Mississauga) |
| Aluminum | Increasing | Aluminum from Chinese supplier |
| Brick | Increasing | Clay brick from Brampton and Burlington plants (Ontario) |
| Electricity | Increasing | Hydropower with some portion of wind and natural gas |

### *5.2.1.2. Life Cycle Inventory (LCI)*

#### 5.2.1.2.1. Attributional LCI

##### 5.2.1.2.1.1. Material production – attributional

Table 4 presents the bill of materials for the studied hybrid wood multistory building. The main data sources are reports provided by the industrial partner (a construction company in the Quebec province) involved in the project. When data were missing, secondary data from literature and the ecoinvent database (v 3.5) were used, which contains regionalized Quebec datasets for several construction materials. The cut-off version of the database was used for the attributional approach and the consequential long-term version for the consequential analysis (see Annex B for more details). Calculations were done with Simapro 8.5 and the impact method Impact 2002+ both mid and endpoint categories.

Table 5.4. Inventory of hybrid multistory building – attributional approach

| Dataset | **Unit process[1] {Geographical location} \| System model** | Unit | Amount |
|---|---|---|---|
| Laminated timber | Laminated timber production {CA-QC} \| Cut-off, U | $m^3$ | 3,704.25 |
| Concrete | Concrete, 30-32MPa {CA-QC}\| production \| Cut-off, U | $m^3$ | 2,316.33 |
| Steel | Steel, low-alloyed {CA-QC}\| Cut-off, U | kg | 19,794,620.76 |
| Brick | Shale brick {CA-QC}\| production \| Cut-off, U | kg | 537,644.84 |
| Aluminium | Aluminium cladding {CA-QC}\| Cut-off, U | $m^2$ | 1,075.99 |
| Gypsum | Gypsum plasterboard {RoW}\| production \| Cut-off, U | kg | 236,575.88 |
| Aggregate | Gravel, crushed CA-QC}\| production \| Cut-off, U | kg | 2,263,842.34 |

[1]The unit processes used are mainly from ecoinvent dataset with some adaptation with Quebec context (i.e. electricity and transport) and the quantity of material is based on site construction.

In the present study, the material input and emissions for wood production are adapted from a study of wood products from the boreal forest of Quebec (Laurent *et al.*, 2013) and of laminated timber (Athena Sustainable Materials Institute;, 2013; Chen *et al.*, 2019; Salazar, 2016). The inventory of concrete production per m3 is adapted from Ecoinvent for Quebec context (Geneviève, 2016a). The inventory of steel and aluminum production in Quebec was obtained from Dussault (Dussault, 2016a, 2016b). The material inputs and emission data for gypsum and brick are generated from Althaus (Althaus, 2016) and Reid (Reid, 2016), respectively. The input and output data of materials and emissions from gravel production are extracted from Lesage (Lesage, 2016). This includes whole manufacturing processes, internal processes (transport, etc.) and infrastructure.

5.2.1.2.1.2. Use phase – attributional

To model energy consumption in the use phase, energy modeling software CAN-Quest is used. CAN-Quest is an adaptation of the eQuest software developed by Natural Resources Canada to model energy consumption in Canadian buildings that provides a monthly dynamic analysis of the designed house consumption. The timeframe of the use phase of the building is 60 years.

5.2.1.2.1.3. End of life – attributional

This stage includes all material waste generated during the demolition, transport of waste, consumption and emissions of equipment fuels, and landfilling. In cut-off approach, if a material is recycled after the demolition, the first producer does not receive any credit for the provision of any recyclable materials. It is because the use of recycled materials and their corresponding impacts or benefits were only accounted at the beginning and not at its end of the building life cycle.

### 5.2.1.2.2. Consequential LCI

5.2.1.2.2.1. Material production – consequential

For the consequential LCI, the material input and emission are adopted from similar sources as in attributional model but adapted to consequential context as presented in Table 5. The inventory of concrete production per m3 is adapted from ecoinvent by changing the marginal cement and clinker production (Geneviève, 2016b, 2016c). In the consequential approach, a previous study monitored the marginal technologies for concrete production in Quebec (Azarijafari *et al.*, 2019), with an additional inventory of cement and clinker production from other sources (Brown *et al.*, 2014; Geneviève, 2016b).

Table 5.5. Inventory of hybrid multistory building – consequential approach

| Dataset | Unit process | Unit | Amount |
|---|---|---|---|
| Laminated timber | Laminated timber production {CA-QC} \| Conseq, U | $m^3$ | 3,704.25 |
| Concrete | Concrete, 30-32MPa {CA-QC}\| production \| Conseq, U[2] | $m^3$ | 2,316.33 |
| Steel | Steel, low-alloyed {CN}\| Conseq, U[3] | kg | 19,794,620.76 |
| Brick | Shale brick {CA-ON}\| production \| Conseq, U | kg | 537,644.84 |
| Aluminium | Aluminium cladding {CN}\| Conseq, U | $m^2$ | 1,075.99 |
| Gypsum | Gypsum plasterboard {CA-ON}\| production \| Conseq, U | kg | 236,575.88 |
| Aggregate | Gravel, crushed CA-QC}\| production \| Conseq, U | kg | 2,263,842.34 |

They are used for concrete production inventory in this study. In the consequential approach, identification of marginal steel production technology is based on Palazzo and Beylot (Beylot, 2016; Palazzo and Geyer, 2019; Remus *et al.*, 2013). Since, in the consequential approach, the marginal technology for steel and aluminum production is predicted to be Chinese steel suppliers, material inputs are adapted to the Chinese context from ecoinvent. In the consequential approach, the marginal technology for gypsum production is based on the conical kettle technology from Ontario, while brick is also produced in Ontario plants. Thus, the material input is adapted to this context.

4.2.1.2.2.2. Use phase – consequential

The energy consumption used in the building is also modeled with CAN-Quest in 60 years timeframe similarly with attributional approach. The only difference is the energy mix in the electricity use. To model this marginal electricity mix, a careful examination must be performed to avoid inconsistency and incomprehensive assessment (L. Q. Luu *et al.*, 2020;

Soimakallio *et al.*, 2011), especially if availability of data is a major issue (Q. le Luu *et al.*, 2020). A mix of natural gas, wind, wood, and hydropower was assigned to the framework as the affected long-term suppliers according to Ecoinvent v.3.5 (Tirado, 2016; Treyer, 2016). This also includes the electricity production in Quebec, electricity loss due to transmission and the imported electricity.

4.2.1.2.2.3. End of life – consequential

The consequential approach also considers collection and recycling rates that vary between materials ranging from 50% to 95%. Unlike attributional modeling, this consequential model uses system expansion (or substitution) to deal with multi-output product. Here, some recyclable materials can be used again for similar or other purposes means the impact of producing virgin materials is avoided.

#### *5.2.1.3. Sensitivity Analysis*

To test how sensitive the LCA results, sensitivity analyses are also carried out by applying different impact method (ReCiPe) in both approaches and changing source import in consequential that is presented in later section.

### 5.2.2. Life Cycle Costing (LCC)

LCC is a tool that summarizes all the life cycle costs of a product, perceived explicitly by one or more product process participants. In 2008, a book was published by the Society of Environmental Toxicology and Chemistry (Hunkeler *et al.*, 2008), which was the result of its working group describing three different categories of LCC: conventional, environmental and social LCC. While conventional LCC ignores the postproduction (end of life) phase, social LCC focuses on indirect social issues. Environmental LCC is the closest to LCA, because it measures the entire cost of the product life cycle that is borne directly by one or more actors in its life cycle. It is generally agreed that environmental LCC should be used in parallel with LCA to support the economic pillar of sustainability (Kloepffer, 2008). In this paper, conventional LCC is adopted, and the end of life is included. It will be divided into two types based on the market mechanism involved: attributional and consequential LCC.

#### *5.2.2.1. Goal and Scope of LCC*

5.2.2.1.1. LCC – attributional study

From the attributional perspective, the goal of this study is to determine the economic costs of a hybrid wood multistory building over its lifecycle. In this study, attributional LCC is defined as conventional LCC that includes direct economic cost related to the physical and mass balances of the building. The cost bearer is the building owner.

5.2.2.1.2. LCC - consequential study

Consequential LCC is defined as the sum of each activity costs in the building lifecycle, including indirect consequences such as benefits and the economic cost from expanded system boundaries. To differentiate between the costs in attributional and consequential LCC, we use a new term called marginal cost. Marginal cost is the cost of the marginal technology defined in consequential LCA to differentiate it with attributional LCC. Marginal costing[2] in consequential LCC is used in accordance with consequential LCA. The word costing is used instead of cost to highlight the difference with the marginal cost, which has frequently been applied in the economic field.

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[2] Marginal costing in consequential approach is the cost of marginal technology. The term costing is being used to differentiate it with marginal cost that has been used for long in economics.

In this study, we applied a three-step procedure to conduct consequential LCC, defined as follows.

1) Defining marginal costing temporality

In a consequential study, we assess activities in a product system that are expected to be modified as a consequence of future demand changes. When the consequences to be modeled happen further into the future, forecasting may be used to better reflect the expected future situation. In this sense, defining the temporality or time horizon of the study is important. A long-term period is considered in this study, which is about 10 years.

2) Identifying outlooks or forecasts of market trends

After the time horizon is fixed, it is important to collect outlook or forecast cost data of material or service prices. Generally, international organizations such as the International Monetary Fund (IMF), the Organisation for Economic Co-operation and Development (OECD), and the World Bank provide such data. If not available, it is recommended to determine market trends from available local sources.

3) Valuing the cost at one point in time (present or future value)

Finally, we need to discount all future costs to a specific reference year, which are referred to as Present Value (PV) dollars. This must be aligned with the reference year in LCA.

### *5.2.2.2. LCC Inventory Data*

#### 5.2.2.2.1. Attributional LCC inventory

The main database used to quantify the cost is the RSMeans database for North America with specific multipliers for cities in Canada (RSMeans, 2019). The initial and finishing parts of the production phase are based on the average value of the total building cost per meter square. The example of the calculation can be seen in Annex B.

##### 5.2.2.2.1.1. Material production cost

To calculate the total production cost (Pca) in the material production phase, some parameters are needed, as in Equation (1).

$$Pc_a = e + s + \sum c_i + f + pl + me \text{ with } c_i = mc_i + lc_i + ec_i + o_i) \text{ x } Ci \quad (1)$$

Equation 1. The total production cost in the material production phase

Where e is the engineering design cost, s is the site work cost, ci is construction cost of each material, f is finishing cost, pl is plumbing cost and m is mechanical and electrical cost. The material construction, ci, can be easily calculated by summing four parameters, mci, bare material cost, li, bare labor cost, eqi, bare equipment cost and oi overheard cost then multiply them with Ci, city index.

##### 5.2.2.2.1.2. Use-phase cost

To quantify the total use cost (U), one must sum the annual electricity consumption and cost throughout the whole building life span, as in Equation (2).

$$U = \sum u_i \text{ with } u_i = el \text{ x } (1+i)^t \text{ x } ec \quad (2)$$

Equation 2. The total use cost and electricity consumption

Where ui is the use cost in year i, t is the time, el is electricity cost per kWh in year i, while i is inflation rate and ec is annual electricity consumption. If the point of reference time for comparison is current year, the future costs must be discounted to present value, as in Equation (3),

$$U = PV \sum u_i = u_i/(1+r)^t \quad (3)$$

Equation 3. The discounting of future cost to present value

Where PV ui is the present value of use cost each year and r is the discounting rate.

In the economic assessment, the future price is estimated based on the price increase rate according to Statistic Canada and Hydro-Quebec.

4.2.2.2.1.3. End of life cost

To calculate the total end of life cost of building materials (E), similar to the previous section, the sum of end of life cost of each material is calculated, see Equation (4).

$$E = \sum eo_i \text{ with } eo_i = eu_i \times (1+i)^t \times u_n \times C_i \quad (4)$$

Equation 4. The sum of end of life cost of each material

The eoi represents end of life cost materiali while t is time, eui is end of life cost per unit materiali, i is inflation rate and un is unit (volume or area). If the point of reference time for comparison is current year, the future costs must be discounted as in Equation (5).

$$E = PV \sum eo_i = eo_i/(1+r)^t \quad (5)$$

Equation 5. The discounting of future cost to current year (end of life phase)

4.2.2.2.2. Consequential LCC inventory

In the consequential assessment, the calculation is based on the cost of future marginal technology. Most of the future costs used in ts study are available from the outlook and forecast sections of the IMF and OECD database for 2030. These future costs are then discounted to present value (PV) of the current year (2019), hence reference year, at a 3% discounting rate for comparison purpose. Secondly, if the future costs are not available, the future cost is then quantified by forecasting current or available cost to the future based on different market growth or market trend; for example, the market growth of material cost was obtained from the Canadian building trend analysis [74,75](Statistic Canada, 2018b, 2018c). The calculation details are provided in the Annex B of this article.

4.2.2.2.2.1. Material production cost

The total material production cost (Pcq) can be easily calculated by summing the future costs of marginal technology, as in Equation (6). The future cost of the material, labor, equipment or other can be obtained from national, regional or global database such as IMF and OECD.

$$Pc_q = mcf_i + lcf_i + ecf_i \quad (6)$$

Equation 6. Total material production cost

Where mcfi is the material cost year n in future, lcfi is the labor cost and ecfi is the equipment cost. If the point of reference time for comparison is current year, the future costs must be discounted as in Equation (7).

$$(mcf_i + lcf_i + ecf_i) = ((mcf_i/ (1+r)^t) + (lcf_i/ (1+r)^t) + (ecf_i/ (1+r)^t)) \quad (7)$$

Equation 7. The discounting of future cost to present value in production phase

If data of future costs are not available, they are then forecasted with specific increase rates (market growth/market trend, m) from the year of available data to 2030 (or any appointed year in the future), as in Equation (8). They are then discounted back to the current year or reference year for comparison purpose, as in previous Equation (7).

$$ecf_i = ec_i \text{ x } (1+m)^t \text{ x } Ci \quad (8)$$

Equation 8. The forecasting of cost from available year

4.2.2.2.2.2. Use-phase cost

The calculation method for use phase for consequential is similar with attributional one. The only difference is the time frame for consequential is prospective from 2030 to 60 years onwards. In other word, it is a sum of future annual use cost from electricity consumption, as in Equation (9). The annual increasing rate of electricity cost used is 1,4% according to Hydro-Quebec. All the future price from 2030 to 2070 is then discounted to present value with 3% annual rate.

$$U = \sum uf_n + uf_{n+1+}uf_{n+2} + .... \quad (9)$$

Assuming the point of reference time for comparison purpose is now, the costs must be discounted as in Equation (10).

$$U = \sum uf_n / (1+r)^t + uf_{n+1} / (1+r)^t + uf_{n+2}/ (1+r)^t + .... \quad (10)$$

Equation 9. Discounting of future cost to present in use phase cost

If future costs are not present, future costs are estimated by extrapolating existing or available costs into the future using the inflation rate as in Equation (11).

$$U = \sum uf_i \text{ with } uf_i = el \text{ x } (1+i)^t \text{ x } ec \quad (11)$$

Equation 10. The forecasting of current cost

Where el is the electricity cost per kWhyear n in $/kWh, i is the inflation rate and ec is the annual electricity consumption in kWh. If the current year is the point of reference, these potential expenses are discounted down to the current year for comparative purposes.

4.2.2.2.2.3. End of life cost

The calculation model used here is similar to the attributional one. The difference lies on the additional quantification of benefits of re-selling building waste materials generated after reaching their end of life. For the calculation of the total end of life of materials (E) can be seen in Equation (12).

$$E = \sum eof_i \quad (12)$$

Equation 11. Total end of life cost of material

Where eofi is the end of life cost of materiali in the future. Assuming the point of reference time for comparison purpose is now, the costs must be discounted to present time.

If data of future costs are not available, the E is calculated by forecasting the available cost to the future by involving inflation rate as in Equation (13).

$$E = \sum eof_i \text{ with } eof_i = eu_i \text{ x } (1+m)^t \text{ x } u_n \text{ x } C_i \quad (13)$$

Equation 12. forecasting the available cost to the future by involving inflation rate

Where eui is end of life cost per unit materiali, i is inflation rate, un is unit (volume or area) and Ci is city index. It is then discounted to present value or any point of reference year.

For the benefit of re-selling building waste materials, Equation (14) is presented

$$B = \sum bf_i \ with \ bf_i = b_i \ x \ (1+m)^t \ x \ u_n \ x \ C_i \qquad (14)$$

Equation 13. the benefit of re-selling building waste materials

Where bfi is the benefits of re-selling building waste materiali in the future, bi is the benefit of re-selling building waste materials of current year or year of the available data and m is the market growth. It is then discounted to present value or reference year for a comparison purpose.

#### *5.2.2.3. Sensitivity Analysis*

LCC price sensitivity is calculated using pessimistic and optimistic scenarios for construction materials. In a pessimistic scenario, the interest rate is assumed lower (0.7%) and market growth of building materials is also weak (0.2%–3.1%). In the optimistic scenario, interest rate is given higher (2.9%) and building material market growth is also stronger (0.7%–11.6%). RSMeans, the main database used for this calculation, also provides range of value with minimum value for pessimistic and maximum for optimistic scenario.

## 5.3. Results and Discussion

The findings are given in two sections. The first section focuses on LCA results and discussion (section 3.1), while the second section focuses on LCC results and discussion (section 3.2). We present the results based on an attributional approach in the endpoint and midpoint categories in the first part of the LCA (sub-section 3.1.1). The consequential approach is then explained in the next sub-section (sub-section 3.1.2). Following that, the LCC results and discussion are submitted in a similar format. The first sub-section is for attributional (sub-section 3.2.1), while the second is for consequential (sub-section 3.2.2).

### 5.3.1. LCA Results

#### *5.3.1.1. Attributional LCA*

Fig. 4 depicts the environmental performance of the lifecycle of the hybrid wood multistory building using the attributional approach in four damage categories.

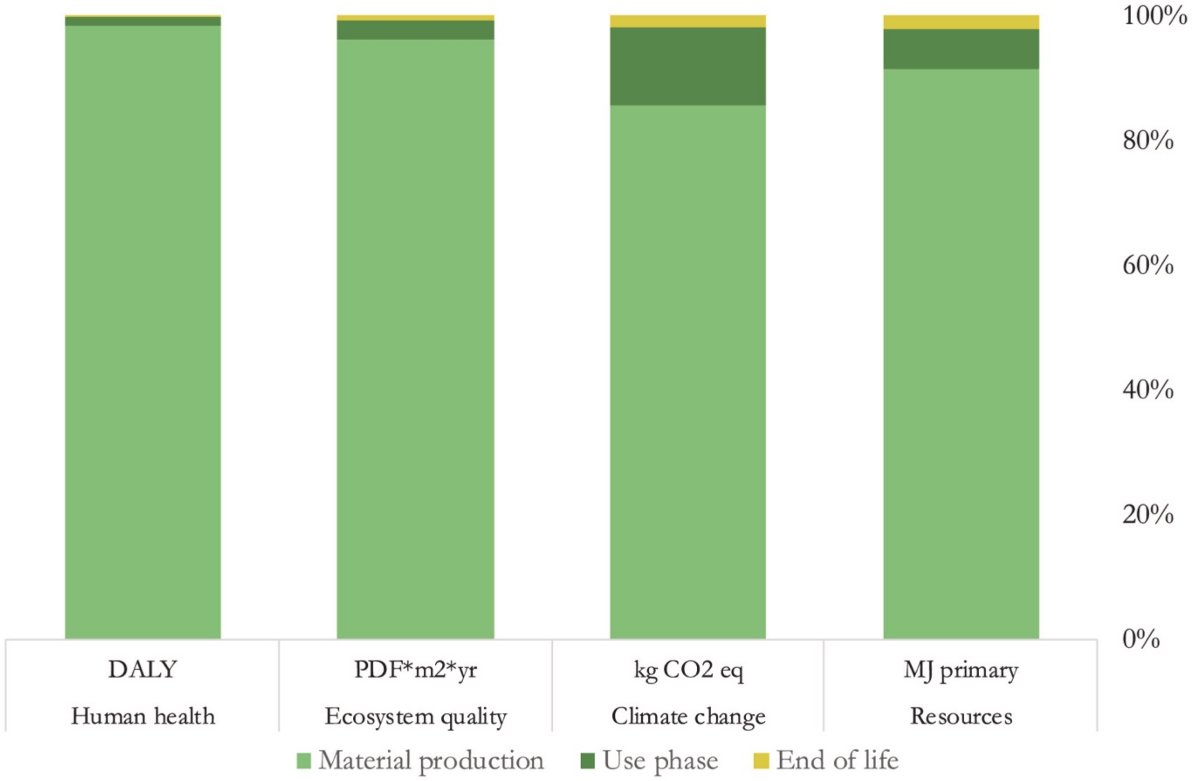


Figure 5.4. Contribution analysis of endpoint results with with the attributional approach

In the human health category, material production causes 98% environmental damage (7.85E+01 DALY), divided over six impact (midpoint) categories: carcinogens, noncarcinogens, respiratory inorganics, ionizing radiation, ozone layer depletion and respiratory organics (see Fig. 5 for midpoint categories). Material production has the largest impact on human health among these six impact categories, except ionizing radiation. As indicated in the Fig. 5, human health is affected by ionizing radiation mainly during the use (49% or 3.92E+01 DALY) and material production phases (48% or 3.84E+01 DALY).

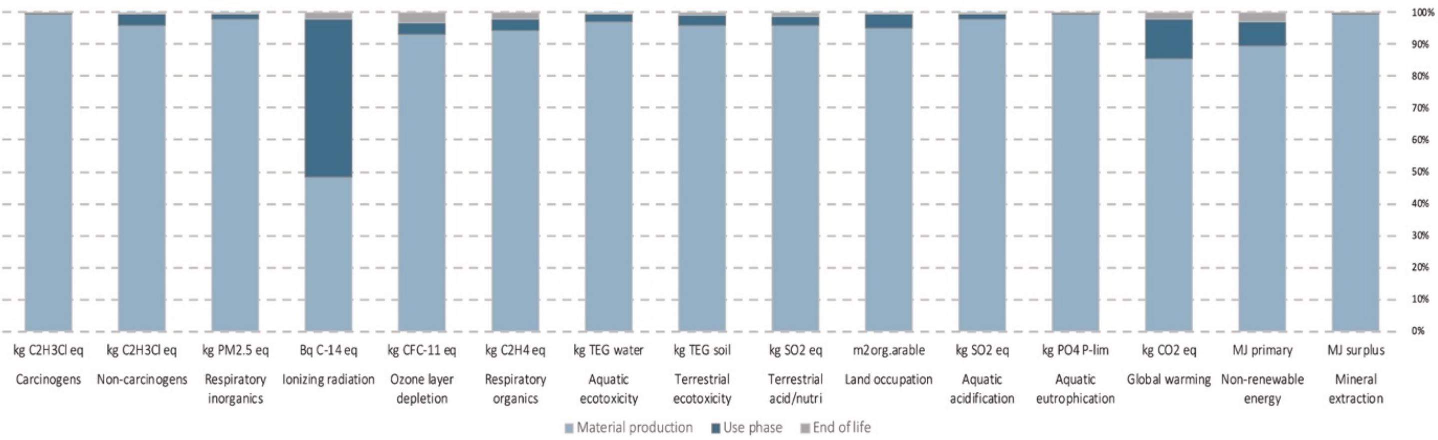


Figure 5.5. Midpoint results of life cycle impact of hybrid building with attributional approach (contribution analysis)

The lifecycle phase that adversely contributes the most is material production in the ecosystem quality category. It affects all six impact (midpoint) categories: aquatic ecotoxicity, terrestrial ecotoxicity, terrestrial acidification/nitrification, land occupation, aquatic acidification and eutrophication. In all categories, except land occupation, the most destructive process is related to the steel alloy production process. The blasting process to mine the molybdenum required for steel production is the prime cause of both aquatic and terrestrial ecotoxicity (26% or 1.08E+07 out of 4.15E+07 potential disappeared fraction (PDF)*m2*y), owing to the aluminum released to the air during this process.

In the climate change category, the most impactful processes vary. About 86% (1.49E+07 kg CO2 eq) of the impact from material production are linked to aluminum wrought alloy production and the heat used in steel and iron production processes.

Material production is the phase with the largest contribution in the resource category. It is indicated in Annex B that two impact (midpoint) categories are considered: nonrenewable energy and material extraction. Natural gas is the main cause of the nonrenewable energy extraction used for heat in the steel production process, with a value of 3.81E+07 Bq C-14 eq (14%) out of a total value of 2.67E+08 Bq C-14 eq. The second prime cause of nonrenewable energy extraction is petroleum, which is used as diesel for fueling natural gas and steel production with a value of 2.34E+07 Bq C-14 eq or 9% of the total impact. Please see Table 6 for the total impact of endpoint category.

Table 5.6. Total impact of endpoint category

| **Impact category** | **Unit** | **Attributional Total** | **Consequential Total** |
|---|---|---|---|
| Human health | DALY | 8.01E+01 | 2.81E+01 |
| Ecosystem quality | PDF*m2*yr | 4.15E+07 | 1.98E+07 |
| Climate change | kg CO2 eq | 1.74E+07 | 3.83E+07 |
| Resource | Bq C-14 eq | 2.67E+08 | 1.06E+08 |

According to the sensitivity analysis conducted using the different impact methods (ReCiPe) (see Annex B), the model provides similar results. Material production is the phase with the largest contribution relative to the other two phases among seventeen impact categories, except ionizing radiation and water consumption. The latter impact category is not included in the IMPACT 2002+ method. Similar effects are also caused by the activities linked to the steel production process, such as steel alloy production and blasting and mining needed to extract raw materials for steel, i.e., nickel and molybdenite. These activities adversely impact human health, negatively alter ecosystem quality and reduce nonrenewable resources. The sensitivity analysis of the LCIA methods in endpoint category proved the validity of the LCIA results for human health that has similar result: material production also contributes most in ReCiPe (more than 98% of the total impact) like in IMPACT 2002+ method. As for the midpoint category, with ReCiPe it shows difference of +7.8%, +40.2%, −63.3% and +56.8% in global warming, respiratory inorganics, terrestrial acid/nutrification and land occupation respectively.

To a certain extent, these results are difficult to compare to existing results in the literature regarding the impacts of wood high-rise building construction with the attributional approach (Althaus, 2016; Chen *et al.*, 2019; Dussault, 2016a, 2016b; Geneviève, 2016a; Salazar, 2016). The omittance of the use phase during assessment in previous studies is the main reason for this difficulty. However, one study of medium-rise building shows similar pattern that materials could greatly contribute to the entire impacts (Reid, 2016).

### *5.3.1.2. Consequential LCA*

The environmental performance in the life cycle of hybrid wood multistory buildings using the consequential approach in four damage categories is shown in Fig. 6.

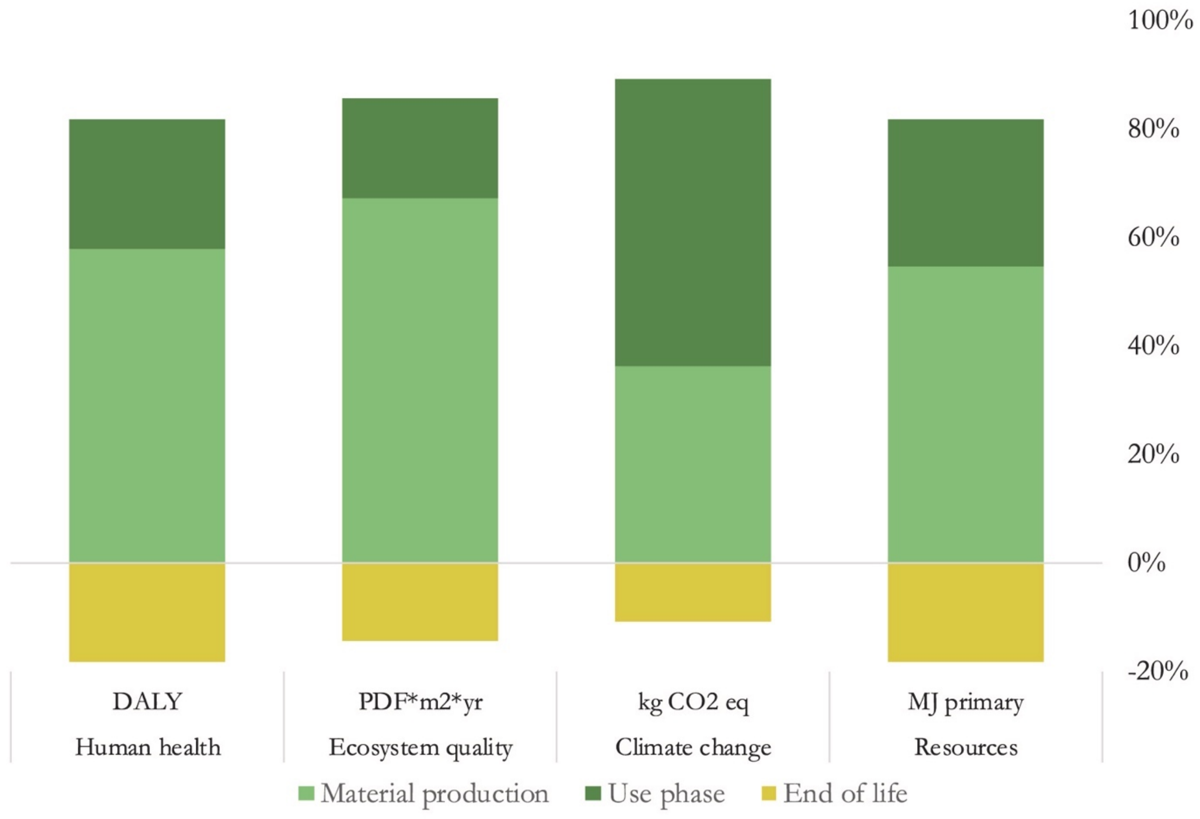


Figure 5.6. Contribution analysis of endpoint results with the consequential approach

It is worth mentioning that in the consequential approach, the increasing demand for some materials fulfilled by present or future marginal technologies is accounted for. For example, as mentioned in earlier sections, the aim of the consequential approach is to determine what will happen if, in the future, more hybrid wood buildings will be constructed in Quebec. This will result in increasing demands for the corresponding building materials. These demands will be satisfied by marginal technologies. Thus, the results here reflect contribution analysis in a larger context.

The material production phase contributes 71% (1.99E+01 DALY), the use phase contributes 29% (8.15E+00 DALY) and the end of life contributes 9% (2.53E+00 DALY) to the total human health damage category. Among the six impact midpoint categories in the human health damage category, material production contributes the most to respiratory inorganics, ionizing radiation and respiratory organics (see Fig. 7 for midpoint categories). These midpoint impacts are mainly from the transcontinental transportation of steel from China as the marginal technology. Material production also causes 48% (1.89E+05 kg C2H3Cl eq) of the impact of carcinogens, which is mainly from the fuel used in the Chinese steel production process. The use phase has the largest impacts on noncarcinogens, ozone layer depletion and carcinogens. These impacts mainly come from the future increased electricity demand that will be partly supplied by Ontario, where natural gas is the main energy source (Wernet *et al.*, 2016). It might be worth noting that the increased contribution of operational energy in CLCA relative to ALCA might not hold if Ontario cleans its grid over time or if domestic demand declines over time (e.g. as a result of energy retrofitting) and frees up electrical capacity that would otherwise have gone elsewhere (Canada Energy Regulator, 2019).

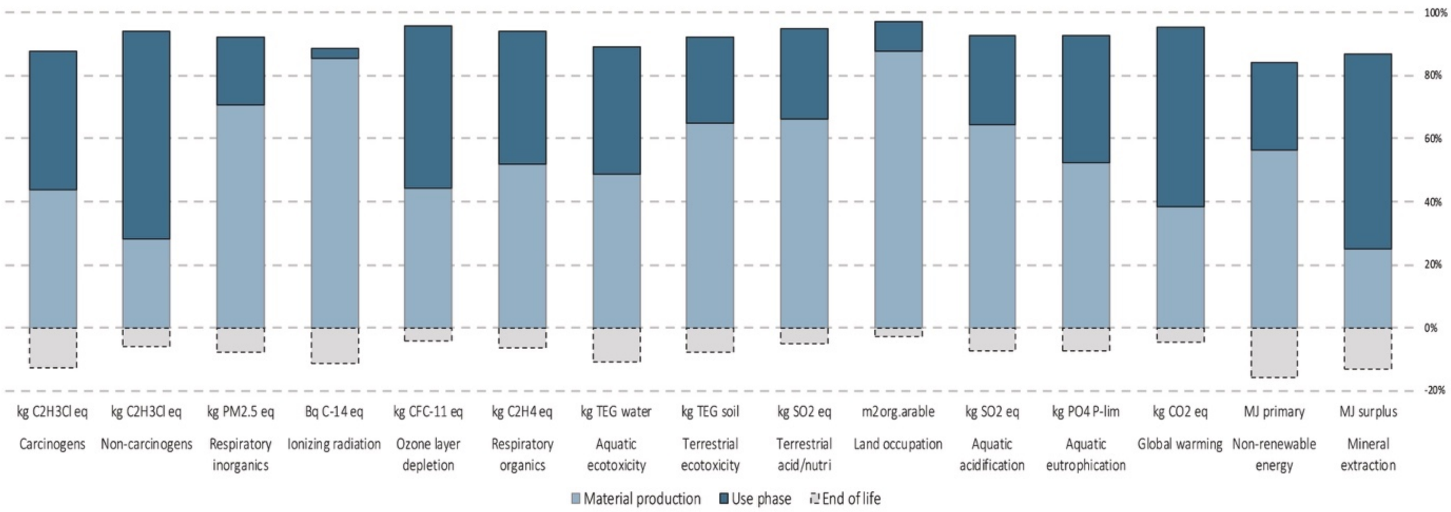


Figure 5.7. Midpoint results of life cycle impact of hybrid building with consequential approach (constribution analysis)

Material production also has the largest environmental impact on the ecosystem quality damage category, accounting for 79% (1.56E+07 PDF*m2*yr). It also has the highest contribution among the six impact midpoint categories. In all of them, except in land occupation, the process with the largest contribution is also linked to the transcontinental transportation of steel imported from China, since the increasing demand of steel in North America will be met by Chinese suppliers. In the land occupation category, 87% of the environmental impact (7.03E+06 m2org.arable) from land occupation is due to softwood production.

The climate change category exhibits different results since the most impactful phase is the use phase (68% contribution or 2.60E+07 kg CO2 eq). Electricity is partly imported by Quebec from Ontario to meet the increasing demand, which includes amounts of natural gas that cause more carbon emissions. In this case, the current low carbon energy mix in the Quebec electricity generation does not ensure low carbon footprint in the future if we do not use attributional approach.

In the resource damage category, material production is responsible for 67% of the impact (7.10E+07 Bq C-14 eq). The latter mainly stems from the steel production process that consumes much nonrenewable energy. In the mineral extraction category, the process that has the most impact is electricity production, especially for Quebec, when wind turbines will penetrate the future market, as turbines require some mineral extraction. Please see Table 6 for the total impact of endpoint category.

In a region like Quebec where most electricity comes from renewable energy, the ALCA shows that to reduce environmental impacts from hybrid multistory building we have to focus on material production phase. While with CLCA, use phase also take part on the high contribution of environmental impacts. This shift appears when we perform both approaches. The CLCA results are sensitive on certain material production such as steel. These results are caused due to a given specific decision such as increased steel demand. This increase leads to increased steel import due to the more construction of hybrid wood building in the future. These larger consequences are not captured in ALCA.

Another value added of using both approaches all together: decision-makers can be aware of knowing the important current hotspot and combining with a consequential can make it even more relevant. For example, we know from attributional approach that in climate change category, the production phase contributes the most to the environmental impacts but from the consequential perspective, we can further understand that Quebec become vulnerable to achieve its carbon-cutting goals if it keeps on relying on importing from its neighbor to fulfill the electricity use in the future. A different point of direction on how to reduce environmental impact can be more accurately captured in CLCA where the decision-makers can perceive their possible decision consequences as the case for steel and electricity importation. Indeed, recent studies of consequential LCA on whole building also confirmed that consequential LCA is used to avoid problem shifting in future policies (Buyle *et al.*, 2018; Ghose *et al.*, 2017). Also, CLCA is also useful as a decision support during the initial plan while attributional is to know past annual performance of the policy (Roux *et al.*, 2016).

Similar to the attributional approach, the sensitivity analysis performed using the different impact methods (ReCiPe) generates similar results. Material production was the most impactful phase among the four impact human health categories and the five human toxicity categories. Similar to the IMPACT method, these results were also due to the nonrenewable electricity used in the steel production process, which partly is obtained from Ontario, and the transcontinental transportation of bulk materials, which adversely impacts human health and climate change. It was revealed that LCIA results with ReCiPe method showed a difference of +1.8%, +28.8% and +56.4% in global warming, respiratory inorganics, and land occupation respectively.

With steel production as the most impactful activity among the various categories, we performed sensitivity analysis by varying the steel import source between the United States, South Korea, Turkey and Brazil as the top five steel sources relative to China. This revealed that importing steel from Turkey and the USA results in impacts smaller than 49% and 32%, respectively, on human health. Similarly, importing steel from Brazil and Turkey has an impact smaller than 52% on the ecosystem quality, while importing steel from the USA and India has a smaller than 34–38% impact. In terms of global warming, importing steel from the USA, Turkey, Brazil and India results in similar impacts of approximately 32–33%. In terms of resource extraction, importing steel from Turkey and Brazil, India and the USA results in impacts smaller than 29% and 12%, respectively. In general, importing steel from South Korea has a similar impact to importing steel from China.

Even though this study has some specific context such as the geographical situation of the case study, it is worth mentioning that some similar Quebec studies had validated that use phase contribute quite amount of impacts in many categories (Lessard *et al.*, 2018)[81]. Also, this study has limitation on the type of marginal technology identification model used. The lack of data made the study cannot go with sophisticated model yet it has further advantage on the simplicity and the applicability.

### 5.3.2. LCC Results

#### *5.3.2.1. Attributional LCC*

The outcomes of life cycle costing with the attributional approach are depicted in Fig. 8 for each of the categories and subcategories.

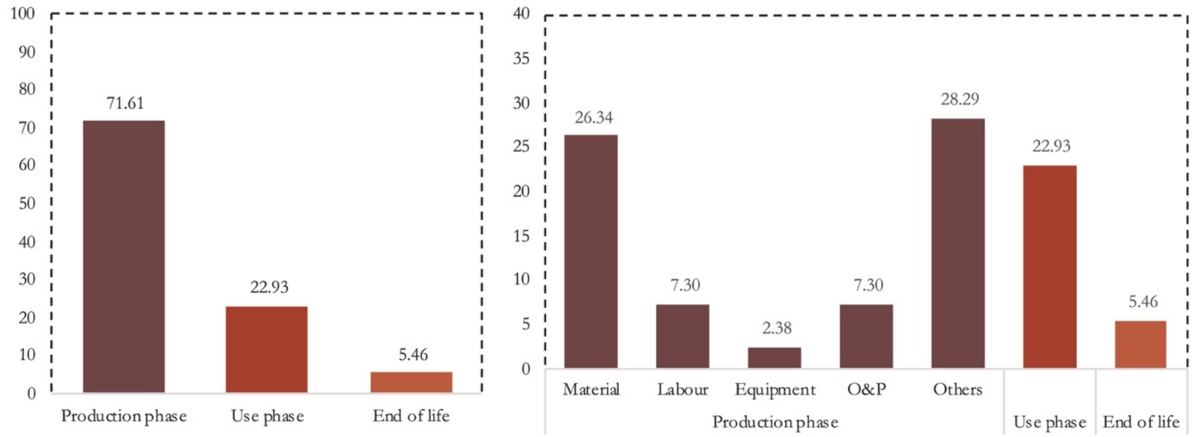


Figure 5.8. Attributional LCC

In the material category, steel and wood have the largest life cycle cost proportions compared to the other structural materials used in construction, followed by concrete and brick. In the labor and equipment category, steel contributes the most (see Annex B). Mechanical and electrical work are the largest contributors to the other category (nonstructural construction), followed by finishing and plumbing work.

To test alternative scenarios due to subjectivity of interest rate and market growth in LCC, sensitivity analysis is performed by changing the price increase rate for building materials using the pessimistic and optimistic scenarios. In the pessimistic scenario, a lower rate and weak market are assumed, and the opposite is applied in the optimistic scenario. Both scenarios revealed that the categories and subcategories with the largest contributions were similar with certain differences (see Annex B).

#### *5.3.2.2. Consequential LCC*

The outcomes of consequential life cycle costing are shown in Fig. 9 for each of the categories and subcategories.

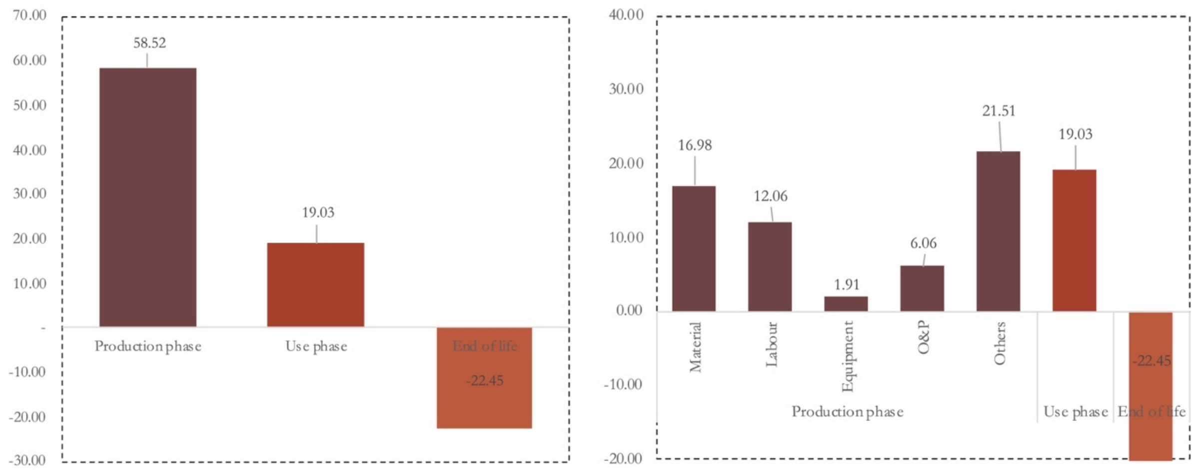


Figure 5.9. Consequential LCC

In the consequential approach where the activities included are the ones that will be affected by the increasing demand, the largest contribution to the marginal costing among those affected technologies comes from the production phase. Compared to the attributional approach, similar patterns are found in the consequential approach. Excluding the initial and finishing costs, the material cost category is the largest contributor in the production phase (please see Table 7 for the total cost in each category). However, interestingly, in contrast to the attributional model, the largest contributor within the material category is wood, not steel (see Annex B). This mainly occurs due to two main reasons: the future price of Canadian wood will increase much more than that based on the average annualized rate, and the increase in steel imports from Chinese suppliers will be less expensive in the future.

Table 5.7. Total cost by category

| Category | Attributional ($) | Consequential ($) |
|---|---|---|
| Material production | 18,659,561.34 | 15,466,473.86 |
| Use phase | 5,976,191.35 | 5,030,747.59 |
| End of life | 1,422,743.10 | −2,618,293.89 |

The main reason why Canadian wood prices will increase is because they are heavily dependent on the activity levels in the U.S. new homebuilding market, which remains considerable. Canada's softwood lumber IPPI has risen at a +4.8% annualized rate, and a nearly identical rate, +4.7%, has been observed in the U.S (Carrick, 2019). The price changes within a country appear to follow their own internally generated increase path without this dramatic course variability expected due to currency alterations.

Moreover, Chinese steel prices will be lower due to the lower forecasted price of raw main materials for steel production in China, such as iron ore, ferrous scrap and coal needed for the main process (Knoema, 2018). When the future price is discounted to the present year of 2019, this materials represents a 16.98% contribution. However, this study does not consider the polluter-pays-principle and carbon taxes, for example, the possibility if they were to be adopted in China or as a trade barrier (tariff) that may be applied for wood, coal and fuel.

Since future market prices are highly unpredictable, similar to the attributional approach above, sensitivity analysis is only conducted by changing the increase rate of the material price in weak- and strong-economy scenarios. Both scenarios revealed that the categories and subcategories contributing the most are similar, except in the optimistic scenario (strong economy), while material production exerts the largest impact.

Regarding the limitation of this study, the LCC methodology applied is limited to conventional type of LCC. Many literatures suggested that when it is combined with LCA or performed under LCSA, it is better to apply environmental type of LCC when value-added is an indicator to measure economic or sustainability performance.

Predicting the future market price is also a hurdle. It contains high uncertainty due to political situation between countries, especially when it comes to global material such as steel and aluminum.

Finally, economic factors strongly affect policy decisions. Thus, having CLCC as a part of assessment is highly desired, especially the positive externalities often are not internalized (Pedinotti-Castelle *et al.*, 2019). By expanding system boundary to focusing the study to the consequences expected to be the most important, CLCC could bring more insights to have a comprehensive assessment.

## 5.4. Conclusion and Outlook

The paper aims to demonstrate the added value of both approaches with the case study from environmental and economic perspectives. The present study identifies the lessons learned and new insights and perspectives that can be gained through a case study of hybrid composite multistory buildings.

The results of the entire life cycle indicate potential differences between the two underlying modeling approach. For example, material production is the most impactful stage environmentally (with 86–98% contribution) and economically (72%) in the attributional approach. However, in the consequential approach, material production is less environmentally responsible (46–94%) and yet still more economically accountable (59%). This proves that consequential LCA-LCC can uncover possible hidden impacts. By implementing consequential LCA-LCC, we will gain additional insights into the consequential impacts of constructing hybrid wood multistory buildings; thus, opportunities to avoid these future consequences are revealed to policy-makers.

It is important to bear in mind that our forward-looking global analysis with wide system boundaries, despite the methodological advancements resulting from integrating LCA and LCC in two approaches, is subject to notable limitations and uncertainties, such as data availability and quality. From a technological viewpoint, one of the main limitations is the marginal technology identification, which depends on data availability regarding future evolutions of technologies. Uncertainty also resides in from where these future technologies will be, as this will be influenced by geopolitical relations between regions or countries.

Even though, there is also uncertainty of the future economic price, its relevance to demonstrates the use of attributional LCA, alongside of consequential LCA, can be defended from a theoretical standpoint. However, more up-to-date economic approach to model the reality of equilibrium causality is needed, especially when dealing with indirect consequences.

Lastly, conducting attributional and consequential LCA-LCC of a product could give more spectrum of possible result for better informed decision making. Supply chain of product, especially in building sector, is indeed resource-intensive, long and has transcontinental activities. Thus, to have a full understanding of impacts occurred by a product for building companies or of consequences for policy-makers, one must go beyond by probably including social aspect. This is further important step since in the complex decision-making process relying on economic-environmental alone is not enough.

# Chapter 6 - On the Possibilities of Multilevel Analysis to Cover Data Gaps in Consequential S-LCA: Case of Multistory Residential Building

Avant-propos

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Date d'acceptation : 3 April 2022
État de l'acceptation : *Accepted and published*

Référence : Fauzi, R.T.; Lavoie, P.; Tanguy, A..; Amor, B. On the Possibilities of Multilevel Analysis to Cover Data Gaps in Consequential S-LCA: Case of Multistory Residential Building. Journal of Cleaner Production

Titre en français : Sur les possibilités d'analyse à plusieurs niveaux pour combler les lacunes dans les données des analyses sociales du cycle de vie conscientielles : cas d'un immeuble résidentiel multiétages.

Contribution au document: Cet article contribue au troisième objectif du projet de recherche sur l'évaluation de l'impact social.

Abstract
Building is affiliated with much of the social impact and benefits. However, for long term assessments that can capture indirect consequences, the current common attributional approach is lacking. The challenge become more obvious with large data amounts required to perform social life cycle assessment (S-LCA), and often less representative non site-specific data must be used to fill data gaps. To address above-mentioned problem, this paper presents a multilevel analysis in consequential S-LCA to further demonstrate the added value of such evaluation on addressing the existing data gaps by integrating the four level of analysis: unit process, company, sector and country. The methodology used is multilevel assessment on these four

levels performed to five stakeholder of worker, local community, user, society and supplier. The case study used to demonstrate this is a multistorey building that has long supply chain from local, regional and abroad. The results show that using multilevel could help to fill the data gaps. For example, with multilevel analysis, material company or activities could fill at least 14 of the 24 social indicators through company's assessment. If it was only performed on one level, the indicators that can be assessed is lesser. Even though more data is not necessarily better but it can broaden the view to understand the potential hotspot of social impact/benefit and the sphere of its influence to the stakeholders. From consequential point of view, it also shows that for a long term, a decision of constructing more hybrid multistory building will be closely related to some social impacts and benefits in different level, different product life cycle and in different geographical area that cannot be captured with single level of analysis.

*Keywords: multilevel, consequential, S-LCA, multistory, building*

Graphical Abstract

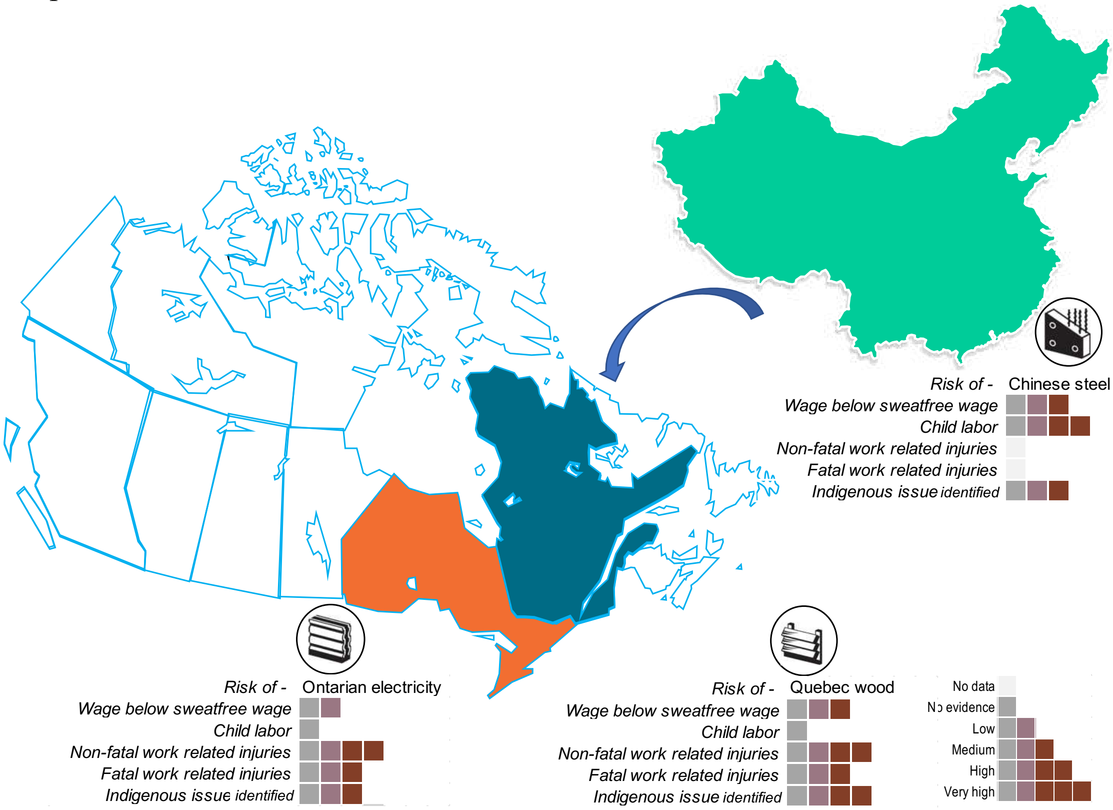



Figure 6.1. Social risk of certain phase in consequential social life cycle assessment

## 6.1. Introduction

*Assessing social consequences in building sector*

Buildings and their downstream and upstream activities are affiliated with some considerable social impacts and benefits to multiple parties (Choi *et al.*, 2019; Dong and Ng, 2016; Dwaikat and Ali, 2018; Winge and Albrechtsen, 2018). Building construction projects deal with some safety and health problems of the workers due to the high risk of dangerous work environments (Jaafar *et al.*, 2018; Khosravi *et al.*, 2014; Sousa *et al.*, 2014; Swuste *et al.*, 2012; Zhang *et al.*, 2015) and the quality of building materials and indoor atmosphere also impacts the occupant's health. (Geng *et al.*, 2017; Kang *et al.*, 2017; Mujan *et al.*, 2019; Zuo *et al.*, 2017). On the positive side, buildings satisfy human being's basic needs and improve life quality, provide many job possibilities and considerably benefit the national economy (Buckley *et al.*, 2016; Garin, 2019; Wu *et al.*, 2018). Among the assessment of three sustainability pillars in building sector (social, environment, and economic), however, the social part is not commonly assessed especially in a life cycle perspective (Alyami and Rezgui, 2012; Petti *et al.*, 2018; Tokede and Traverso, 2020).

Even though positive points exist, above-mentioned negative concerns have been increasing in recent years, which have shifted the efforts from the narrow-minded assessment on cost-accounting, ecological, and social footprint that is often performed separately to balance those three dimensions and improve whole sustainability performance, especially in social aspect that is often left behind. Here, social life cycle assessment (S-LCA) came forth and has been applied in some building case studies (Dong and Ng, 2015; Hosseinijou *et al.*, 2014; Liu and Qian, 2019). However, the current approach used to assess environmental impacts is mainly attributional that cannot capture the long-term consequences of a given decision (Bamber *et al.*, 2020; Saade *et al.*, 2020). Attributional LCA describes the environmentally relevant physical flows into and out of a life cycle of a product and its subsystems. Consequential LCA describes how environmentally relevant flows would alter as a result of potential decisions. Thus, to improve the future long-term environmental or sustainability profile of a decision, rather than looking at it as a normative rule, one needs to look at the activities in the system that are likely to change as demand increases. (Ekvall, 2020; Schaubroeck *et al.*, 2021; Weidema *et al.*, 2018). For example, instead of using average technology, the technology that must be included in the system is the one that is going to fulfil the demand in the future (Earles and Halog, 2011; Weidema, 2003; Zamagni *et al*., 2012). It is the main key in a consequential approach. In the revised S-LCA guideline itself, consequential S-LCA is, however, not well defined as attributional ones (UNEP Setac Life Cycle Initiative, 2020). Thus, further research is needed to enrich and improve the development of consequential S-LCA.

*Data and different level of analysis*

One research avenue for this development lies in the data. Data is the major issue when performing S-LCA (Benoît Norris, 2014; Huertas-Valdivia *et al.*, 2020; Ramos Huarachi *et al.*, 2020; Sureau *et al.*, 2020; Valdivia *et al.*, 2021). To assess social performance in the whole product life cycle in S-LCA as common practice, large data sets are required, but sometimes site-specific data are absent, hence less representative non-site-specific data must be utilised to cover data gaps. There are no defined procedures for addressing data gaps and completeness. The primary data gathered from the site are massive challenges to acquire in terms of quality and quantity (Aung *et al.*, 2021; Benoît Norris, 2014; Tsalidis *et al.*, 2020). It also takes time to collect if the product has long a life cycle and supply chain. Secondary data can be gathered from databases, however these databases are often too generic and can only be used for identifying hotspots as they are aggregated at the sector or country level. Another way to perform the analysis, if primary data is difficult to obtain, is from academic literature or reports from independent organisations like NGOs. Also, if the assessment is performed at the company level, the data from the company's sustainability and annual reports can be used as well. This is, however, not a suitable approach for one who tries to make progress in input selection or assess specific process or activity where the overall life cycle impact could be neglected.

From above-mentioned, it is possible to divide social impact assessment into four levels: unit-process, company or organisation, sector and country level (Macombe *et al.*, 2013a; Wu *et al.*, 2014). Each different level of analysis has its own particularities. Unit process level requires information and datasets similar to environmental LCA. In S-LCA it can, so far, only be represented by a man-hour (working hour) indicator (Traverso, 2018; Benoit, 2009; Achten, 2020). Assessment at the company level also has been carried out in many studies (Macombe *et al.*, 2013b; Tsalis *et al.*, 2017; Zanchi *et al.*, 2018). The challenge to perform S-LCA in companies is the linkages of social inventory such as the potential or verified behaviour of companies to the product systems. In the sector and country levels, many databases are available for gathering the information (Hannouf *et al.*, 2020; Springer *et al.*, 2020; Sureau *et al.*, 2018). However, these databases often used average information representing the typical social situation in a country and an economic sector/industry. Thus, the real social performance may vary from the average. Each type of assessment has its own challenges.

To address these challenges, this paper presents a multilevel S-LCA, integrating the four levels of analysis: unit process, company, sector and country. The objective of the study is to demonstrate the added value of such evaluation on covering data gaps. It is useful and relevant for assessing a complex system and long-term oriented approach such as consequential S-LCA. Second, this paper also fills the limitation in the scientific literature that is lacking on how to carry out consequential social life cycle assessment that so far has been done by a single study (Tsalidis and Korevaar, 2019). The case study is a multistorey building that has long supply chains, located at the local, regional and global scales. The attributional results will also be presented as a comparison to consequential one.

## 6.2. Methodological Approach

### 6.2.1. Social Life Cycle Assessment

*The goal and scope definition*

Even though the objective of the main paper is to demonstrate multilevel analysis in S-LCA, we develop a proposed method and present the case study based on the S-LCA framework and guidelines. The S-LCA conducted here followed the procedures of ISO-14040 (2006) and 14044 (2006) (ISO 14040, 2006; ISO 14044, 2006) and UNEP guidelines consisting of the goal and scope definition, data inventory, impact assessment and interpretation (Benoît and Mazijn, 2009).

The function of the studied system is defined as follows: providing habitable floor area for residential use within the expected life span of 60 years. The functional unit is defined as a 10,341.2 $m^2$ habitable floor area in both attributional and consequential approaches. It is an eight-story hybrid wood-concrete structure consisting of seven primary building materials: wood, concrete, steel, gravel, aluminum, gypsum, and brick.

The main question to ask within consequential approach is “how the global social burdens will be affected by constructing one multistory building?”. This asked the consequence that is located in the future. While in attributional approach, the question will be “what is the social impacts of the construction of one multistorey building?” implying the past social impact from the raw material extraction to construction and the future impact of the use phase and end of life. For the sake of practicality, we present both approaches to see the difference even though both are used for different aim and answer. For consequential approach, transport from abroad from certain materials is included. In the use phase, the focus only lies on the electricity excluding the building maintenance, repair, and cleaning.

For both, difference arose to address disagreements over which input data to use in a LCA. In this paper, however, the marginal suppler identification is extracted from previous study (Fauzi *et al.*, 2021) where we applied five step-wise procedure from (Weidema, 2003), see Table 1.

**Table 6.1.** The long term affected technology (Fauzi *et al.*, 2021)

| Material | Attributional | Geographical consequential scenario | Technological consequential scenario |
|---|---|---|---|
| **Wood** | Quebec | Quebec | Faster in manufacturing process |
| **Concrete** | Quebec | Quebec | Faster in drying time |
| **Steel** | Quebec | China | - |
| **Gravel** | Quebec | Quebec | - |
| **Aluminium** | Quebec | China | - |
| **Gypsum** | Quebec | Ontario | - |
| **Brick** | Quebec | Ontario | - |
| **Electricity** | Quebec | Partly from Ontario | - |

*b. Selecting stakeholders and indicators*

Five groups of stakeholders were selected for this study following the five suggested stakeholder categories in the guidelines for S-LCA. These include workers, consumers, local community, society and value chain actors (suppliers of material component).

The indicators were selected based on literature review of S-LCA studies in construction sector to understand which indicators were repeatedly used. Besides, new indicators were also defined or if existing indicators seemed relevant, we refined it to be used based on our need. The step to select indicator can be seen in the Figure 1.

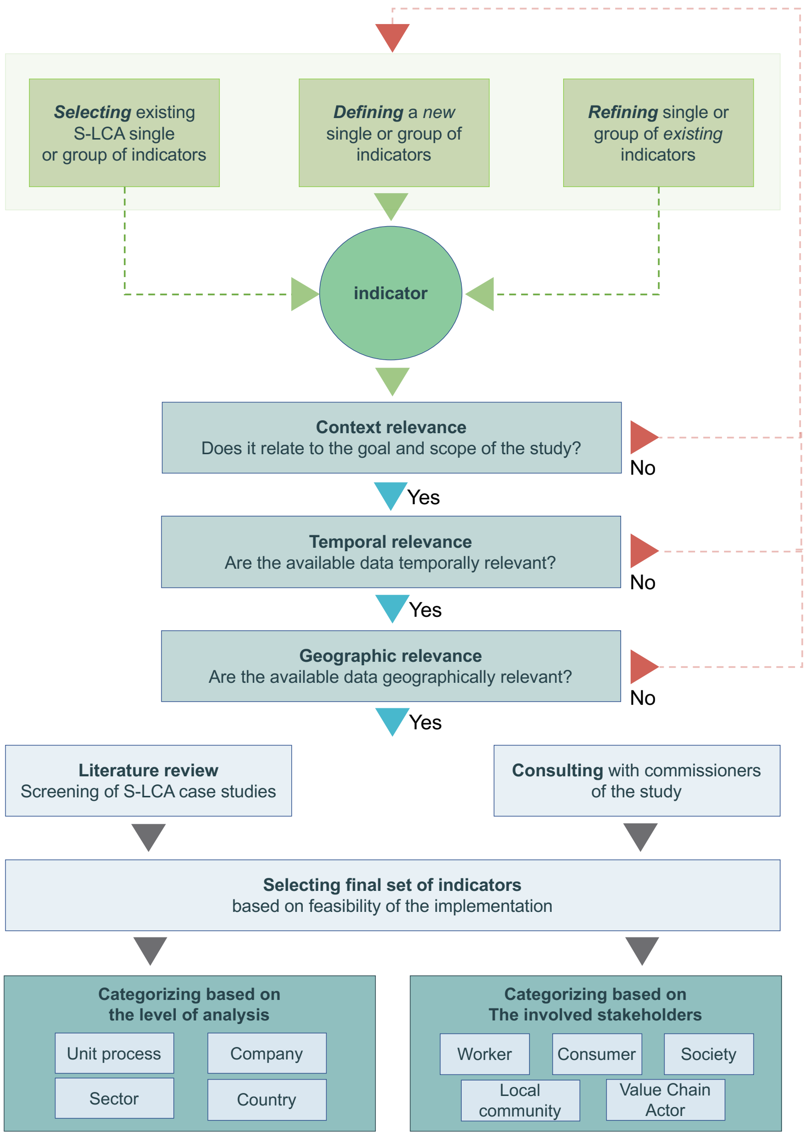



Figure 6.2. Step by step on selecting indicators

Table 6.2. The list of social indicators applied in this study

| | Unit Process | Company[1] | Sector | Country |
|---|---|---|---|---|
| **LOCAL COMMUNITY** | ***Employment (employability)*** | ***Employment***<br>***Respect of indigenous rights***<br>Secure living condition (prevention from conflict)<br>Access to material resources<br>Access to immaterial resources<br>Community engagement | ***Employment***<br>***Respect of indigenous rights*** | ***Respect of indigenous rights***<br>Secure living condition (prevention from conflict) |
| **WORKER** | | ***Child labour***<br>***Health& safety***<br>Freedom of association<br>Forced labor<br>Equal opportunities/ discrimination<br>Fair wage<br>Working hours<br>Social benefits and security | ***Child labor***<br>***Health & safety***<br>Fair wage | ***Child labor***<br>***Health& safety***<br>Fair wage<br>Freedom of association<br>Forced labor<br>Equal opportunities/ discrimination |
| **SOCIETY** | | Corruption<br>Public commitment to sustainability issue<br>Contribution to economic development<br>Technological development | | Corruption |
| **CONSUMER/ USER** | | Health and safety<br>Feedback mechanism<br>End of life responsibility | | |
| **SUPPLIERS** | | Fair competition<br>Promoting social responsibility | | |

[1]Companies assessed are only manufacturing companies
Indicators with bold, italic and underline mark means they are repeated in three levels.
Indicators with green colour means they are repeated in two levels.

## 6.2.2. Applied Methodology

### a. Unit Process Level

Unit process is the first level in multilevel analysis. In this level, only one indicator is applied that is employment in the local community subcategory. It can be called employability since it quantifies man-hour needed for producing a product based in individual unit process. In other word, the defined functional unit is only applied to this level of analysis. A procedure for social life cycle assessment in unit process level has been proposed by (Hunkeler, 2006) derived from life cycle inventory data in man-hour. There are some other indicators that fit to this level as well such as number of hours of child labor, number of hours of accident or number of hours of forced labor (Neugebauer *et al.*, 2017; Traverso *et al.*, 2018; Weidema, 2006). However, due to limited data we only assessed the number of man-hours required to construct the building based on data on individual unit process. It is recommended that employment should be estimated on an individual process rather than from a company or organizational process from real working site since that data is readily available. However, for this study, the authors used RSMeans Database (RSMeans, 2019), due to lacking data from construction site. In this database, the type of material/building element, the method of construction and the type of worker as well as the amount of man-hours needed are provided. In the type of material/building element and the method of construction, it includes information such wood laminated timber with different type of dimension and how to construct it or different type of concrete for different purpose. The type of worker includes some information such labor foreman, cement finisher, equipment operators, bricklayer, etc. As for the consideration whether or not more (local) labour (man-hour) input is considered positive, it is not detailed in this study and remains a debate. More man-hours could be positive since it creates more job but less man-hours needed for production could also be positive due to creating more wealth from efficiency.

The matrix to structure employability is comparable with LCA and LCC but not for the characterization stage. Like LCC, the basic matrix formulation starts from the technology matrix of the physical system which is given by A. The similar scaling factors are also obtained through:

$$s = (A)^{-1} f \quad (15)$$

Equation 15. Scaling factors for job opportunity

where f is the final demand vector and is associated with reference flow. Matrix E is called the employment intervention matrix because it represents the employment interventions of each unit processes. If it is transferred or scaled to the functional unit, then E is objected as

$$E_{scaled} = E\ diag(s) \quad (16)$$

Equation 16. Transformation the employment intervention matrix (E)

into its total employability form (E_scaled)

The employability aggregation is simply done by summarizing all of numbers of man-hour employed by each unit processes or activity..

$$E_{total} = E_{scaled}^{T} 1 \quad (17)$$

Equation 17. The employability aggregation

The example of how the matrix and calculation operate can be found on the Annex C.

### b. Company Level

Second level in multilevel analysis is company level. It is performed through text and content analysis of any report, documented publication and website of the company. This type of assessment has been previously performed (Du *et al.*, 2019; Hannouf and Assefa, 2018). This includes sustainability report, corporate social responsibility report or annual report published by the company. The number of the companies assessed are 22 companies with 17 assessed under consequential framework and 13 under attributional with 8 companies are both assessed in both approaches. The company assessed were the companies that are going to penetrate the market share and / or proxies of average companies whose products used in the market based on statistical sources such data from statista, worldsteel, construction canada, etc. In attributional approach, all of these companies are from Quebec while in consequential approach, the companies are from China for steel and aluminium, from Ontario for brick, gypsum and electricity and from Quebec for the rest. Company A, B represent wood company in both approaches and so do company C, D for concrete and G for gravel. It is because in consequential approach, the marginal suppliers of wood, concrete and gravel will be assumed similar with in attributional in terms of geographical scenario. Company N, O, P represent Chinese steel and so do company R and S for Chinese aluminium. In consequential approach, company Q, T, U, V represent brick, gypsum, electricity from Ontario respectively and K, L, M represent Quebec end-of-life material. In attributional approach, aluminium, brick, gypsum, electricity are from Quebec and they are represented by company E-F, H, I-J respectively. The example of company level assessment has been applied in (Andrews *et al.*, 2009; Aparcana and Salhofer, 2013; Ciroth and Franze, 2011; Dreyer *et al.*, 2010; Franze and Ciroth, 2011; Vinyes *et al.*, 2013).

The evaluation will be allocated to one of the four color representing different level. White color means no documented or report that can be assessed. Red color means there is writing text as evidence of negative violation of the subcategory or indicators. Light green means no evidence of negative violation while dark green means it is reported with good amount of positive evidence (Du *et al.*, 2019). The example of sets of questions and keywords used can be found in Annex C.

#### c. Sector Level

How the construction of multistory building will affect the social aspect of industrial group and stakeholders involved is also assessed in sector level, the third level in multilevel analysis. We used Exiobase and social hotspot database (SHDB) as our main databases for analysing the potential of social consequences and the sphere of influence to two stakeholders: worker and local community (Weidema, 2018; Zimdars *et al.*, 2018). The social indicator assessed with Exiobase is the employment. The social indicators assessed with SHDB are risk of child labour, non-fatal work-related injuries, fatal injuries, violation of indigenous rights and the risk of sector average wage under sweat-free wage. The social risk exposed to some indicator and sub-indicators are presented between two approaches with five bars indicating very high risk and one bar indicating no evidence of risk.

#### d. Country Level

Note to remind, the consequential approach used revealed that some marginal suppliers in the future will be coming from abroad as it is a prospective study when the building will be constructed in the future. Thus, in the country level, we compare the social risk of some indicators in China and Canada. It is because the geographical location is all centered in Canada when we take attributional approach and partly located in China when we take consequential approach. The results from the analysis of country-specific data were presented using the SHDB's four-level risk scale based on even distributions of the data, where quartiles were defined as low, medium, high, and very high risk (Benoit-Norris *et al.*, 2012). The indicators applied in this study can be seen in Table 2. They include but are not restricted to the following: freedom of association, health and safety, child labor, fair wage, equal opportunity, respect of indigenous right, secure living condition and corruption. In consequential perspective, the country level of assessment on China only applies to steel and aluminium as they are from there while the rest are from Canada. In attributional, all of them are from Canada.

## 6.3. Result and Discussion

Result and discussion section will be presented in two sub-section. First section will present and discuss the last two phases of S-LCA framework. Second section will present the added value of using multilevel analysis on S-LCA.

### 6.3.1. On Data Inventory, Social Life Cycle Impact Assessment and Interpretation

The results of S-LCA are presented in four part according to the four level of assessment in multilevel analysis: unit-process, company, sector and country.

#### a. Unit Process Level

As first level of result in multilevel analysis, Figure 1 depicts employment creation of certain type of construction workers based on attributional and consequential scenario. Since, in consequential scenario, it is predicted that future technology will have some advancement on fastening in manufacturing process for some wood technology, it will give a little different on the results. This is according to prospective analysis when the building will be constructed in the future.

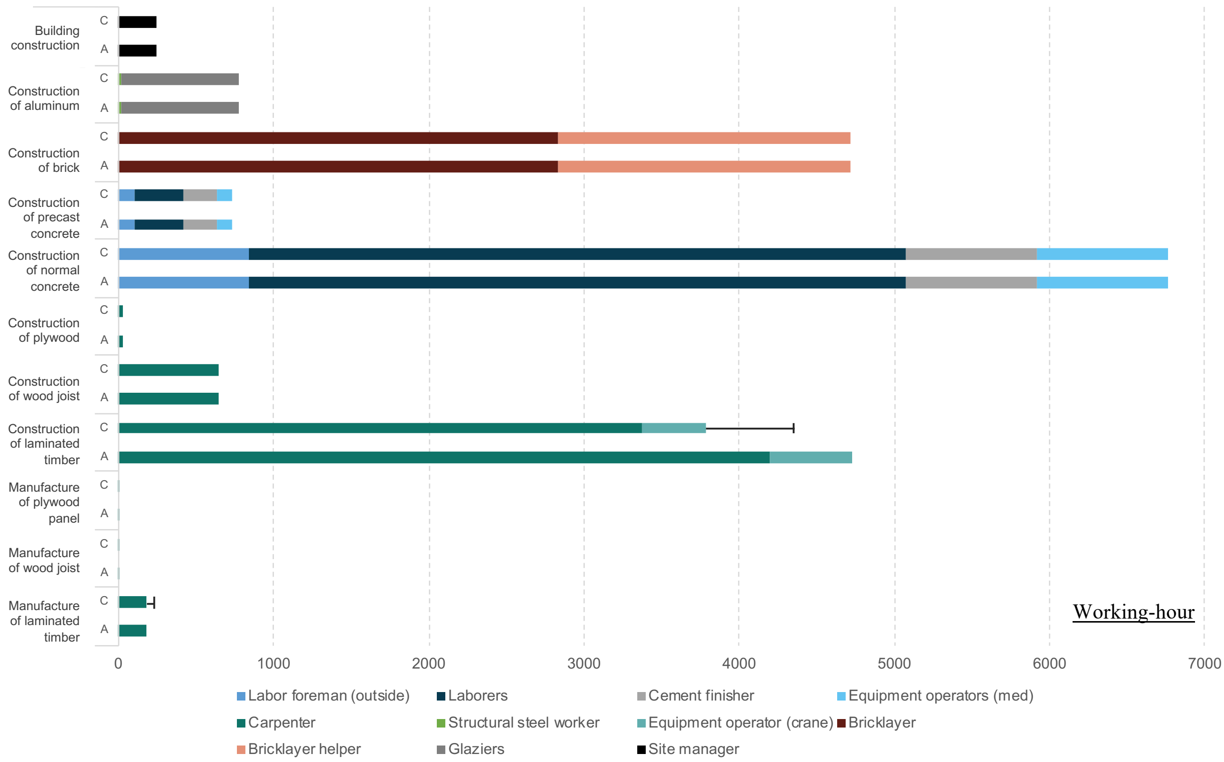


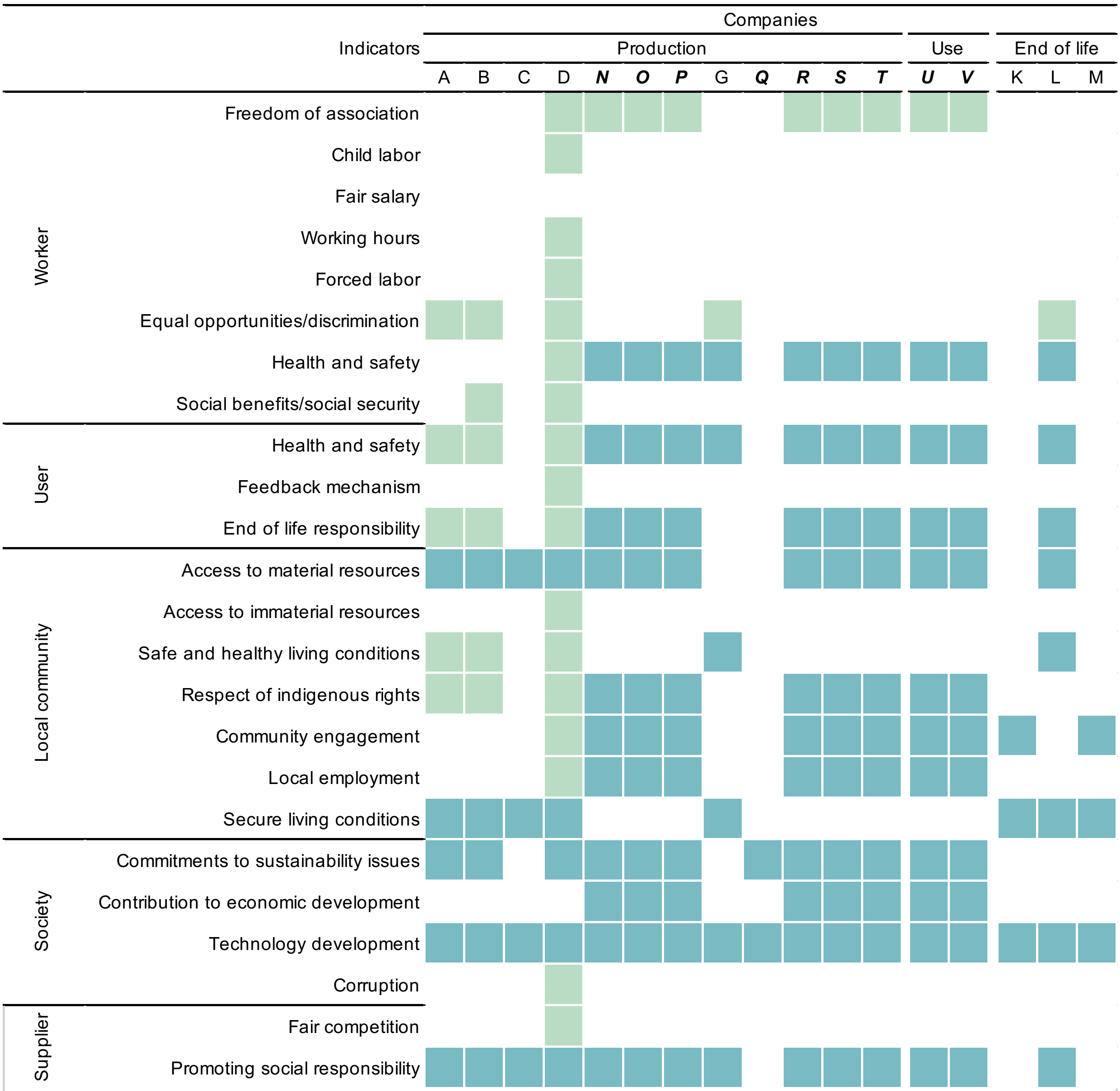

Figure 6.3. First level of multilevel analysis – unit process level analysis with indicator: employment creation in **working-hour**. Employability of one multistorey building with consequential approach

Reflecting with attributional approach, the result shows a little different as can be seen in Figure 1. In the consequential model where the manufacturing of some building materials (i.e. laminated timber and concrete) is assumed to be 10-30% less time consuming than in attributional (Brandner, 2014; Smyth, 2018), the job created are lower. In the future, the timber, as predicted, needs less time thus less worker, to be constructed as compared to current situation. As for concrete, fastening in drying time will not give much different man-hour reducement.

The limitation in this model lies on the database used for this case study since this is not based on site specific data rather from average construction data in North America. Second limitation regarding the man-hour is that not all types of employability are included. Most of them are the on-site worker such as laborers, operators, bricklayer, etc while managerial professions are not included except in company and sector levels. The third limitation is the lack of data itself. If the real site-specific data is available, the use of database can be avoided and the real number of man-hour can be quantified.

### b. Company Level

We assessed the social performance of the companies involved through content and text analysis. Chinese steel and aluminium corporate (represented by N, O, P and Q, R) as well as brick, gypsum and electricity companies (S, T and U-V) in Ontario are considered here, beside Quebec companies. Figure 2 illustrates the overall results and the following text summarize the highlights.



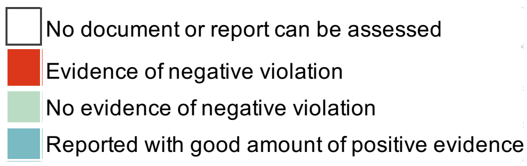



Figure 6.4. Social performance of companies with consequential approach

- *Steel and aluminium production in China.* Chinese steel and aluminium firms have an overall positive social performance. That is the case, for instance, of employee health and safety practices, whether they pertain to occupational accident, physical health or worker's wellbeing. This commitment is self-evident from a corporate standpoint but it is also significant from a legal standpoint, as it complies with Chinese society's regulations. The company engagement to their local community is also considerable, with the vast majority participating in variety of ways. However, it is suggested that more could be done in terms of raw material mining (such as iron and aluminium ore), with more corporations adopting methods aimed at reducing social risk to the health community.

- *Brick production in Ontario.* The technology development and sustainability commitment indicators are described in detail in their documented report. However, for other aspects there have not much discussion further on employee working condition neither on their engagement with local community, customer and supplier.

- *Gypsum production in Ontario.* The company practices good occupational health and safety for its workers. The lost time and recordable injury rates are well documented. It is considered low rate compared to lost time and injuries from manufacturing industry average. The company promotes equal opportunities for all diverse background. The top management leaders are diverse as well as the full-time workers. Women in manufacturing industry are also well highlighted. For society, the company holds many patents and has significant role to boost local economy.

- *Electricity generation in Ontario.* Safety and health measure is reported annually and the fatality, injury rate and occupational accident declined each year. Transparency and high satisfaction rate are highlighted in the report and their commitment towards sustainability in electric sector. The engagement with indigenous business for their procurement are also their top priority for supporting local economic development.

According to the sources considered, figure 3 shows the result of content and text analysis for attributional approach. The technologies and activities assessed in attributional are located in Quebec and from the geographical standpoint, this will give different result with consequential approach where some materials are located in Ontario and China.

Company level assessment under attributional approach shows more positive evidence of the company's social performance. Companies in production phase have more data to assess but it is not the case for end-of-life phase. In the production phase, concrete and steel companies are the ones that provide most data and so do the electricity company in use phase.

Speaking for impact assessment across indicator, access to material resources, secure living conditions, commitment to sustainability issue, technology development and promoting social responsibility are five indicators that have been addressed most in more positive way in all companies. In other hand, most of indicators within worker categories are challenging to find thus resulting in difficulty to mention social situation related to freedom of association, child labor, working hours and forced labor.

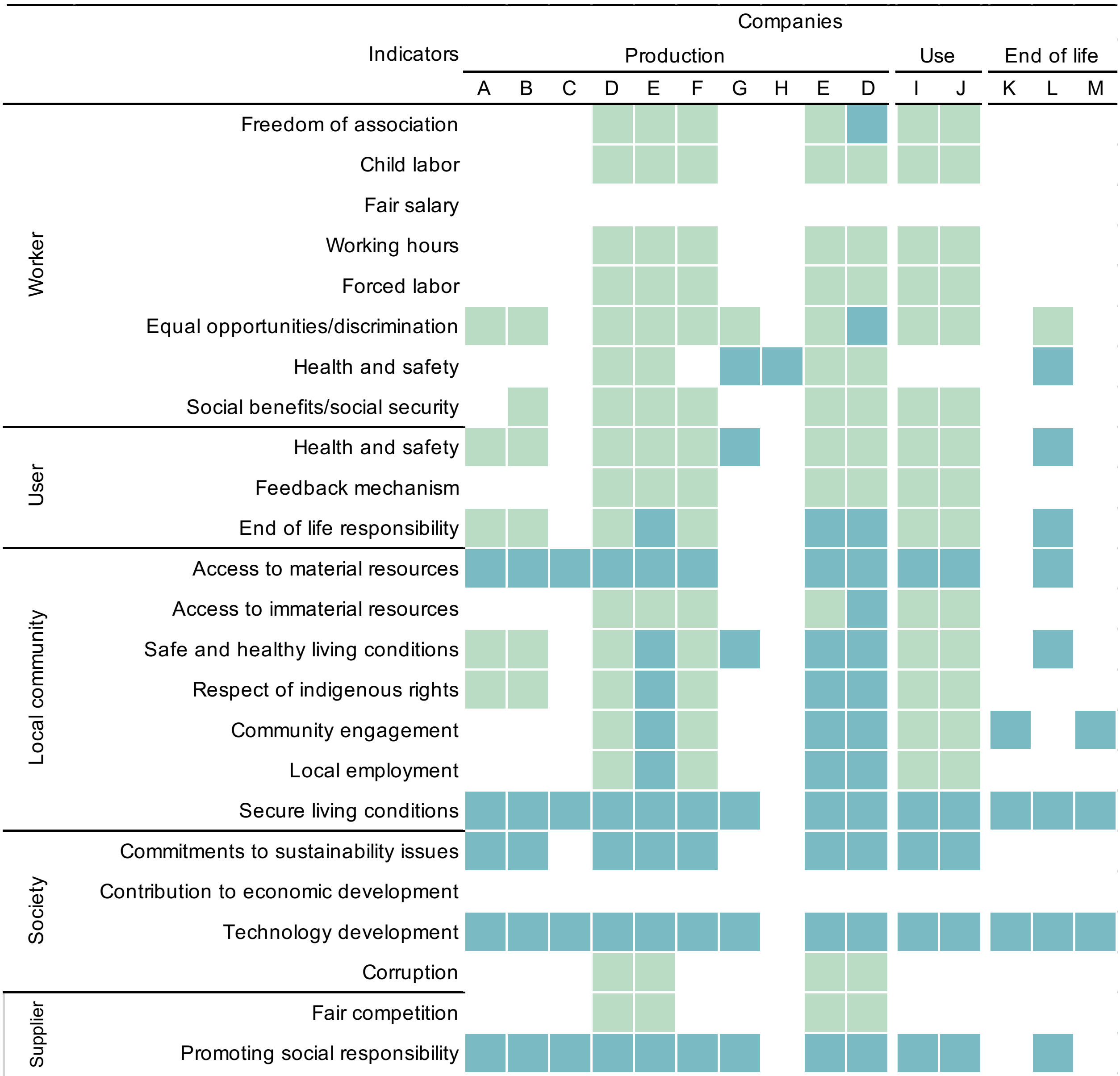


Figure 6.5. Social performance of companies with attributional approach

### c. Sector Level

Third level assessed within multilevel analysis is sector level. Table 3 below presents the social performance of associated sector towards the stakeholder (worker and local community) from consequential perspective.

Table 6.3. Social impact or benefit in sector level – consequential approach

Worker and Local Community

| Indicators | Unit | Wood production (forestry and manufacture) | Concrete production (manufacture of cement, lime and plester and construction) | Steel production (ferrous metal and manufacture of basic iron and | Aluminium production (metal product) | Gypsum production (mineral products) | Electricity production | Re-processing secondary material to aggregates (Canada) | Re-processing secondary steel into new steel | Re-processing secondary wood material into new wood material |
|---|---|---|---|---|---|---|---|---|---|---|
| Risk that Sector Avg Wage is below Sweatfree Wage | | Medium | Low | Medium | Low | Low | Low | | | |
| Risk of Child Labor by Sector (qualitative) | | No evidence | No evidence | High | High | No evidence | No evidence | | | |
| Non Fatal Work Related injuries by sector | | High | High | No data | No data | High | High | | | |
| Fatal injuries by sector | | Medium | Low | No data | No data | Medium | Low | | | |
| Indigenous Sector Issues Identified | | High | High | Medium | Medium | Medium | High | | | |
| | ton | 18,631,340.00 | 89,241,960.00 | 60,000,000.00 | | | 1,313,190.00 | 789,535.00 | 7,118,136.00 | 4,312,904.00 |
| Employment: low skilled male | 1000 pers | 9.74 | 154.53 | 28.06 | | | 2.09 | 0.00 | 2.858 | 2.17 |
| Employment: low skilled female | 1000 pers | 2.30 | 12.36 | 5.55 | | | 0.12 | 0.00 | 0.44 | 0.51 |
| Employment: medium-skilled male | 1000 pers | 50.40 | 793.97 | 165.19 | | | 42.40 | 0.01 | 14.78 | 11.25 |
| Employment: medium-skilled female | 1000 pers | 10.30 | 71.55 | 28.78 | | | 13.70 | 0.00 | 1.96 | 2.29 |
| Employment: high-skilled male | 1000 pers | 20.40 | 72.08 | 80.96 | | | 25.27 | 0.00 | 5.98 | 4.55 |
| Employment: high-skilled female | 1000 pers | 5.10 | 1.99 | 11.26 | | | 9.06 | 0.01 | 0.96 | 1.12 |
| Employment: vurnerable employment | 1000 pers | 3.20 | 1,005.38 | 1.04 | | | 0.04 | 0.00 | 0.06 | 0.72 |
| Employment hours: low skilled male | million hours | 18.70 | 376.73 | 45.64 | | | 3.90 | 0.00 | 5.49 | 4.18 |
| Employment hours: low skilled female | million hours | 4.40 | 30.13 | 9.09 | | | 0.23 | 0.00 | 0.84 | 0.98 |
| Employment hours: medium-skilled male | million hours | 96.40 | 1,935.52 | 269.09 | | | 79.00 | 0.02 | 28.27 | 21.5 |
| Employment hours: medium-skilled female | million hours | 19.70 | 174.45 | 46.83 | | | 25.00 | 0.01 | 3.78 | 4.41 |
| Employment hours: high-skilled male | million hours | 39.10 | 175.70 | 131.75 | | | 47.00 | 0.01 | 11.47 | 8.73 |
| Employment hours: high-skilled female | million hours | 9.70 | 4.86 | 18.31 | | | 16.00 | 0.01 | 1.85 | 2.15 |
| Employment hours: vurnerable employment | million hours | 5.10 | 2,450.90 | 1.71 | | | 0.00 | 0.00 | 0.072 | 1.14 |

No data
No evidence
Low
Medium
High
Very high

In sector level, the social impacts associated to each life cycle phase are elaborated. In production phase, almost all materials are linked to medium to high risk of child labor, non-fatal and fatal work-related injuries and indigenous issues. Steel and aluminium produced in China are exposed to high risk of child labor while wood and concrete produced in Quebec to non-fatal work-related injuries as well as Gypsum produced in Ontario. As for indigenous issue, all materials are associated to it with wood and concrete being classified to high risk while steel, aluminium and gypsum to medium risk. As for some health and safety indicator in China such fatal and non-fatal work-related injuries, they are not found in the database. For employment indicator, the main structural material (wood, concrete and steel) sectors absorbed more medium skill male than low or high skill employee.

In use phase, the electricity production is affiliated to high risk of non-fatal work-related injuries and indigenous issue as well. As for end-of-life phase, the impacts are not captured in database.

Besides SHDB, we also performed literature review from scientific journal resulting in similar results from what we found from databases. The highlight of the results can be explained as follows:

- *Steel sector in China.* Steel workers in China are exposed to higher mortality and cancer according to a 2015 study, especially in Anshan region (Guo *et al.*, 2015; Wu *et al.*, 2019).
- *Aluminium sector in China.* Aluminium workers in China are exposed to some health risks and occupational injuries (Li *et al.*, 2016). Cognitive impairment of the workers in large-scale aluminium factory in the country has been studied by many researchers (Li *et al.*, 2016; Meng *et al.*, 2019). This includes cerebral vascular disease, epilepsy, brain trauma, Parkinson's and mental diseases.

In the next paragraphs we will present the results from attributional perspective. To remind again, all sectors assessed here is located in Quebec, Canada and Table 4 shows the results.

Table 6.4. Social impact and benefit in sector level – attributional approach

| | Indicators | Unit | Wood production (forestry and manufacture) | Concrete production (manufacture of cement, lime and plester and construction) | Steel production (ferrous metal and manufacture of basic iron and | Aluminium production (metal product) | Gypsum production (mineral products) | Electricity production | Re-processing secondary material to aggregates (Canada) | Re-processing secondary steel into new steel | Re-processing secondary wood material into new wood material |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Worker and Local Community | Risk that Sector Avg Wage is below Sweatfree Wage | | | | | | | | | | |
| | Risk of Child Labor by Sector (qualitative) | | | | | | | | | | |
| | Non Fatal Work Related injuries by sector | | | | | | | | | | |
| | Fatal injuries by sector | | | | | | | | | | |
| | Indigenous Sector Issues Identified | | | | | | | | | | |
| | | ton | 18,631,340.00 | 89,241,960.00 | 60,000,000.00 | | | 1,313,190.00 | 789,535.00 | 7,118,136.00 | 4,312,904.00 |
| | Employment: low skilled male | 1000 pers | 9.74 | 154.53 | 25.76 | | | 2.09 | 0.00 | 2.858 | 2.17 |
| | Employment: low skilled female | 1000 pers | 2.30 | 12.36 | 3.96 | | | 0.12 | 0.00 | 0.44 | 0.51 |
| | Employment: medium-skilled male | 1000 pers | 50.40 | 793.97 | 133.28 | | | 42.40 | 0.01 | 14.78 | 11.25 |
| | Employment: medium-skilled female | 1000 pers | 10.30 | 71.55 | 17.72 | | | 13.70 | 0.00 | 1.96 | 2.29 |
| | Employment: high-skilled male | 1000 pers | 20.40 | 72.08 | 53.96 | | | 25.27 | 0.00 | 5.98 | 4.55 |
| | Employment: high-skilled female | 1000 pers | 5.10 | 1.99 | 8.72 | | | 9.06 | 0.01 | 0.96 | 1.12 |
| | Employment: vurnerable employment | 1000 pers | 3.20 | 1,005.38 | 0.56 | | | 0.04 | 0.00 | 0.06 | 0.72 |
| | Employment hours: low skilled male | million hours | 18.70 | 376.73 | 49.48 | | | 3.90 | 0.00 | 5.49 | 4.18 |
| | Employment hours: low skilled female | million hours | 4.40 | 30.13 | 7.64 | | | 0.23 | 0.00 | 0.84 | 0.98 |
| | Employment hours: medium-skilled male | million hours | 96.40 | 1,935.52 | 254.80 | | | 79.00 | 0.02 | 28.27 | 21.5 |
| | Employment hours: medium-skilled female | million hours | 19.70 | 174.45 | 34.12 | | | 25.00 | 0.01 | 3.78 | 4.41 |
| | Employment hours: high-skilled male | million hours | 39.10 | 175.70 | 103.44 | | | 47.00 | 0.01 | 11.47 | 8.73 |
| | Employment hours: high-skilled female | million hours | 9.70 | 4.86 | 16.68 | | | 16.00 | 0.01 | 1.85 | 2.15 |
| | Employment hours: vurnerable employment | million hours | 5.10 | 2,450.90 | 0.64 | | | 0.00 | 0.00 | 0.072 | 1.14 |

All sectors, under attributional approach, are relatively affiliated to low risk (if not, medium risk) of child labor, unfair wage and fatal injuries. However, for non-fatal work-related injuries are found on high risk state in Canada.

Second noteworthy to mention is about the medium to high risk of conflict with indigenous rights. All sectors in Canada are linked to issues that involved land and/or forest management. Sectors such wood, cement, steel, aluminium and gypsum required organized land management for their mining activities. However, forest management certification and regulation that concerns aboriginal or indigenous people are not strict and well defined. This could potentially open a room for land and/or forest conflict (Teitelbaum and Wyatt, 2013) and collaboration between different authorities is needed if they have commitment to reduce it (Fortier *et al.*, 2013; Wyatt *et al.*, 2019, 2013).

For employment indicator, the main structural material (wood, concrete and steel) sectors in Quebec, Canada also absorbed more medium skill male than low or high skill employee.

Even though, the social performance of product is more linked to company or organizational behaviour but it is relevant to assess indicators in sector and country level.

### d. Country Level

Last level to explore in multilevel analysis is country level. Since not all data could be found in three previous levels, having country level aggregated data could help identifying the potential area of social impact or benefit. We used SHDB to understand the social impact that could potentially be happening in country level. This SHDB quantifies the social risk for country-specific sectors and identify the risks based on the themes and category such worker, local community, society, etc. The data are obtained from various international databases that consider the representativeness of the geographical coverage. Figure 4 presents the results of this for Canada and China. Results on China might only be relevant for steel and aluminium since these materials are from there.

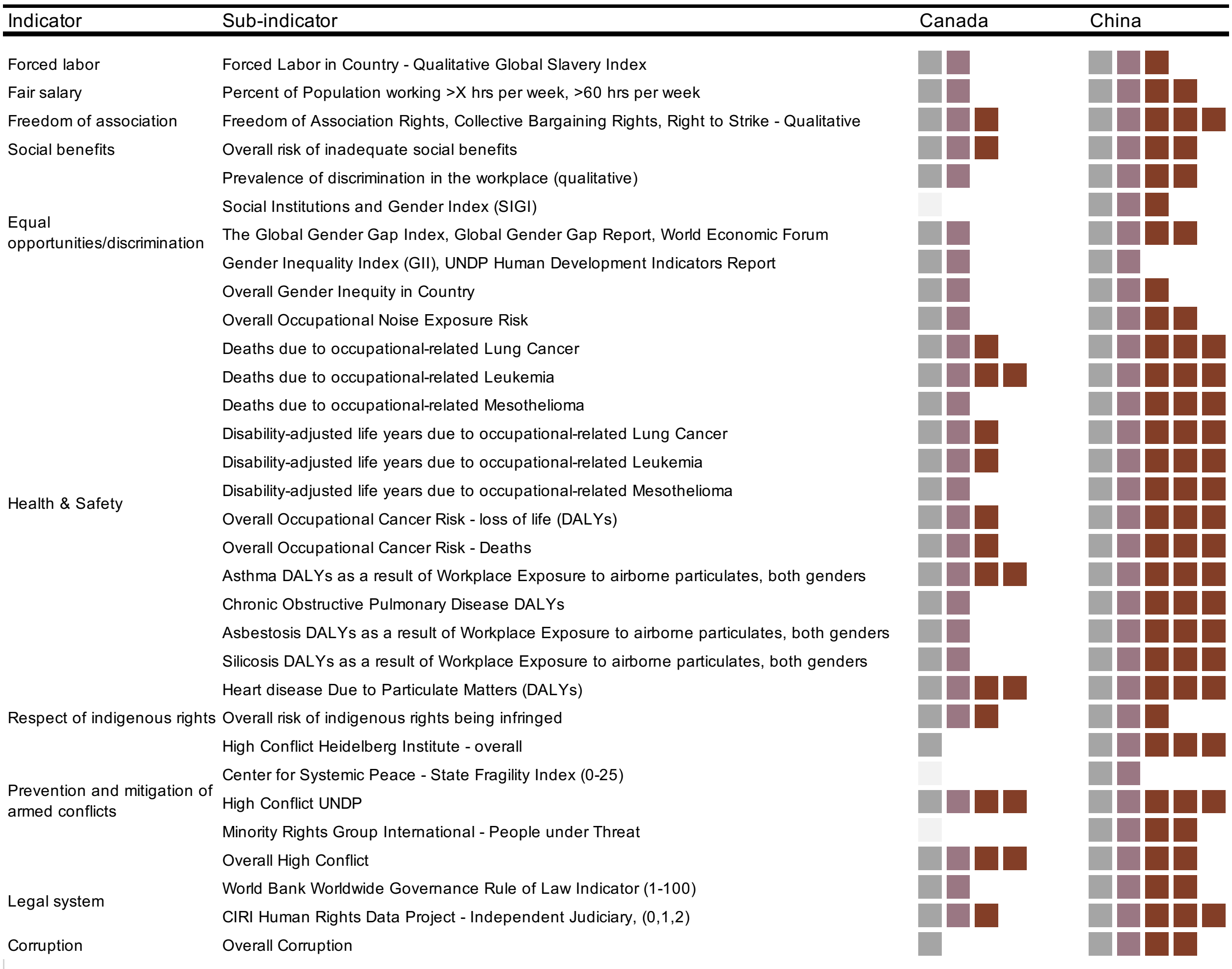


Figure 6.6. Social impact or benefit on given indicators in China and Canada

In most indicators, China is associated with social issues in higher risk than Canada. The social issues are found with the risk being classified to "very high" on freedom of association, equal opportunities or discrimination, health and safety, respect of indigenous rights and prevention and mitigation of armed conflict. Of the risk categories presented in China, the one with the most indicators in very high risk level is health and safety.

- Social risk in China. The working condition itself is considered negative for some indicators, i.e. the percent of people working excessively over time, high risk of their freedom for association, collective bargaining and rights to strike. Moreover, in higher risk level, wage replacement for paid parental leave as well as maternity and paternity leave pay are considered low. For migrant worker, worker's remittances and compensation paid is considered in very high risk. In other sense, deaths due to occupational-related diseases (lung cancer, leukimia, mesothelioma) are reported in very high risk as well as worker's exposure to airbone particulate (asbestos, silicosis). They also have high risk of occupational toxics and hazards, discrimination in the workplace, and restriction of association rights.

- Social risk in Canada. Mining in Canada in general has issue with social acceptability (Campbell and Prémont, 2017). This has been study also by (Bergeron, 2021; Collins and Kumral, 2021), concluding that besides social risks, opportunities also exist to address them.

### 6.3.2. On Data Gaps Filling by Multilevel Analysis

We now analyze the above results with a view on addressing the research goals of data filling posed in the introduction.

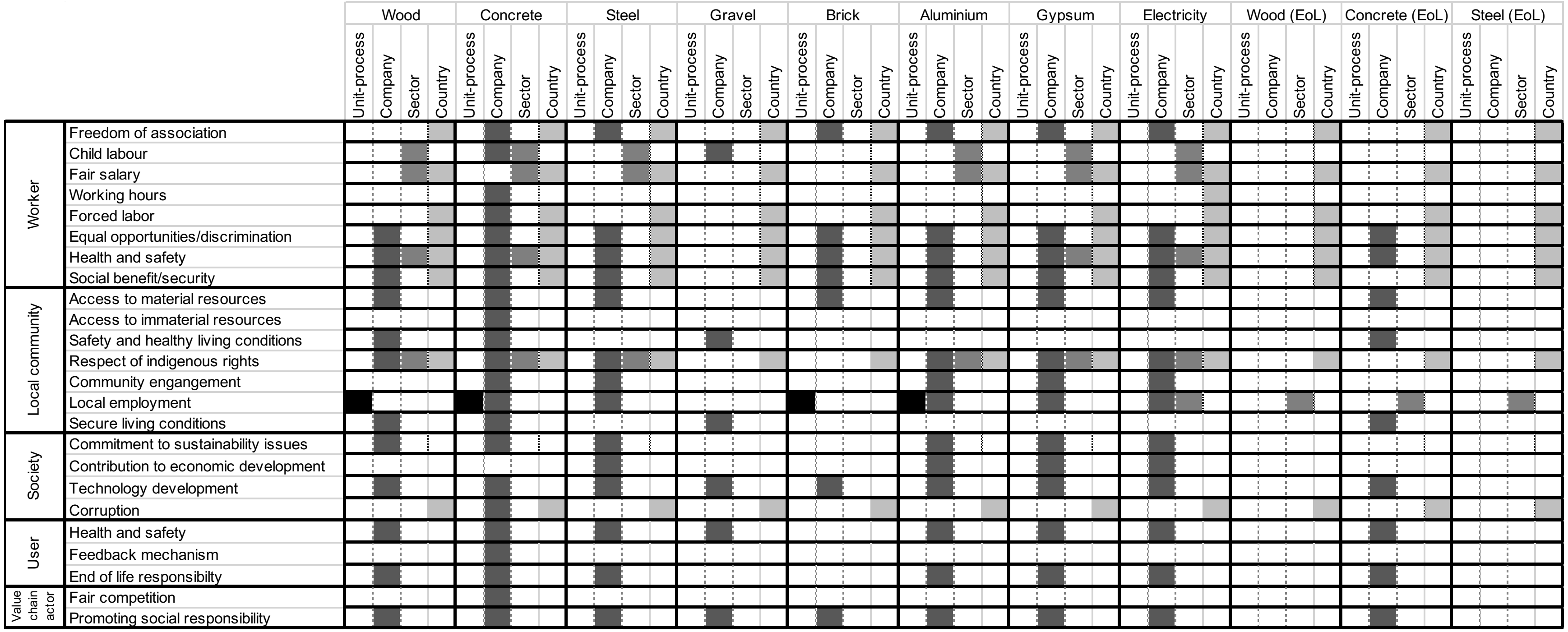



Figure 6.7. The overall data found on multilevel analysis

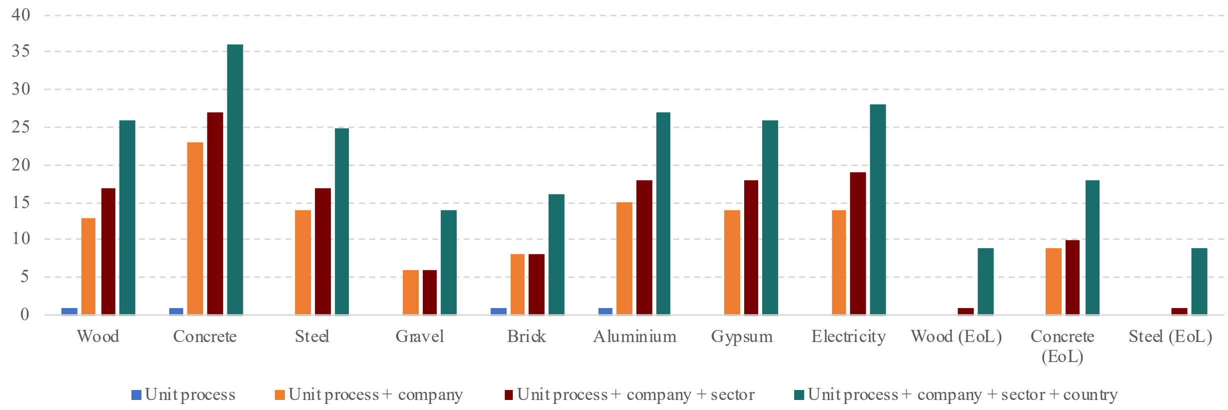



Figure 6.8. Total cumulative indicators covered

*The advantage of using multilevel analysis*

Using multilevel analysis to fill data gaps could be beneficial. Consider this case study: if this consequential S-LCA was only performed at the company level, the data filling would be limited to specific materials and indicators. Only concrete, steel, aluminum, gypsum, and electricity materials or activities could fill at least 14 of the 24 social indicators through company's assessment. The rest could not assess 14 indicators, and no indicators could be assessed for wood and steel waste material or activities during the end-of-life phase. If it was only performed at one level (company level), it is also shown that only seven social indicators (from five stakeholders) can be evaluated for at least eight different materials or activities. For the remaining indicators, fewer than eight materials or activities could show fewer than seven social indicators. Even, in the case of fair salary and access to immaterial resources, zero material or activity could provide the social indicators.

For certain indicators, having a single indicator that is assessed in more than a level can be favorable. For example, two indicators (health & safety in worker category and respect to indigenous people in local community) are assessed in three levels (company, sector and country level). We can cross-check if the result is conflicting or not within these three levels and this can also give the reader different perspectives to interpretate because the stakeholders involved in each level is different. The worker assessed in company will be narrower with the worker assessed in sector and country and likewise for local community.

If we go one step further and add one other level of assessment, for example, sector level, we will have more coverage in terms of both the material (life cycle) and the social indicators assessed (the stakeholders). More activities/materials in the production phase and end of life can show us their social impacts by performing another level assessment like this. Wood manufacturing can demonstrate more social impacts/benefits in four additional indicators (child labor, fair wages, health and safety, and respect for indigenous rights) or two stakeholders (worker and local community), whereas wood and steel end-of-life can demonstrate one additional indicator (employment) for worker stakeholder. Furthermore, more indicators can be evaluated by a larger company/sector. Child labor, fair wages, health and safety, respect for indigenous rights, and local employment are just a few examples of indicators that can be easily assessed by more activities/companies. This would not be possible without adding one more level of analysis. This would not be possible without adding one more level of analysis. The additional coverage from adding one level more from unit-process to company, sector and country and the data gap filling depicted can be seen in Annex C.

The level that needs to be developed more is unit process level and fortunately it can be linked to environmental and cost assessment since it has similar matrix formulation. In this case study, the level that gives many available data is company and county level. Adding level assessment from sector to country does not give many advantages but from unit process to company and from sector to country can have more advantages, as can be seen in Figure 6.

One more to note for user is the relevance. The sector and country level assessment result are from database. These databases often used average information representing the typical social situation in a country and an economic sector/industry. Thus, the reality social performance may vary from the average. The result from company level assessment could be outlier sometimes. However, the results could still help facilitate knowing the background in the country where the company produce and having them as complementarities is still beneficial for narrowing the data gap and to accompany the available data.

Even though more data is not always better, if gathered with care, it can broaden the view of understanding the potential hotspot of social impact/benefit and the sphere of the social impact/benefit to the stakeholders.

## 6.4. Conclusion and Recommendations

*General conclusion on the application of multilevel analysis on consequential S-LCA*
S-LCA was carried out by evaluating the potential social impact and benefit from the product's life cycle. Using multilevel analysis, which is applied to consequential and attributional social LCA, could aid in filling data gaps, particularly in consequential. While more data is not always better, it can help to understand the possible hotspots of social impact/benefit and the field of influence of social impact/benefit to stakeholders. Filling data gaps is important in two ways: 1) filling data gaps on indicators and 2) filling data gaps on the product system's life cycle (cradle to grave).

*The advantage of multilevel analysis on filling data gaps on indicators*
Using multilevel analysis in consequential social LCA, it was discovered that importing steel and/or aluminum from China is potentially associated with certain negative social impacts (restrictions on worker association, risk on health and safety, and child labor) but also some beneficial contributions (employment). Ultimately, revealing these types of indicators may help policymakers predict and plan for negative consequences before they occur, and vice versa promote positive benefit.

*The advantage of multilevel analysis on filling data gaps on life cycle phase*
More importantly, as with LCA, the need to include a full life cycle perspective exists because the impact throughout the product's life cycle phase is frequently overlooked due to missing data. Also, even if a specific phase's contribution to the system-wide impact is minor, an LCA that spans only one process or phase cannot be called as such. Performing a multilevel analysis could help to fill in data gaps from material's life cycle perspective.

*Limitation on the use of databases*
Social situation changes dynamically. Because the social impacts are located in the future, the consequential approach has higher uncertainties. Predicting future social consequences from current product or activity using current databases is subject to notable limitations, such as data

availability and quality. Although much remains unknown about the future and how technology will be affected, many things could be debated and improved in the future, such as a more sophisticated modeling approach, less aggregated data, and more site-specific information.

# Chapter 7 – Discussion

This research has a main question on how a consequential LCSA can help in assessing environmental, economic and social consequences (sustainability) of a decision more comprehensively. It can be achieved by applying consequential LCA, LCC and S-LCA. By these three tools, this research project intends to provide a methodological contribution by reducing the existing gaps in the field of LCSA. As previously stated, these gaps are practically considered in LCA, LCC, and S-LCA individually and/or in LCSA as a whole framework, as well. This chapter focuses on the research project contribution while the answer to the main question will be elaborated in the next chapter.

*Methodological Contribution*

There have only been a few LCA studies on the construction of multistory hybrid buildings that have been found in the LCA literature review. A new layer of contributions is added to the building industry by this thesis's **second article** (chapter five), which provides information on the environmental impact of an eight-story building constructed of wood-concrete-steel. This study can serve as a comprehensive example on how to carry out a life cycle assessment for a hybrid multistory building, more precisely in consequential approach. Aside from the insights gained from conducting both approaches, as explained in the second article, the detail of practical steps conducted in consequential approach is a successful attempt to answer the research gap on the lack of a consequential approach on LCA when it is combined with LCC (**research gap – RG 2**) (the term of research gap is called research issue in the first article or chapter 2). Beside that, there have only been a few LCA studies on the construction of multistory hybrid buildings that have been found in the LCA literature review. A new layer of contributions is added to the building industry by this thesis's **second article** (chapter five), which provides information on the environmental impact of an eight-story building constructed of wood-concrete-steel.

In the field of LCC, the most common type of LCC that can be found in the literature is attributional LCC. Owing to that fact, none of them, on the other hand, convey the long-term repercussions of the causal-effect relationships. The purpose of this study, which stems from the second article, is to present a consequential approach that may be used in LCC. The three-step approach described in the article provides a straightforward method of performing LCC under the consequential approach. Additionally, it was a research opportunity and a proposal to define and draw step-wise procedure for capturing the lacking consequential approach in LCC. In the same way in consequential LCA, consequential LCC has an additional layer of complexity as well, particularly when it involves future estimation when accounting for long-term economic impact from a past or current database. Due to the fact that this is not a one-way solution, having attributional LCC as a complement is recommended. The lessons learned and new insights and perspectives can be gained by doing so, i.e. the largest contributor within the material category can be different due to the future price influence, as can be seen in second article or chapter 5. This is also an accomplishment for answering research gap on the lacking of consequential approach on LCA when it is combined with LCC or S-LCA (**research gap – RG 2 and RG 4**).

In S-LCA research, the first contribution is the consequential approach that is developed. The consequential approach also needs to be considered in social aspect and this research project filled the gap regarding the lack of consequential approach in S-LCA. The consequential method used in this S-LCA study took into account marginal technologies that were impacted by a change in the system's boundary conditions.

Secondly, multilevel analysis is also contribution from **the third article**. So far, the assessment in S-LCA is limited to a certain level (company or country). This thesis presents four levels of assessment at unit processes, company, sector and country level. The practical step to conduct at unit level and company level is also presented. Even though in the third article, the presentation of the S-LCA at unit-process level are not accompanied by LCA nor LCC, the inventory modeling is in accordance with LCA and LCC inventory. Text and content analysis, supported by documented evidence, is carried out at the company level in order to better understand the social performance of the companies participating in the supply chain. In order to complete the social performance evaluation in S-LCA, an additional two levels of analysis (at the sector and country level) were added. The article does, in fact, close the current research gap in S-LCA regarding the multiple levels of evaluation (**research gap – RG 6**). From this assessment, it can be learned that these types of evaluations can provide a broader spectrum of possible results in more comprehensive manner even if it risks becoming less precise due to the expanded assessment and the greater data to collect. From there, it can be determined which consequences are expected to be the most important for decision-making and it can be communicated to the different stakeholders at different levels on how to address them.

In the field of LCSA research, no study has ever conducted a life cycle sustainability assessment in isolation or as part of a consequential approach. This thesis consists primarily of the results of consequential LCSA, which is comprised of consequential LCA, consequential LCC, and consequential S-LCA, each of which was performed individually.

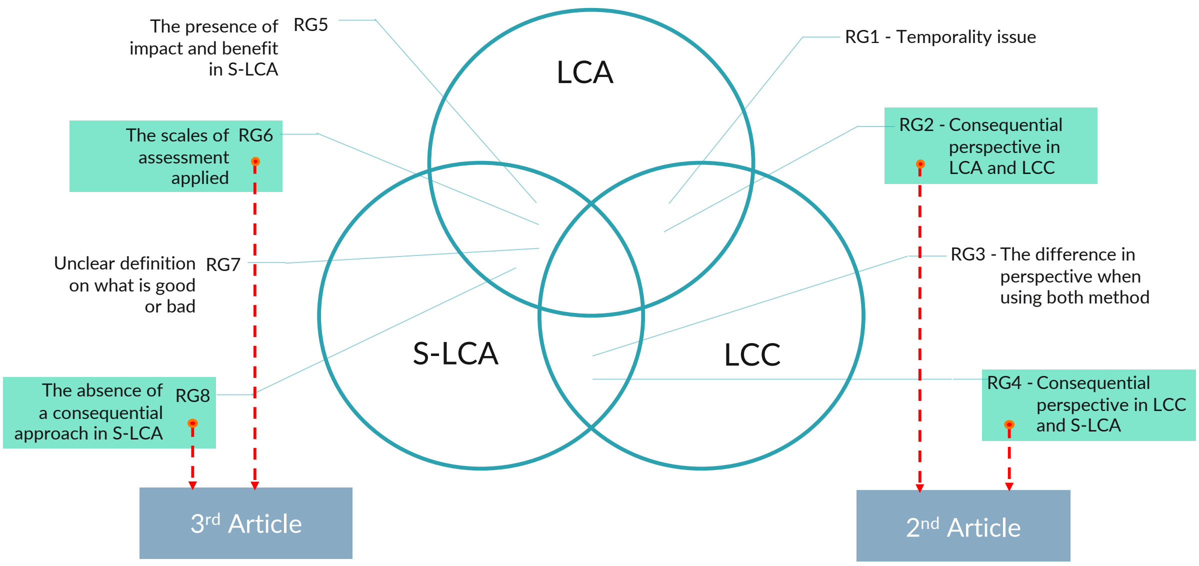



Figure 7.1. Research question and its relevant article addressed (adapted from Fauzi, 2019)

*Contribution to Policy-maker and Practitioner*

This thesis also provides to policy-makers the possibility in understanding the whole picture of the supply chain to avoid unintended consequences in environmental, economic and social aspect.

This thesis provides policymakers and other important stakeholders with the understanding that, if the existing supply and demand in the construction sector is maintained, importing steel and aluminum from China will be unavoidable. As a result, key stakeholders must consider the potential social effects (risks) of steel and aluminum imports from China before they occur. These potential consequences may include negative social impacts such restrictions on worker association, risk on health and safety, and child labour but also some beneficial contributions like employment.

Second, within the same framework, policy-makers must consider the environmental repercussions of the material production phase, particularly in the case of certain imports from China and Ontario. For example, 71 percent (1.99E+01 DALY) of the probable consequences are related to human health (midpoint category), with the majority of the effects occurring in the respiratory organics-inorganics and ionizing radiation categories. The transcontinental transportation of steel from China is primarily responsible for these consequences. The impact of carcinogens on the environment accounts for 48 percent (1.89E+05 kg C2H3Cl eq) of the total, which is mostly due to the fuel used in the Chinese steel manufacturing process. Noncarcinogens, ozone layer depletion, and carcinogens are the pollutants that have the greatest influence during the usage phase. These ramifications are primarily due to projected increases in electricity consumption, which will be partially met by Ontario, where natural gas is the primary source of electricity generation. Among the other most significant environmental consequences is the degradation of ecosystem quality, which accounts for 79 percent (1.56E+07 PDF*m2*yr) of the total. The process with the greatest contribution is also linked to transcontinental transportation of steel imported from China, as the growing demand for steel in North America will be met by Chinese suppliers. In climate change category, use phase, again, gives most impact with 68% contribution or 2.60E+07 kg CO2 eq. It is from electricity that is partly imported from Ontario which includes amounts of natural gas. This also accounts for mineral extraction in resource category where electricity is the main contributor due to penetration of wind turbine in Ontario future market that require some mineral mining.

Even though the overall result is quite similar but from consequential approach applied in LCC, it can be seen that there is a shift of the most contributing material from steel to wood compared to attributional approach. This shift is due to the increasing wood price that is predicted to outperform the increasing steel price in the future. The steel price will go down because of the increasing demand globally and locally in China.

For the consequential approach applied in S-LCA, the decision maker should be aware of social consequences could be present from importing steel and aluminium abroad. These consequences are linked to worker and local community category from mainly sector and country level, i.e. risk to restriction to freedom of association, equal opportunities, good health and safety, respect of indigenous rights and prevention and mitigation of armed conflict. Attributional approach that excludes marginal technology could not reveal potential risks like this.

From the assessment of these tree pillars above, by using consequential LCSA (LCA, LCC and S-LCA, decision makers can have broader view of direction when taking a policy in sustainability area. Consequential LCSA can answer the question of what are the social, economic and environmental consequences of taking a decision of constructing more hybrid multistory building. Meanwhile, attributional LCSA will show what are the (sustainability) record of a hybrid multistory building and where is the sustainability hotspot located. Even though the result of the most contributing factor can be similar for certain assessment and indicator, but if we dig more, the result can point the decision maker to different direction for the case of LCA and S-LCA. Having consequential LCSA for decision making is enough but if it can be accompanied with attributional it can give more meaningful inspiration.

Depending on the need, the decision maker can also give weights on the assessment or indicator that seem need to be more emphasized than the other for taking a policy. When the trade-off of different environmental, economic and social risks exist, the role of weighting can inform judgement and policy making, but definitely not replace discussions about the overall sustainability values.

*On the Added Value of the Decision-Making Process with Consequential Approach*

The decision of constructing more hybrid buildings in the future will have certain potential environmental, economic and social consequences. Relevant stakeholders should be aware of these potential effects. In terms of the environment, for example, the material production phase is the most significant and will have a negative influence on human health, ecosystem quality, and resource consumption, whereas the usage phase is the greatest contributing component to climate change. For the former phase, decision-maker should aim to carefully select the material and to understand where it will be coming from with informed-picture of its associated impacts from consequential approach. For the latter phase, the decision-makers must understand electricity that is partly imported from Ontario including certain amounts of natural gas that cause more carbon emissions. In this consequential case, the existing low carbon energy mix in Quebec electricity generation does not guarantee a future low carbon footprint. Some activities, such as reducing imports from Ontario and increasing local clean energy generation, can be considered actionable policy.

*On the Discussion on Accuracy and Validity*

As mentioned in previous chapter, using database and relying on company report to assess social risk and performance could add the uncertainty in the assessment if not performed carefully. There are two groups of qualitative assessment in this study. First is the company report assessment and second is with Exiobase and SHBD databases. The former is based on the evaluation of the company report that can be subjective and in terms of accuracy and validity, it has higher degree of both since company tend to hide their unjust performance to their worker, local community or relevant stakeholders. It is true that this type of assessment is less objective, however, this can still be beneficial to give some positive nuance to what the company has been working towards improving their social performances. From this, it can be highlighted what type of international standard and management they apply and how far they have achieved.

For the latter, social databases, it can give some overview of the potential social hotspot that we can go further or as a starting point. It is also true that this type of assessment is too aggregated but if we have no data at all, having an overview of the potential impact is still beneficial.

To add accuracy and validity, the best way to assess social life cycle assessment of a product is by performing on-site assessment like carrying out an interview with the worker or user, auditing the working place and document checking according to standard. To add more picture, then, assessment through company report or using database like in this study can be used as complementary.

*On the Integration of LCA, LCC and S-LCA*

Having an integrated model of LCSA (LCA, LCC and S-LCA) from the beginning is indeed possible. However, it all depends on the practitioner preference. Having separate three tools help the practitioner understand better how to improve environmental, social and economic aspect separately. However, having refined and integrated one LCSA tool can also add some benefit, for example, the practicality of the use for decision making but there will be room for exclusion some indicators. To the best of the author knowledge, there are at least two ways to have a refined and integrated LCSA tool.

1. Having a cost as universal indicator for three aspects. For example, after we understand the environmental impact on climate change, human health and resource consumption as well as the social impact. We then quantify and monetize these impacts, i.e. how many dollar the impacts of climate change due to constructing a multistory building or how many dollar the job opportunity created from it. We will end up having a single cost that represent the cost caused from consequences induced in three aspects or we can call it a sustainability cost.
2. For environmental impact and social impact, there is also a unified indicator that can be used, human health. One of endpoint indicator in environmental LCA is human health and one of indicator in social LCA is also human health and safety. From these two, a unified indicator to integrate two tools can possibly be done.

# Chapter 8 - Conclusion

## 8.1. Conclusion

The response to the gaps raised during the literature review constitutes the original contributions of this research project. Indeed, the main aim is to fill some of those gaps identified in two of the tools, S-LCA and LCC, as a consequential approach has never been done. This research provides methodological insights into consequential LCC, consequential S-LCA and consequential LCSA.

*Methodological Conclusion on Consequential LCSA*

Having three tools for conducting LCSA (LCA, LCC and S-LCA) in a consequential approach mean that consequential LCSA also have been carried out. The forward-looking lens of consequential approach helps to improve sustainability performance in a causal-effect manner. In LCA, the environmental impacts of the process or activity or technology assessed are the ones from process or activity or technology that are going to supply the increased demand.

In LCC, the cost considered would be the cost from process or activity or technology that are going to meet the demand, not costs from the average process or activity or technology such as in the attributional approach. The type of LCC performed is conventional LCC where carbon pricing is excluded. It is becoming clear that with a consequential approach, there is an involvement of responsibility chain. The value-laden of the future responsibility in consequential approach can be understood through the inclusion of the future marginal (affected) technology. When performing consequential LCC, inflation rate is also included and it takes main factor to the total LCC analysis.

In S-LCA, the stakeholder and company assessed are the ones that are going supply the increased demand. Thus, the assessment has logic on answering the future consequences. This possibly includes the involvement of global material suppliers from abroad such observed in this study where the social consequences can have different possible outcomes. The social working situation and labor condition in other countries (especially in developing countries) may have poor practices. Having consequential approach helps the policy makers anticipate the impact of different possible outcomes and identify weaknesses. For example, policy makers may discover that it needs to reduce the steel and import from abroad and more focus on using local products. A transformation plan can be made in advance to cope with possible technical and operational problems from shifting from abroad to local and deliver more measurable future value.

Moreover, In S-LCA, similarly, the technologies that are going to supply the future demand has been assessed using multilevel analysis. It is important to use multiple level analysis since single level analysis cannot capture the whole social consequences that may happen. The combination of performing S-LCA on different level can be a complementarity.

For the building industry, the hybrid multistory construction is the future of construction. The conclusion of the thesis can be elaborated by answering the research questions raised in Chapter 4 of Problem Statement related to the case study of the multistory building.

• *What are the environmental consequences from constructing more of hybrid multistory buildings using consequential approach (as compared to attributional one)?*

Using a consequential approach, results from the completed life cycle analysis suggest that there may be some distinctions with the attributional one. For example, according to the attributional approach, material production has the greatest environmental impact (86–98 percent contribution) on all categories, human health, ecosystem quality, climate change and resources. However, material manufacturing is less ecologically responsible (20-46 percent) on similar categories when using the consequential approach. The shift of ecosystem quality, climate change and resources impact as the categories that are more affected by production phase to use phase leads to some consideration. In attributional assessment/perspectives, the hotspot lies on the mining activity related to steel and concrete process while in consequential, it has potential risks in another region.  Steel making process in China, where the affected technology is located, and its transportation contribute to the resource extraction and global warming impacts. Additionally, the electricity imported from Ontario add contribution to the latter as well.

This demonstrates how consequential LCA can find previously unknown possible implications. By applying consequential LCA, more insight into the consequential repercussions of constructing hybrid wood multistory structures can be obtained; as a result, policymakers will be made aware of possibilities to avoid these future consequences.

• *What are the economic consequences from constructing more of hybrid multistory buildings using consequential approach (as compared to attributional one)?*

The complete life cycle data suggest potential discrepancies between the two underlying modelling approaches. For instance, according to the attributional approach, material production has the greatest economic influence (72%). Material production remains more economically accountable under the consequential approach (59%) but with lower percentage. Reflecting on consequential approach, since the technologies considered are the affected ones by the future increasing demand, it is worthy to note that the cost of those technologies that are going to supply the market contributes differently with those in the attributional approach. In the attributional approach, steel contributes the most while wood is second in material category. The result is the opposite with the consequential approach where the latter contributes the most and is followed by the former.

This demonstrates the value of consequential LCC in revealing potential unintended consequences. As a result, policymakers will be made aware of ways to minimise these future consequences.

• *What are the social consequences from constructing more of hybrid multistory buildings using consequential approach (as compared to attributional one)?*

The findings indicate that employing multilevel analysis may aid in filling in data gaps. While more data is not always better, it can help broaden the view in order to better understand possible hotspots of social impact/benefit and their field of influence among stakeholders. From a consequential standpoint, it also demonstrates that over the long term, the decision to construct more hybrid multistory buildings will be inextricably linked to a variety of social impacts and benefits at various levels, throughout the product life cycle, and across geographic regions that cannot be captured by a single level of analysis.

It was determined that importing steel and/or aluminium from China may have some unfavourable social consequences (restrictions on worker association, risk to health and safety, and child labour), but may also have some positive consequences (employment opportunity). Finally, identifying these indicators may aid policymakers in safeguarding against undesirable repercussions before they occur, and vice versa, promoting favourable outcomes.

## 8.2. Conclusion en Français

La réponse aux lacunes soulevées lors de la revue de la littérature constitue la contribution originale de ce projet de recherche. En effet, l'objectif principal est de combler certaines de ces lacunes identifiées dans deux des outils, ACV-S et CCV, car une approche conséquentielle n'a jamais été réalisée. Cette recherche fournit un aperçu méthodologique du CCV conséquent, du ACV-S conséquent et du ADCV conséquent.

### Conclusion méthodologique sur la ADCV conséquente

Le fait que les trois outils de ADCV (ACV, CCV et ACV-S) soient utilisés dans l'approche conséquente signifie que la ADCV conséquente a également été réalisée. L'optique prospective de l'approche conséquentielle permet d'améliorer les performances de durabilité de manière causale. Les impacts environnementaux du processus, de l'activité ou de la technologie évalués sont ceux du processus, de l'activité ou de la technologie qui vont répondre à la demande accrue.

Dans le CCV, le coût pris en compte serait celui du processus, de l'activité ou de la technologie qui va répondre à la demande, et non celui du processus, de l'activité ou de la technologie moyenne comme dans l'approche attributionnelle. Il devient clair qu'avec l'approche conséquentielle, il y a une implication de la chaîne de responsabilité. Nous pouvons comprendre la valeur chargée de la responsabilité future dans l'approche conséquentielle par l'inclusion de la future technologie marginale (affectée).

Dans l'ACVS, les parties prenantes et les entreprises évaluées sont celles qui vont répondre à la demande accrue. Ainsi, l'évaluation a pour logique de répondre aux conséquences futures. Cela peut inclure l'implication de fournisseurs de matériaux étrangers, comme cela a été observé dans cette étude, où les conséquences sociales peuvent avoir différents résultats possibles. La situation sociale et les conditions de travail dans d'autres pays (en particulier dans les pays en développement) peuvent présenter de mauvaises pratiques. L'approche conséquentielle aide les décideurs politiques à anticiper l'impact des différents résultats possibles et à identifier les faiblesses. Par exemple, les décideurs peuvent découvrir qu'il faut réduire l'acier et les importations de l'étranger et se concentrer davantage sur l'utilisation de produits locaux. Un plan de transformation peut être élaboré à l'avance pour faire face aux éventuels problèmes techniques et opérationnels liés au passage de l'étranger au local et fournir une valeur future plus mesurable.

De plus, dans le ACV-S, les technologies qui vont répondre à la demande future ont été évaluées en utilisant une analyse à plusieurs niveaux. Il est important d'utiliser une analyse à plusieurs niveaux car une analyse à un seul niveau ne peut pas saisir l'ensemble des conséquences sociales qui peuvent se produire. La combinaison de l'ACV-S à différents niveaux peut être complémentaire.

Pour l'industrie du bâtiment, la construction hybride multi-étages est l'avenir de la construction. La conclusion de la thèse peut être élaborée en répondant aux questions de recherche soulevées dans le chapitre 4 de l'énoncé du problème lié à l'étude de cas du bâtiment multi-étages.

- Quelles sont les conséquences environnementales de la construction d'un plus grand nombre de bâtiments hybrides à plusieurs étages en utilisant l'approche conséquentielle (par rapport à l'approche attributionnelle) ?

En utilisant l'approche conséquentielle, les résultats de l'analyse du cycle de vie complet suggèrent qu'il peut y avoir certaines distinctions avec l'approche attributionnelle. Par exemple, selon l'approche attributionnelle, la production de matériaux a le plus grand impact environnemental (contribution de 86 à 98 %) sur toutes les catégories, la santé humaine, la qualité des écosystèmes, le changement climatique et les ressources. Cependant, la fabrication de matériaux est moins écologiquement responsable (20 à 46 pour cent) sur des catégories similaires lorsqu'on utilise l'approche conséquentielle. Le déplacement de l'impact de la qualité des écosystèmes, du changement climatique et des ressources comme catégories les plus affectées par la phase de production vers la phase d'utilisation conduit à une certaine considération. Dans l'évaluation/perspectives attributives, le point chaud se situe au niveau de l'activité minière liée au processus de fabrication de l'acier et du béton, tandis que dans l'approche conséquentielle, il existe des risques potentiels dans d'autres régions. Le processus de fabrication de l'acier en Chine, où se trouve la technologie concernée, et son transport contribuent à l'extraction des ressources et au réchauffement climatique. De plus, l'électricité importée de l'Ontario contribue également à ce dernier.

Ceci démontre comment l'ACV conséquentielle peut trouver des implications possibles inconnues auparavant. En appliquant l'ACV conséquentielle, nous obtiendrons une meilleure compréhension des répercussions de la construction de structures multi-étages en bois hybride ; en conséquence, les décideurs seront informés des possibilités d'éviter ces conséquences futures.

- Quelles sont les conséquences économiques de la construction d'un plus grand nombre de bâtiments hybrides à plusieurs étages en utilisant l'approche conséquentielle (par rapport à l'approche attributionnelle) ?

Les données sur le cycle de vie complet suggèrent des divergences potentielles entre les deux approches de modélisation sous-jacentes. Par exemple, selon l'approche attributionnelle, la production de matériaux a la plus grande influence économique (72%). La production de matériaux reste plus responsable économiquement selon l'approche conséquentielle (59%) mais avec un pourcentage plus faible. En ce qui concerne l'approche conséquentielle, étant donné que les technologies considérées sont celles qui sont affectées par l'augmentation future de la demande, il est intéressant de noter que le coût des technologies qui vont approvisionner le marché contribue différemment de celui de l'approche attributionnelle. Dans l'approche attributionnelle, c'est l'acier qui contribue le plus et le bois le second dans la catégorie des matériaux. Le résultat est inverse avec l'approche conséquentielle, où les seconds contribuent le plus et sont suivis par les premiers.

Cela démontre la valeur de l'approche CCV conséquentielle en révélant les conséquences potentielles non intentionnelles. En appliquant la CCV conséquentielle, nous obtiendrons une meilleure compréhension des répercussions conséquentes des structures multi-étages en bois hybride ; en conséquence, les décideurs politiques seront sensibilisés aux moyens de minimiser ces conséquences futures.

- Quelles sont les conséquences sociales de la construction d'un plus grand nombre de bâtiments hybrides à plusieurs étages en utilisant l'approche conséquentielle (par rapport à l'approche attributionnelle) ?

Les résultats indiquent que l'utilisation de l'analyse multiniveau peut aider à combler les lacunes des données. Bien que plus de données ne soit pas toujours meilleur, cela peut aider à élargir la vue afin de mieux comprendre les points chauds possibles de l'impact/avantage social et leur champ d'influence parmi les parties prenantes. Du point de vue des conséquences, cela démontre également qu'à long terme, la décision de construire davantage de bâtiments hybrides à plusieurs étages sera inextricablement liée à une variété d'impacts et d'avantages sociaux à différents niveaux, tout au long du cycle de vie du produit, et à travers les régions géographiques, qui ne peuvent être saisis par un seul niveau d'analyse.

Il a été déterminé que l'importation d'acier et/ou d'aluminium de Chine peut avoir certaines conséquences sociales défavorables (restrictions sur l'association des travailleurs, risque pour la santé et la sécurité, et travail des enfants), mais peut également avoir certaines conséquences positives (opportunité d'emploi). Enfin, l'identification de ces indicateurs peut aider les décideurs politiques à se prémunir contre les répercussions indésirables avant qu'elles ne se produisent, et inversement, à promouvoir des résultats favorables.

## 8.3. Limitations and Recommendations

There still remain several limitations and challenges that impacted the degree of applicability of the consequential LCSA framework. These challenges and recommendation are presented in three parts according to their tool respectively. The limitation is presented in each paragraph followed by the recommendation right after (in *italics*) then it is followed again by limitations and recommendations.

*Life Cycle Assessment*

As previously mentioned in chapter 5, marginal technology identification remained a challenge. It depends on data availability regarding future evolution of technologies. What specific type of technology is going to fulfill the future market, what will be the material used, and for how long the technology will be used are difficult to decide unless a good amount of data are available to predict it. Uncertainty also resides in the difficulty to know from where these future technologies will be, as this will be influenced by geopolitical relations between regions or countries.

*For a step towards improving the uncertainty analysis, having economic and supply market data are the best way to predict the future suppliers. However, if not available, expert judgment can also be a possible alternative. These alternatives can give better prediction of the marginal technologies that are going to supply the market in the future. All in all, to develop a framework for incorporating modeling uncertainty associated in consequential approach is needed. One of the examples is by performing Monte Carlo simulation with various scenarios and inputs (reference). Even though it has limitation in itself due to the randomness of the sampling, relying on the simulation result still can bring overview of the variety and spectrum of the possible environmental impacts.*

Another limitation, in the use phase, is that the environmental impact of electricity use based on the behavioral and lifestyle of the building occupants are not considered in this thesis. The electricity consumption is calculated annually neglecting the different parameters that can be an influence during the building lifetime. Moreover, more indicators should be added to the assessment, not just electricity consumption, i.e. water consumption, natural gas consumption and waste generation.

*As a recommendation, the inclusion of the use phase is indeed needed to give a complete picture of the environmental that is based on building occupant lifestyle.*

Life cycle costing

Accessing internal cost data from a company is a challenging task. Financial data can be sensitive as well, especially if the results are intended to be published. For that reason, independent data sources and references were used. However, the current database applied for LCC has certain limitations. It only considers the cost for certain components and works.

*For a way forward, it is still recommended that the data used for calculating the cost should ideally be from an on-site assessment. Using real cost data can give better results without* *neglecting certain parameters. It can give more accurate numbers that is also accordance with man-working-hour needed used for S-LCA.*

There are three types of LCC, conventional, social, and environmental ones, for short recapping. Conventional LCC accounts financial cost accounted like in this thesis. Social LCC includes social externalities while environmental LCC has similar matrix with environmental LCA. Conventional LCC has certain limitation that cannot capture the added value in the economic system while it can be accounted with environmental LCC theoretically.

*To have a similar alignment with LCA and S-LCA, it is preferable for practitioners to apply environmental LCC instead of the other two approaches. However, the further degree of detail in data gathering must be considered carefully, especially if the intention is to have full cost assessment in similar system boundary with LCA or S-LCA.*

Third limitation lies on the indicators that can be used in life cycle costing. There are many other economic indicators such as revenue, benefit, tax, etc. However, related to the first limitation in LCC, financial data may be sensitive/private and not suited to be published.

*It is suggested to first look at other relevant economic indicators as well such profit, externality cost, net present value and others. If not, we can look at the economic impact not from a narrow lens at product level but rather from a broader lens such as at sector or country level.*

Social Life Cycle Assessment

Still, in relation to the limitation on data availability and quality, in S-LCA, first and foremost, the social condition of a human being is constantly changing. It is insufficient to rely solely on macro data from database that account the average information or value.

*In order to fully comprehend the social ramifications of qualitative assessment, on-site evaluation while the b*uilding is being constructed *should be given careful consideration.*

Second, if on-site evaluation is not possible and secondary data is employed, the database of social inventory and impact analysis should be less aggregated and more thorough.

*The use of databases is critical in order to reduce data gaps. However, if the scale of databases is too macro, it will not be able to accurately depict social distress and represent the social reality. Having less aggregated and more regionalized data is then needed.*

The social impact of non-implemented life cycle should also be assessed. When discussing consequential consequences, it is important to consider the impact that could have been prevented or avoided. This is a simple task that may be accomplished in LCA and LCC.

In the case of S-LCA, however, including avoided impact means covering non-implemented life cycle as well. For example, if more wood in our construction is utilised, we can eliminate the usage of some concrete and steel. These must be taken into consideration. Second, if more wood for structural construction (instead of the wood that is typically used for panelling, for example) is used, we are indirectly substituting or avoiding the primary usage of the wood that is commonly used for panelling.

*The impact of non-implemented life cycle should be accounted.*

Fourth, it is a real challenge to assess the social impact if secondary data is used. Databases do not present social impact but rather social risks from average data gathered from specific region and time.

*Thus, getting back to the first recommendation in the first paragraph, it should be called potential social risk, not social impact.*

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# Annex A

## Table S1. Highlight of LCSA related studies

This supplementary material provides summary of the literature review conducted for LCSA-related articles including case study and methodological ones. Each summary of the article contains informations on goal and scope of the study,  life cycle inventory analysis (data collection sources), life cycle impact assessment, methodology, main results and challenges addressed.

| # | Artic-les | Area | Title | Functional Unit | | Life cycle impact assessment | | | Methodology | Main results | Challenges |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Env | Eco | Soc | | | |
| 1 | [1] | Electric vehicle | Integration of system dynamics approach toward deepening and broadening the life cycle sustainability assessment framework: A case for electric vehicles | N | broad functional unit taking into account the interactions between three aspects of sustaina-bility | $CO_2$ emission, particulate matter formation (PMF), photoche-mical oxidant formation (POF), etc. | vehicle ownership costs, contributio n to GDP, etc. | Contribu-tion to employ-ment, human health impacts | Quantification of macro-level sustainability aspects was performed by using causal loop diagram and model formulation based on the parameters in transportation sector such as average annual vehicle miles traveled, the sales of new vehicles, efficiency of fuel, population, carbon emissions from certain life phases (vehicle manufacturing and operation, etc). | Many but the authors stressed the importance of capturing dynamic interactions among the sustainability indicators. | To increase accuracy and reduce the uncertainty, some model validation methods were used i.e., ANOVA, two-sample Kolmogorov-Smirnov, Shapiro-Wilk. |
| 2 | [2] | Electric vehicle | Geopolitical-related supply risk assessment as a complement to environmental impact assessment: the case of electric vehicles | Y | one electronic vehicle | geopolitical-related supply risk | | | The calculation method used was based on the equation of geopolitical-related supply risk or resource criticality called "GeoPolRisk". | Many but to name a few is the conventional metals depletion indicator. For instance, as employed by ReCiPe, it has weaknesses that is partially addressed by the GeoPolRisk approach. This result could perform better on the mapping critical material flows. | The geopolitical supply risk aggregated for a number of platinum group metals or rare earth elements is not examined at individual metal elements. |

| # | Artic-les | Area | Title | Functional Unit | | Life cycle impact assessment | | | Methodology | Main results | Challenges |
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| | | | | | | Env | Eco | Soc | | | |
| 3 | [3] | Energy and industrial system | Multi-actor multi-criteria sustainability assessment framework for energy and industrial systems in life cycle perspective under uncertainties. Part 1: weighting method | Y | 1 t of product produced by these six different energy and industrial systems | PCOP, GWP, AP, etc. | investment cost (IC), net present value (NPV) and internal rate of return (IRR), etc. | added job (AJ), impact on local culture (ILC), etc. | A methodology for multi-actor multi-criteria sustainability assessment of energy and industrial options has been developed in this study. The traditional extension theory has been modified to address the uncertainty issues. The proposed method can rank the alternative energy and industrial systems with the decision- making matrix. | It can result more accurately the willingness and preferences of decision-makers. | This study does not address the methodology used for identifying the classical fields which seperate the sustainability into different levels. |
| **4** | [4] | Energy and industrial system | Multi-actor multi-criteria sustainability assessment framework for energy and industrial systems in life cycle perspective under uncertainties. Part 2: Improved extension theory | Y | 1 t of product produced by these six different energy and industrial systems | Idem. | | | | Multiple decision-makers are not allowed to take part in the assessment process. Yet, the method has the capability to reach sustainability assessment under uncertainties. | Idem. |
| 5 | [5] | Kitchen set | Using life cycle sustainability assessment to trade off sourcing strategies for humanitarian relief items | Y | A kitchen set enabling the storing and cooking of food and water | human health, ecosystem diversity, resource availability using ReCiPe method | transportati on cost, procure-ment costs | working condition, health and safety, etc. | UNEP-SETAC guideline was used as a guide. The results were analyzed using ReCiPe method. Two sourcing scenarios identified: one international and one local. | Many but the authors pointed out on the importance of the research on the humanitarian supply chain context and in the emerging economies. | Data quality reporting has bias due to the local suppliers who collected the data. The accuracy of the social analysis is subjective as data of different functional units are collected for the different subcategories. |

| # | Artic-les | Area | Title | Functional Unit | | Life cycle impact assessment | | | Methodology | Main results | Challenges |
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| | | | | | | Env | Eco | Soc | | | |
| 6 | [6] | Waste manage-ment | Sustainability assessment and prioritisation of bottom ash management in Macao | Y | 1 tonne of MSW | climate change, ecosystem quality, human health and resources | cost and benefit | integrity and acceptabi-lity | Five different incinerator bottom ash management scenarios were applied. LCA was carried out with modified localised HRA. CBA was applied representing economic assessment. For social assessment, fuzzy set theory and AHP were conducted. | Many but the main point is that this approach try to give decision makers information to compare different management scenarios using tools and implement a localised approach. | - |
| 7 | [7] | Carbon fibers | Extending the geopolitical supply risk indicator: Application of life cycle sustainability assessment to the petrochemical supply chain of polyacrylonitrile-based carbon fibers | N | - | human health, ecosystem service and natural resources | geopolitical supply risk | geopolitica l supply risk | Quantification of geopolitical supply risk are applied on multi-stage supply chains for 54 countries. It is an extension of the previous work on Geopolitical Supply Risk methodology for assessing global production and trade patterns for different commodities. | Geopolitical Supply Risk (GPSR) factors for 54 countries in six supply chain scopes are quantified. It provides four different supply risk patterns. | - |
| 8 | [8] | Energy systems (electricit y mix) | Towards sustainable production and consumption: A novel DEcision-Support Framework IntegRating Economic, Environmental and Social Sustainability (DESIRES) | N | - | GWP, depletion of minerals and metals, ecotoxicity , etc | fuel price, levelised costs | total employ-ment | Multi-attribute decision analysis using equal weighting were applied with different stakeholder preferences (expert stakeholder preferences and public preferences). A novel decision-support framework incorporating three domains of sustainability called DESIRES has been developed. | The approach allows stakeholders to understand their sustainability preferences and the opinions of others to help to reach a consensus. | - |

| # | Artic-les | Area | Title | Functional Unit | | Life cycle impact assessment | | | Methodology | Main results | Challenges |
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| | | | | | | Env | Eco | Soc | | | |
| 9 | [9] | Electric vehicles | Uncertainty-embedded dynamic life cycle sustainability assessment framework: An ex-ante perspective on the impacts of alternative vehicle options | N | - | GHG emission, carbon fossil fuel, water footprint, hazardeous waste, etc. | GDP, foreign purchase, profit, etc. | Employ-ment, tax, injuries, etc. | Two MCDM methods were utilized to rank different types of conventional and alternative passenger vehicles in the US, the Intuitionistic Fuzzy MCDM and the Technique for Order-Preference by Similarity to Ideal Solution or TOPSIS. Seven different vehicle types with respect to the US vehicle market were identified with an average and a 100% solar electricity generation mix scenario). | Many however this study primariliy is about the ranking of alternative vehicle technologies and the dominance/contribution analysis in the sustainability triangle. | Social indicators selected were macro-level social indicators. |
| 10 | [10] | Wind energy | Intuitionistic fuzzy multi-criteria decision making framework based on life cycle environmental, economic and social impacts: The case of U.S. wind energy. | N | - | GHG, land, water and energy, etc. | profit, import, etc. | Employ-ment, tax, income, etc. | EE-IO-LCA was carried out for off-shore wind turbine and a 9-step fuzzy MCDM tool was also performed. | The results were obtained, considering the weight of each identified criterion in each life cycle phase. | The uncertainties might come from errors in modeling and data gathering. |

| # | Artic-les | Area | Title | Functional Unit | | Life cycle impact assessment | | | Methodology | Main results | Challenges |
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| | | | | | | Env | Eco | Soc | | | |
| 11 | [11] | Housing retrofit | Modeling socioeconomic pathways to assess sustainability: A tailored development for housing retrofit. | Y | the housing unit (the entire building in this case), the household, and the ensemble of retrofitting works, repair and mainte-nance | Climate change, human health, etc. | retrofit cost, fuel cost | health of workers, contribu-tion to growth, household poverty, etc. | Various methods were applied for assessing environmental, eonomic and social aspect. Some guidelines were also adopted, i.e. EN 15804 (CEN 2012), EN 16627 (2015) and EN 16309 (2014) | The results could show the comparison between generic hypotheses which are frequently used in policy making studies and in household situations. | This case study was only limited to certain housing stock and must be further compared to other typologies. More different variables need to considered the discount rate, price increase and remaining service life. |
| 12 | [12] | Forestry | The distinctive recognition of culture within LCSA: Realising the quadruple bottom line. | Y | the three forestry scenarios (i.e. use of 1 ha of unmanaged land) | GHG, energy use, etc. | profit, production cost, etc. | Employe-ment | A LCSA case study was conducted participatoryly with a mixed methods approach. Cultural Indicator Matrix was also utilized. Research was performed in cooperation with main members of New Zealand indigenous community. | The method helps the participants to perform progressively towards representing culture in LCSA with transparent and distinct way. This study performs an inclusion of a cultural compliance process for the forestry activities the product`s life cycle. | - |
| 13 | [13] | Rice husk bioelec-tricity | Life Cycle Sustainability Assessment: A Holistic Evaluation of Social, Economic, and Environmental Impacts | Y | 1 MWh, and an economy wide scale of 9.46E+07 MWh which is equal to around 500 MW of | human health, ecosystem loss, etc. | benefit and cost | child labor, total hours of employ-ment and of knowledge intensive jobs, etc | A LCSA for comparative study of two types of electricity were performed. | The comparative results were presented between two types of electricity in different impact assessments. | - |

| # | Artic-les | Area | Title | Functional Unit | | Life cycle impact assessment | | | Methodology | Main results | Challenges |
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| | | | | | | Env | Eco | Soc | | | |
| | | | | | installed capacity of bioelec-tricity | | | | | | |
| 14 | [14] | Passenger cars | Combined application of multi-criteria optimization and life-cycle sustainability assessment for optimal distribution of alternative passenger cars in U.S. | N | - | GHG, energy use, etc. | foreign purchase, profit, etc. | GDP, employ-ment, injury, etc. | A multi-objective optimization model was carried out to calculate the optimal distribution of passenger cars in the U.S.. It was performed by considering environmental and socio-economic goals and their weights. | Many, however the authors pointed that this study shows the results by considering the macro-scale socio-economic impacts that many studies ignored to incorporate. | Incapability to capture global trade-links between trading partners and to include other uncertainties from temporal and spatial aspects (effects of behaviors on driving, fuel consumption, charging times and locations, performances of battery, regional TBL impact variations, etc.) |
| 15 | [15] | Wind and Thermo-Electric Power Stations | MCDA and LCSA | N | - | - | - | local communit y category (except indigenous rights and delocaliza-tion & migration) | S-LCA with impact matrix and open exchange interactive multi-criteria software was performed. | The potency of multi-criteria approach (the aggregation of preferences) applied in the complex problem were presented and discussed. | - |

| # | Artic-les | Area | Title | Functional Unit | | Life cycle impact assessment | | | Methodology | Main results | Challenges |
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| | | | | | | Env | Eco | Soc | | | |
| 16 | [16] | Resource consump-tion | Weighting and aggregation in life cycle assessment: do present aggregated single scores provide correct decision | N | - | ecosystems , human health and resources | - | - | A linear weighted sum (LWS) method was performed with distance-based approach. | A distance-based multiple attribute decision-making method for acquiring single scores were proposed. | The ReCiPe single-score calculation method does not quantify dominating alternatives (alternatives having high values across all endpoints) nor the mutuality of the aggregated indicators. |
| 17 | [17] | Resource consump-tion | Enhanced data envelopment analysis for sustainability assessment: A novel methodology and application to electricity technologies. | N | - | GWP, ozone deple-tion, acidifica-tion, etc. | capital cost, operation and mainte-nance cost and fuel cost | Employ-ment, injury, human toxicity, etc. | Data envelope analysis for macro scale assessment was conducted. | This approach can handle macro scale sustainability aspect and enable the ranking of alternatives with quantitative targets | Incapability to integrate the unit in the assessment. Efficiency scores are sensitive to the number of inputs, outputs, and size of sample. |
| 18 | [18] | Energy Systems | Sustainability Assessment of Complex Energy Systems Using Life Cycle Approach-Case Study: Arizona State University Tempe Campus. | Y | Not clearly mentioned | GHG emissions, water pollution, air pollution, etc. | initial, operational, mainte-nance costs, etc. | safety assess-ment, system accounta-bility, etc. | Multi-criteria sustainability appraisal framework was conducted with two scenarios: Business as Usual (BAU) and Climate Neutrality Roadmap (CNR). Sustainability index calculation was also utilised. | System boundaries are significant to help stakeholders to comprehend consequences of a specific action. | - |
| 19 | [19] | Electricit y genera-tion | An integrated life cycle sustainability assessment of electricity generation in Turkey | Y | generation of 1 kWh of electricity in Turkey | abiotic depletion potential, GWP, etc. | capital and annualised costs, levelised costs, etc. | Employ-ment, accident, etc. | Multi-criteria decision analysis was performed with ranking and weighting of different options. | The ranking of the electricity options and the weights of importance placed on the sustainability aspects could help to understand the most sustainable option. | Data were limited. Complete data were needed for future works with more regionally-specific and recent ones. |

| # | Artic-les | Area | Title | Functional Unit | | Life cycle impact assessment | | | Methodology | Main results | Challenges |
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| | | | | | | Env | Eco | Soc | | | |
| 20 | [20] | Heat pump | Life cycle sustainability assessment of ground source heat pump in Shanghai, China | N | Not clearly mentioned | GWP, EP, AP | cost, benefit, net benefit | Employ-ment | GaBi was used to performed the LCA. LCC and employment rate were also accounted. | An innovative sustainability method was proposed with its practicality | Information and data could not be gathered sufficiently. |
| 21 | [21] | Vehicle techno-logies | Application of the TOPSIS and intuitionistic fuzzy set approaches for ranking the life cycle sustainability performance of alternative vehicle technologies | N | Not clearly mentioned | GHG, energy, water, etc. | foreign purchases, business profits, GDP, etc. | Employ-ment, tax, injury, etc. | Institutionistic fuzzy MCDM and TOPSIS were carried out for LCSA with the Life Cycle Sustainability Triangle (LCST) for interpretation. | A combination of applying both LCSA and two MCDM methods (Intuitionistic Fuzzy MCDM and TOPSIS) were presented to give a rank the sustainability performance of different vehicle types in U.S. | Additional key social indicators were suggested for future studies, i.e. safety, air pollution health impact, employment levels by income and gender group, affordability, equity, etc. |
| 22 | [22] | Building | A modeling framework to evaluate sustainability of building construction based on LCSA. | Y | Not clearly mentioned | Climate change, ozone depletion, etc. | Costs of material and service | child labor, fair salary, working hours, etc. | Three different models were employed to perform LCSA: the environmental model of construction (EMoC) (Dong and Ng 2015a), cost model of construction (CMoC), and social-impact model of construction (SMoC) (Dong and Ng 2015b) representing each pillars of sustainability. | Material stage on the environmental and social aspects in building construction project gets less attention. | Data availability was a major concern affects the quality of assessment and the adoption of non-local LCI databases and national social statistics were questioned by stakeholders. |

| # | Artic-les | Area | Title | Functional Unit | | Life cycle impact assessment | | | Methodology | Main results | Challenges |
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| | | | | | | Env | Eco | Soc | | | |
| 23 | [23] | Building | Life cycle sustainability assessment of RC buildings in seismic regions | Y | The structural components of the entire building | Environ-mental impact of construc-tion through EPS (environ-mental perfor-mance score) | initial and end-of-life costs | deaths and injuries | LCSA combined with seismic and earthquake hazard assessment on comparisons of alternative designs. | The results showed that the cost, environmental and social impacts in the structural use stage could be highly lowered by applying a resilient plan. | Uncertainty has been found in repair cost, environmental impact and downtime values due to inavailability of data and the assumptions used in the definition of damage states. |
| 24 | [24] | safeguard subjects | A selection of safeguard subjects and state indicators for sustainability assessments. | N | - | energy, mineral, water, etc. | financial, income | human health, jobs, occupa-tion, knowledge, peace, social security, etc. | A top-down approach was used for identification of indicators for LCSA. | The comparison between capital categories for assessing sustainable development by UNECE and safeguard subject in this work were presented as well as the comparison between UNEP/SETAC's impact subcategories, safeguard subjects and state indicators in this work. | Some simplifications and also complications has been found in defining certain state indicators. |
| 25 | [25] | Raw material | Import-based Indicator for the Geopolitical Supply Risk of Raw Materials in Life Cycle Sustainability Assessments. | N | - | Import-based Indicator for the Geopolitical Supply Risk of Raw Materials | | | Various different methods were used for assessing the supply risk of resources. | Many but the authors pointed out the importance of geopolitical and associated indicators to solve issue within the LCSA where the current impact assessment practice in LCA lack of the AoP | Data availability and lack of different supply chain levels are main challenges. |

| # | Artic-les | Area | Title | Functional Unit | | Life cycle impact assessment | | | Methodology | Main results | Challenges |
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| | | | | | | | | | | (area of protection) of natural resources. | |
| 26 | [26] | Electronic systems | Evaluation of Indicators Supporting the Sustainable Design of Electronic Systems. | Y | relative energy consump-tion (relative indicator) the light output | Cummula-tive energy demand, carbon emission, etc. | cost | - | Indicator matrix linking resource and emission impacts to three life cycle stages was used and case scenarios were also built for the hotspots analysis. | Many but the authors assessed the complex product structures and used ascertained data for transparency. | The main challenges is data availability and therefore lower the certainty for the inkterpretation. |
| 27 | [27] | Waste-water treatment | Life cycle-based decision support tool for selection of wastewater treatment alternatives. | N | - | global warming, eutrophi-cation, etc. | cost, benefit, etc. | labor or manpower | Decision support tools (DSTs, TOPSIS, vector normalization and scenario selection were utilized. | Many but the authors proposed that selecting correct wastewater treatment technologies is challenging task however this approach can robust computational platform that help significantly in the decision making process. | A participation of a large group of stakeholders might be difficult in real situation. More site-specific information is needed. There is also a risk of selecting an incorrect set of indicators that could lead to a biased decision. |
| 28 | [28] | Biorefi-neries | Integrated life cycle sustainability assessment—A practical approach applied to biorefineries. | N | - | climate change, resource depletion, energy, etc. | NPV, IRR, profit, etc. | rural develop-ment, feedstok, labor condi-tion, etc | LCSA was combined with ex-ante decision support model called integrated life cycle sustainability assessment (ILCSA) | A result from interim assessment methodologies for individual sustainability aspects was presented. | Comprehensive result was shown it was yet incapable of delivering simple answer. |

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| 29 | [29] | Citrus farming | Social life cycle assessment and participatory approaches: A methodological proposal applied to citrus farming in Southern Italy | Y | One ha of clementine orchard | climate change, water, etc | various costs | health and safety, etc. | S-LCA was perfomed with AHP and more locally relevant criteria was used. | The integration of LCC and LCA with S-LCA results could deliver a broader impact categories. | There is a risk for double counting considering various aspects considered. |
| 30 | [30] | Bioetha-nol | Prioritization of bioethanol production pathways in China based on life cycle sustainability assessment and multicriteria decision-making | Y | 1 t bioethanol | climate change, ozone depletion (OD), human toxicity, etc. | capital, feedstock, production, operation and mainte-nance costs. | working condition, cultural heritage, govern-ment, etc. | LCSA was combined with MCDM methodology, i.e. (AHP) and the VIKOR method. | Many but the authors proposed this approach could help to identify alternatives to select the most sustainable option. | Uneasiness for users to conduct the MCDM method. |
| 31 | [31] | Solar Photovol-taic | Solar Photovoltaic Development in Australia—A Life Cycle Sustainability Assessment Study. | Y | 1 kWh of electricity produced by UQ Solar | climate change, abiotic depletion, acidifica-tion, etc. | cost, tax, discounted cost, etc. | supplier relation-ship, transpa-raency, etc | Financial metrics were quantified using SAM, including LCOE, electricity cost per year and other economic parameters. | Many, however the authors intended to identify the sustainability performance of solar PV installations on the project level to better understand whether solar photovoltaic is desirable or not. | Expert review and stakeholder participation were suggested to better understand the issue. |

| # | Artic-les | Area | Title | Functional Unit | | Life cycle impact assessment | | | Methodology | Main results | Challenges |
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| 32 | [32] | Buildings | AHP based life cycle sustainability assessment (LCSA) framework: A case study of six storey wood frame and concrete frame buildings in Vancouver. | N | - | global warming potential, acidifica-tion, eutrophi-cation potential, etc. | initial, mainte-nance costs, etc. | occupant comfort, safety, and afforda-bility. | LCSA was combined with AHP to evaluate the sustainability performance of a building. | The results of life cycle impacts for each unit area of buildings were comparatively presented. Building alternatives have various impact level with regards to different (sub)criterias. | No agreed method has been found to ensure the relative importance of different impacts. Decison making based on AHP, in some cases, creates ambiguity and redundancy among different criteria. More advanced MCDM techniques was recommended by the authors. |
| 33 | [33] | Modular machine | Addressing Sustainability and Flexibility in Manufacturing Via Smart Modular Machine Tool Frames to Support Sustainable Value Creation. | N | - | carbon footprint | Manufactu-ring cost | salary | LCSA was undertaken with emergy-based assessment and AHP analysis. GaBi software was used with CML characterisation factor. | Production phase accounts the highest contribution for carbon footprint while fair wage assessment have been found more significant for the sensor nodes (electronic components). A sustainability footprint as a result of carbon footprint, fair wage and manufacturing cost assessment was presented. | More indicators need to be included in the assessment. Difficulties on comprehending the results since in-depth ecological knowledge is required. |
| 34 | [34] | Electricit y | Life cycle sustainability assessment of UK electricity scenarios to 2070 | N | per unit of electricity generated | GWP, AP, EP, ODP, etc | capital, operational, fuel and total costs | salary, employ-ment, worker injuries, etc. | Varying scenarios and sub-scenarios on electricity mix and national target were undertaken in the assessment. | Overall, the sustainability impacts of the five electricity scenarios were compared and presented. | The challenges are related to the lack of data on the technologies that are not commercially available yet and the uncertainty on the technological development. |

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| 35 | [35] | Sewer pipe material | Life cycle sustainability assessment (LCSA) for selection of sewer pipe materials. | Y | the 3 m length and 400 mm diameter of sewer pipes of different materials with the same design life of 100 years. | global warming, NOx emission and SOx emission, etc | initial, mainte-nance, repair and replacemen t cost | - | LCA and LCC were performed and then combined with AHP analysis. | Environmental and economic assessment result on four types of sewer materials were presented along with each pros and cons. | The challenges are linked to the subjectivity of the evaluation and limited researches on documenting the uncertainties in emergy-based LCA. |
| 36 | [36] | Fertilizer s (agricul-ture) | Application challenges for the social Life Cycle Assessment of fertilizers within life cycle sustainability assessment. | Y | 1 ton of tomato (henceforth , 1 ton of fertilized tomato) | GWP, ODP, human toxicity, etc. | fertilizer market price, price of transpor-tation, extra application costs | various impact assessment from SHDB | E-LCA, LCC and S-LCA was carried out. Additionally, SHDB was performed for S-LCA. | Many but to sum up, the results of E-LCA, LCC and S-LCA in a integrated fashion were presented using LCSD. | The primary challenge is related to the uncertainty in data collection since several indicators in SHDB are not filled with real but extrapolative data and few sector data are available for most of issues, sectors and countries. Challenges are also dealt in the integration of the scopes of the three tools. |
| 37 | [37] | Pavement | Ranking the sustainability performance of pavements: An intuitionistic fuzzy decision making method. | N | - | carbon emission, water footprint, energy consump-tion, etc. | import, tax, income, etc. | injuries | TOPSIS method based on intuitionistic fuzzy entropy was performed to select the most appropriate asphalt. | The results of decision making method applied in MCDM problem were presented in order to weight the best of the pavement alternatives. | The uncertainty will increase when EIO model use the aggregated sector data where several sub-sectors are evaluated under the same main sector. The subjectivity of expert judgment for sustainability indicators also affects the uncertainty |

| # | Artic-les | Area | Title | Functional Unit | | Life cycle impact assessment | | | Methodology | Main results | Challenges |
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| 38 | [38] | Waste Electrical and Electronic Equip-ment (WEEE) | Reusability based on Life Cycle Sustainability Assessment: case study on WEEE | Y | the typical components of 100 waste mobile phones | climate change, acidifica-tion, ecotoxicity, etc | costs | Employ-ment, housing, and education | LCSA was used to assess the reusability of waste mobile phone. Three assessments were conducted, environmental reusability assessment, economic reusability assessment and social reusability assessment. | Many but overall the results show the comparison of the two systems of telephone end of life treatment: (a) components reuse (b) materials recovery mode. | The definition on what is good or bad and what is positif and negative impact in the case of whether job creation is more important than the health risk or not is the challenge faced. More other macro or micro factors need to be concern i.e. reusability time range, physical condition and technology innovation speed. Improvements is needed in the integration methods of three sustainability pillars. |
| 39 | [39] | Buildings | Integrating triple bottom line input-output analysis into life cycle sustainability assessment framework: The case for US buildings. | N | - | GHG, water, energy, etc. | GDP, import, business profit | injury, income, govern-ment tax, etc. | Triple Bottom Line (TBL) LCA, a type of input-output based LCA model was used to incorporate the environmental impacts and financial flow as well as the social state. | Many but overall results show the various TBL impacts of residential and commercial buildings. | Limited data are available for certain indicators. Aggregated sector data that contain many other less-relevant sub-sectors are used thus increases the uncertainty. Certain impacts are assumed to happen in domestic level thus a global view of those impacts are highly reccommended for the future study. |

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| 40 | [40] | Passenger vehicle | Towards Life Cycle Sustainability Assessment of Alternative Passenger Vehicles. | Y | 1 mile of vehicle travel | GHG, water, energy, etc. | GDP, profit, import, etc. | Employ-ment, human health, injury, etc. | TBL indicators were used to measure the sustainability performance of passenger vehicles with two scenarios: when no additional infrastructure requirement exists and when electricity to power BEVs and PHEVs are produced. | The quantified results on economic, social, and environmental impacts are presented based on each life cycle phase and two scenarios considered. | Limited number of processes considered could be a drawback of this approach. The selection of processes to be included is also quite subjective thus could increase the uncertainty. |
| 41 | [41] | Pavement | Stochastic decision modeling for sustainable pavement designs. | Y | one-km pavement using sustainability weights ranging between 0 and 1 | GHG, water | GDP, import, tax, etc. | Employ-ment, injury, etc. | A hybrid TBL-LCA was performed and combined with MCDA for hot- and warm-mix asphalt. | Varying results on macro-level environmental and socio-economic assessment were presented in each life cycle stage. At last, the optimal percentages of each alternatives were presented. | The variability of input parameters need to be considered since it affects the certainty. |
| 42 | [42] | Marble slab | A UNEP/SETAC approach towards a life cycle sustainability assessment—our contribution to Rio+20 | Y | 1 m3 of marble types A, B, C and D | $CO_2$, $N_2O$, water, etc | wage cost, material cost, etc | Employ-ment, working hours, presence of child working, etc | LCSD methodology was used to compare sustainability performance of product systems where expert and non-expert stakeholders were involved. | Many but in general LCSD marble slab results and scores were presented based on the types and and overall index. | Data unavailability is a major issue. Linkages of the indicators to some techniques need to be regarded. |
| 43 | [43] | Biodiesel | Evaluating the Sustainability SWOT as a streamlined tool for life cycle sustainability assessment. | N | - | GHG, raw materials, NOx, SOx | various costs | social welfare and incomes | SWOT was used to have more streamlined assessment. | The results of the analyses on the usability of SWOT in both business and LCSA framework have positive remarks. | Even though this approach is adapted to the logic sense of the business stakeholders but it does not follow strictly the impact assessment guideline. The inclusion of uncertainty in this |

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| | | | | | | | | | | | approach should be streamlined |
| 44 | [44] | Economi c | Economic modeling and indicators in life cycle sustainability assessment | Y | 1 GWh of electricity | - | cost (labor and capital), taxes, etc. | - | Economic modeling and calculation using Taylor series expansion of the Leontief inverse with the representation of variables in a hybrid IO LCA model was performed for macro-scale economic formulation. | The cost of indicator results was presented as well as indicator results on productivity measurements. This appoach is believed could be used for consequential approach of LCC in LCSA. | The uncertainty found in this study is not methodological but rather the availability of relevant data. |
| 45 | [45] | Building refurbish-ment | Multidimensional Pareto optimization as an approach for site-specific building refurbishment solutions applicable for life cycle sustainability assessment | N | - | - | - | - | This method used was a multidimensional Pareto optimization combined with LCC, LCA and the first stages of a social assessment. | The performance of 729 normalized results were presented from 6 measurements and 3 possible options for LCC and ReCiPe indicators in site in Paris/France. Single technology measurements for the marked concepts were also deliberated. | Technologies and measurements considered in the approach were limited. Some that are not considered in the approach might create a gap and thus could miss the suitable options. The results were presented with relative values (percentages). The calculation used was the static values. No dynamic approach scenarios was involved. The social aspect was also left out of the formulation. |

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| 46 | [46] | PET bottles | Life cycle sustainability assessments (LCSA) of four disposal scenarios for used polyethylene terephthalate (PET) bottles in Mauritius | Y | 1 tonne of post-consumer PET bottles | climate change, ecotoxicity, ozone depletion, etc. | operating and mainte-nance costs | almost all S-LCA indicators (UNEP) were covered. | LCA+LCC+S-LCA was performed with combination of AHP and was applied in four different four disposal scenarios. | The summary of results for the three disposal facilities and final ranking were presented. Sensitivity analysis was also shown. | - |
| 47 | [47] | Cooking oil waste manage-ment | Application of LCSA to used cooking oil waste management. | Y | the UCO generated in a neighbour-hood of 10,000 inhabitants for 1 year in the city of Barcelona | GWP, ODP, abiotic depletion, etc. | personnel cost, transpor-tation cost, collection and storage cost, etc. | Employ-ment, equality, public commit-ments to sustaina-bility issues, etc. | LCA, LCC and S-LCA were carried out. | Many but the authors emphasized on the selection of UCO collection system that performs best in the three assessments. | The uncertainty exists in the weighting of each indicators within each and among three sustainability dimensions. Second uncertainty is linked to the connection of social indicators and its fine-tuning to the functional unit. |
| 48 | [48] | Hydrogen technolo-gies | A grey-based group decision-making methodology for the selection of hydrogen technologies in life cycle sustainability perspective | N | - | water | costs | job creation, working condition, social influences, etc. | LCA, LCC and S-LCA were performed with stakeholder involvement on the decision-making group. Twelve scenarios on the hydrogen technology development were considered. | The result of twelve different scenarios of hydrogen technologies was presented for selecting the most suitable hydrogen production as well as for delivering the interpretation for decison-makers. | Uncertainty and availability of data & models are the big chunk. The subjectivity in the qualitative evaluation also play part increasing the uncertainty. |

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| 49 | [49] | Electricity option | Life cycle sustainability assessment of electricity options for the UK | N | - | GWP, marine ecotoxicity potential, etc. | fuel price, levelised costs, etc. | Employ-ment, injuries, accidents, human toxicity, etc. | Methodological framework used was a life-cycle approach to assess techno-economic, environmental and social sustainability on various electricity options in the UK. | Many however the results were presented in each aspect such as techno-econoomic, environmental, and social sustainaibility and were divided based on the higher and lower value preferred. | - |
| 50 | [50] | Natural hard floor covering | Life Cycle Sustainability Dashboard | Y | cubic meter of slab | energy, GWP, HTP, PO, acidifi-cation, eutrophi-cation, etc. | extraction, manufac-turing, finishing, waste disposal, electricity costs and revenues | salary, employ-ment, injury and accident, equality and social benefits. | LCA+LCC+S-LCA was undertaken. Various indicators in each aspects were used. | Many however the authors emphasized on the application of LCSD as a tool to present the interpretation results of sustainability performance of a product. | The unavailability of data was a major challenge. |
| 51 | [51] | Photovol-taic modules | Towards life cycle sustainability assessment: An implementation to photovoltaic modules. | Y | 1 m2 of modules | GWP, ecotoxicity, acidifica-tion, land use, etc. | cost | working hours, benefits, wage, etc. | LCSA was carried out and the results were presented using LCSD. | LCSA and LCSD ere used as tools to assess sustainability performance and present the results to policy makers in order to support decison making process effectively. | The overall objective in each aspect is a main challenge. LCA was used clearly for minimizing environmental impacts. For the other two, it depends on the perspectives. |
| 52 | [52] | Solid waste manage-ment systems | Framework for life cycle sustainability assessment of municipal solid waste management systems with an application to a case study in Thailand. | Y | Manage-ment of one tonne of generated MSW in Nthaburi within the integrated system. | CO2, CH4, N2O, CO, NH3, H2S, Nox, Sox, VOCs, land, etc. | income and cost | labor force, communit y participa-tion, living standards | Integrated systems of LCA, LCC and S-LCA was undertaken with different formula and theoretical concept. | Results on the damage to ecosystem & abiotic resources, net LCC of the technologies and income & job creation were presented. | Certains informations could be lost when data is aggregated was the primary challenge. |

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| 53 | [53] | Biogas produc-tion | Multi criteria sustainability assessment of biogas production in Kenya. | Y | 1 m3 of biogas | CED, GHG, energy | total investment cost, labor cost | - | Multi criteria sustainability assessment characterisation was carried out with environmental, technological and economic sustainability evaluation. | Multi-criteria sustainability assessment spider-gram comparing the performances with respect to the unit square of area used in biogas production was presented. | - |
| 54 | [54] | Remanu-factured alterna-tors | Life Cycle Costing in Sustainability Assessment—A Case Study of Remanufactured Alternators | Y | 100,000 km | - | cost for warranties, transport cost, labor cost, cost of energy, etc. | - | LCA-type LCC method was applied. The main focus of method is rather about the complex parameters need to consider in the remanufactured alternators. | The results were presented based on the remanufacturer perspective and from the user perspective. | The uncertainties found are linked to the ambiguity of cost (positive or negativea) and the economic grwoth (rather a mean or an end). The AoP for economic assessment is needed. |
| 55 | [55] | Plantatio n on waste-lands | Simplified life cycle sustainability assessment of mangrove management: a case of plantation on wastelands in Thailand | Y | the plantation area of 1000 ha would be divided into 10 plots and mangroves would be planted on one plot every year | carbon emission | cash flow | Employ-ment | Assessment on the sustainability aspects were conducted by looking at the net carbon sequestration, employment, and cash flow. | The results were presented based on the site-specific investigation and sensitivity analysis were also undertaken. | Data availability is the biggest challenge in this study. |
| 56 | [56] | Fuel | Life cycle sustainability assessment of fuels. | N | - | GWP, energy and non-renewable resources | costs | - | Multi-criteria analysis was performed based on sustainability indicators (environment, economy, energy and renewability indicators) in six cases. | Many but the authors highlighted the interpretation of sustainability index and evaluation of the cases. | Macro-indicators used to assess the fuel performance could lower the scientific value of the assessment. |

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| 57 | [57] | Rare Earth Perma-nent Magnets | Lessons Learned from a Life Cycle Sustainability Assessment of Rare Earth Permanent Magnets | Y | 1 kilogram (kg) of magnet | fossil fuel depletion, climate change, ozone depletion | OPEC, CAPEX indicators | forced labor, wages, employ-ment and other risks based on SHDB | LCSA was applied with different normalization, aggregation methods, and weighing factors. | The results of the comparison of the three magnet production systems were shown with different normalization and weighting methods. | Insufficient of data and methodological documentation increases the uncertainty. What the future sustainable trend should go in certain impact categories could be problematic, for instance, "*does a high risk of unemployment imply the need to invest in that country to improve the situation or does it suggest that a country with a lower risk should be sought*". |
| 58 | [58] | Energy alterna-tives | Understanding Full Life-cycle Sustainability Impacts of Energy Alternatives | N | - | - | - | - | It is a comparative study of LCSA applied in energy alternative sector. | A suggestion for future work was made that coupling life cycle sustainability with scenario planning will be beneficial for energy-related policy making. | - |
| 59 | [59] | solid oxide fuel cells | Life cycle sustainability of solid oxide fuel cells: From methodological aspects to system implications | Y | - | - | - | - | Literature review was done focusing on the system boundary, impact assessment & method and economic aspect. | The results show about the status of each stage of LCA in solid oxide fuel cells application along with eco-efficiency and impact assessment. | Lack of methodological consistency was one of the main points where the attention needs to be paid to. |

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| 60 | [60] | soybean farming systems | Evaluation of the environmental, economic, and social performance of soybean farming systems in southern Brazil | Y | 1 ton of GM, Non-GM, or organic soybeans | GWP, land occupation and energy use | profitability | Employ-ment | Environmental, economic and social life cycle assessment were done with stochastic model using Monte-carlo simulation. | The results of the simulated sustainability performance for the three soybean farming systems were presented based on the performance indicators. The cumulative distribution function was also shown. | Data limitation is the biggest issue. |
| 61 | [61] | Solar Photovol-taic | A Regional Life Cycle Sustainability Assessment Approach and its Application on Solar Photovoltaic | Y | The generation of 1 kWh electricity | GWP, energy, AP, HTP, EP | reliability and profitability | land use, local communit y and fuel poverty | A framework for assessing three dimensions of sustainability were proposed. The indicators used were selected basing on some criteria, i.e. no double counting, the indicators must be quantifiable, applicability and easiness to understand. | Sustainability performance results were presented in lower and higher value preferred. | - |
| 62 | [62] | Non-case study (Theore-tical article) | A Revision of What Life Cycle Sustainability Assessment Should Entail Towards Modeling the Net Impact on Human Well-Being | N | - | - | - | - | - | A roadmap on what we need to focus to enhance the LCSA. (1) how to frame which areas should be sustained (2) how to account for the interconnectedness among AoPs (e.g., the interconnectedness between ecosystems and human well-being); and (3) how to assess both benefit and damage to the AoPs properly. | - |

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| 63 | [63] | Non-case study (Review article) | Review of Life Cycle Sustainability Assessment and Potential for Its Adoption at an Automotive Company | N | - | - | - | - | - | Current state of LCSA in automotive industry was presented as well as bibliometric study. | The inconsistency of the execution in three methods, the low maturity of S-LCA, different way of result interpretation were the challenges found in this study. |
| 64 | [64] | Concrete structure | Life cycle sustainability assessment of fly ash concrete structures | Y | The production of 1m3 FA concrete | climate change, respiratory effect, terrestrial acidifica-tion, etc | cost of material, transporta-tion and energy consump-tion | living condition, health, education, culture and necessities | Many calculation model was used in each stage, i.e. impact assessment, durability analysis, single-objective optimization. Also, quantitative calculation process of SLCA of FA concrete was performed. | Overall environmental and economic results were presented with characterization, weighting results, and social life cycle impact of concrete with different substitutions. | Two suggestions were made: 1. Uncertainty modeling for future work is needed. 2. A number of a key factors of sustainability should be added. |
| 65 | [65] | Manufac-tured product | Total life cycle sustainability analysis of additively manufactured products. | N | - | Environ-ment sub-index score | economy sub-index score | social sub-index score | Product sustainability index method was performed with normalization and weighting. | The results were presented in various sub-index scores for each components for each sustainability dimensions. | The subjectivity of the weighting and normalization and the relativity to its components make the analysis incomparable to each other. The inability of this approach to take the quantity of production as a factor that affect sustainability was a drawback. |
| 66 | [66] | Alkaline Water Electro-lysis | Towards a Life Cycle Sustainability Assessment of Alkaline Water Electrolysis | Y | The production of 1 kg H2 (33 bar, 40 °C, 99.8% purity) | climate change, ozone depletion, terrestrial acidifica-tion, etc. | investment cost, levelised cost, electricity cost, etc. | labor, risk of excessive working time, wage, right of strike, etc. | LCSA was performed with additional step of normalization, weighting and aggregation | Performance matrix was shown comparing the results in three different countries in three aspects of sustainability. | - |

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| 67 | [67] | Photovol-taic power genera-tion | Life cycle sustainability assessment of grid-connected photovoltaic power generation: A case study of Northeast England | Y | one unit of electricity produced by the selected solar PV system | material circularity, energy payback, GWP, AP, EP, ODP | cost, financial feasibility | fuel poverty, employ-ment provision | LCSA was undertaken with 17 indicators selected, 7 addressed techno-economic aspects, 6 examined environmental aspects and 4 assessed social aspects | Results on various indicators were presented in different stages and at the end sustainability ranking of solar PV systems was given. | Some bias-factors existed due to the sensitivity analysis carried out and the cross-validation method need to be employed for future works. |
| 68 | [68] | biodiesel | Inclusive impact assessment for the sustainability of vegetable oil-based biodiesel e Part I: Linkage between inclusive impact index and life cycle sustainability assessment | N | - | embodied energy, GWP, HTP, AP, EP, ADP,TEP | extraction, manufactu-ring, finishing, waste disposal, electricity costs and revenues | salary, employ-ment, accident, discrimi-nation, social benefit | Inclusive impact index was undertaken to assess sustainability performance of biodiesel along with LCA, LCC and S-LCA. | No result was presented since it is the first part of work that only covers goal and scope definition and life cycle inventory analysis stage. | The absence of social issues in the method is part of the limitation found in this study. The model used also face uncertainties due to the choices, model, parameter, spatical variability, etc. |
| 69 | [69] | green building | Agent-Based Modeling of Temporal and Spatial Dynamics in Life Cycle Sustainability Assessment | Y | construc-tion of 100 new buildings | waste | cost | incentive | Hypothetical example was applied and ABM was incorporated in the LCSA model. | Annual LCSA results on waste, cost and incentive from all of scenarios applied were presented. Spatial distribution of green building development in various scenarios for certain years was also shown. | This study does not specify the type of the building and stakeholders involved. The unoccupied cells were also considered available to be developed. The oversimplification of the variety of cost difference that is related to building types, geographical location, green building technology applied, infrastructure and policy. |

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| 70 | [70] | energy system | A review of life-cycle approaches coupled with data envelopment analysis (DEA) within multi-criteria decision analysis for sustainability assessment of energy systems | N | - | - | - | - | review on the 62 articles in the topic of sustainability assessment and MCDA of energy systems were conducted. | The growing role of MCDA in energy policy and the increasing number of the LC+DEA application make LCSA methodological framework is highly needed. | - |
| 71 | [71] | food industry | Regionalized Input-Output Life Cycle Sustainability Assessment: Food Production Case Study | N | - | biotic resources | monetized value | - | Regional Sustainability Assessment Methodology (RSAM) with input output analysis was performed | Biotic resources, absolute and monetized value comparison of food industry for certain regions in Germany were shown. | The detail data is reccommended for the future work to expand RSAM method to become more holistic. The dynamic time series application is also needed to have more precise result. |
| 72 | [72] | Manufac-turing | Life Cycle Sustainability Assessment Approaches for Manufacturing | N | - | - | - | - | Literature review and research needs were presented at LCA, LCC, S-LCA and LCSA as a whole. | The authors emphazised on the importance of LCA for the identification of product and process hotspots for decision making in production development. Tiered approach was also reccommended to be applied. | - |

| # | Artic-les | Area | Title | Functional Unit | | Life cycle impact assessment | | | Methodology | Main results | Challenges |
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| 73 | [73] | cement | Introducing Low Carbon Cement in Cuba - A Life Cycle Sustainability Assessment Study | Y | The production of one ton of cement | climate change, ozone depletion, human toxicity, etc. | monetary, direct, labor cost, etc. | hours of work, health & safety, cultural heritage, local employ-ment, etc. | The adapted LCSA combining LCA, EcLCA and S-CA was conducted. | The results of sustainability performance of three types of cement (Portland cement, blended cement and low carbon cement) were presented. | - |
| 74 | [73] | olive growing system | Evaluation of sustainable innovations in olive growing systems: A Life Cycle Sustainability Assessment case study in southern Italy | Y | 1 hectare of cultivated surface | climate change, toxicity, land use | profitability, costs, investment feasibility | social health, job opportu-nities, contribu-tion to national welfare | LCSA was conducted with AHP weighting and sensitivity analysis | Integrated sustainability performance of olive growing scenarios was shown. AHP weights of each sustainability dimensions and of each impact categories were also presented. | The uncertainty is related to the assumption of data invariance. |
| 75 | [75] | grazing dairy | Tiered life cycle sustainability assessment applied to a grazing dairy farm | Y | 1 kg of fat and protein corrected milk (FPCM) delivered at the farm gate | GWP, AP, EP, mineral extraction, water use, land occupation, etc. | production cost | health and safety, producti-vity of land and labor, work time, fair wage | Tiered LCSA (Neugebauer 2015) was performed and coupled with MCDA. | Mid-point results of impacts and triangle of sustainability to illustrate the iterpretation for each tier was presented. | Uncertainty occurs due to data quality and number of indicators applied in this study. |

| # | Artic-les | Area | Title | Functional Unit | | Life cycle impact assessment | | | Methodology | Main results | Challenges |
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| 76 | [76] | Chemical process | Life cycle sustainability assessment of chemical process: a vector-based three-dimensional algorithm coupled with AHP | N | - | GWP, AD, HT, AP, EP | costs, NPV, discounted cash flow | health & safety, social responsi-bility, politcal applica-bility, etc. | LCSA with MCDA was conducted on three alternatives of chemical process | Comparison matrix for scoring the criterion and vector-based results in three alternatives were presented. | The inconsistency of data collected and the subjectivity and vagueness of the expert's judgement were the main challenges found. |
| 77 | [77] | Methodo-logical article | The Need for a Preference-Based Multicriteria Prioritization Framework in Life Cycle Sustainability Assessment | N | - | - | - | - | Participatory decision making including survey and interview was done to see the proof of concept | Aggregated and cluster preference rank values based on the survey were presented. In this LCSA approach, the main aim lies on where different fields of science and inquiry can best contribute. | - |
| 78 | [78] | Review article | Towards life cycle sustainability assessent of cities. A review of background knowledge | N | - | - | - | - | This review article explored at the background knowledge of sustainability assessment in the entire life cycle phase as well as at the different scope from construction product up to urban region. | This review article concludes that current sustainability assessment in building missed out the holistic point of view while in urban region missed out the proper guidelines. | Many. One of them is for future work, comparison of the results among different cities or urban regions would be very beneficial for policy or decision makers. Consensus on how to conduct sustainability assessment in urban region is also reccommended. |

| # | Artic-les | Area | Title | Functional Unit | | Life cycle impact assessment | | | Methodology | Main results | Challenges |
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| 79 | [79] | electricity | Life cycle sustainability assessment of electricity generation in Pakistan: Policy regime for a sustainable energy mix | Y | The generation of 1 KWh of electricity and | abiotic resource depletion, GWP, AP, EP, etc. | capital, O&M, fuel, annualized and levelized costs | Employ-ment, imported fossil fuel avoided, diversity of fuel supply mix | LCSA was conducted and 20 out of 161 indicators were chosen. These indicators represent indicators related to electricity sector. A scenario for future energy mix was also applied. | The impacts of three pillars of sustainability per functional unit were shown. Besides, the score of sustainability with equal weight to all dimensions was presented along with the score of proposed future electricity mixes. | Scope limitations and data constraints could impose uncertainty. The equal weigthing process of three pillars of sustainability could also affect the uncertainty for policy-making. |
| 80 | [80] | food waste | A Parameter Selection Framework for Sustainability Assessment | N | - | GWP, ozone depletion, photoche-mical oxidation, AP, EP, HTP, etc. | acquisition cost, operational cost, mainte-nance cost, EoL disposal cost, environ-mental cost | impacts on worker, consumer, local commu-nity, society and value chain | LCSA combined with PESTEL was performed. | The identification of PESTEL parameters related to food waste management system were presented along with relevance ranking and uncertainties from low to high level. | The lack of an MFA to see the the flow of food waste and the subjectivity of ranking process could impose the uncertainty. The links between different value domain were forgotten due to analysis that is done at each domain individually.<br>The transfer of parameters of political, technological and legal into the LCSA domains of sustainability pillars/impacts is uncertain. |

| # | Artic-les | Area | Title | Functional Unit | | Life cycle impact assessment | | | Methodology | Main results | Challenges |
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| 81 | [81] | Agricultu -ral waste | Life cycle sustainability assessment of community composting of agricultural and agro industrial waste | Y | The treatment of one ton of waste | AP, EP, GWP, HTP, POP | capital, operational, mainte-nance, wage and damage costs | child labor, fair salary, employ-ment, accident, health and safety | LCA, LCC and S-LCA was performed using SimaPro software 7.3.3. Two alternatives of composting sytems were considered: powder compost system (PCS) and granular compost system (GCS). | LCSA impact assessment result of PCS and GCS were presented and compared along with normalization and sensitivity results. | LCA, LCC and S-LCA was performed using SimaPro software 7.3.3. Two alternatives of composting sytems were considered: powder compost system (PCS) and granular compost system (GCS). |
| 82 | [82] | Review article | Greenhouse gas mitigation in animal production : towards an integrated life cycle sustainability assessment | N | - | - | - | - | - | This review showed that most studies captured production systems in developed countries and on a single indicator, i.e. GHG. They do not taking into account the interconnected effects on other GHGs or with other aspects of sustainability, i.e. economic and social aspect | Consequential setting has never been discussed before and to tackle sustainability challenges in food industry consequential approach is highly reccommended. |
| 83 | [83] | Review article | Advancing Integrated Systems Modeling Framework for Life Cycle Sustainability Assessment | N | - | - | - | - | Different methods were compared and the strengths of each then was analysed to see the opportunity of its use in supporting sustainability decision making. | Integrated sustainability frameworks were provided along with their conceptual, theoretical, empirical and computational background. | The data availability and how to incorporate stakeholder's interest were two main challenges considered in this approach. |
| 84 | [84] | Methodo-logical article | Towards a Life Cycle Sustainability Assessment | N | - | - | - | - | LCA, LCC and S-LCA was suggested to be carried out together in the same system boundary under the similar functional unit. | Some suggestions on how to perform LCSA and some real examples are provided. | Some challenges addressed are the harmonization of database management system, strengthening the application, developing more |

| # | Artic-les | Area | Title | Functional Unit | | Life cycle impact assessment | | | Methodology | Main results | Challenges |
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| | | | | | | | | | | | streamlined approaches, etc. |
| 85 | [85] | Methodo-logical article | Life cycle assessment and sustainability analysis of products, materials and technologies. Toward a scientific framework for sustainability life cycle analysis. | N | - | - | - | - | The review was carried out by addressing the sustainability concept and then life cycle analysis. | Two elements of sustainability and LCA then are combined and general modeling framework was suggested. | LCA, LCC and S-LCA have different satellite accounts to extract indicators thus makes the integration not easy. |
| 86 | [86] | Methodo-logical article | Towards life cycle sustainability assessment | N | - | - | - | - | Three aspects of sustainability were explored in terms of approachs and methods. | For environmental aspect, well structured LCA is available but not for the other two aspects. Robust methods are needed to measure individual sustainability dimensions. | Comprehensive and undertsandable interpretation and presentation are disirable. |
| 87 | [87] | Theoreti-cal article | Life cycle sustainability assessment of products | N | - | - | - | - | The analysis was conducted thoroughly for LCA, LCC and S-LCA. | The development was much needed for S-LCA, compared to the other siblings, LCA and LCC. | The biggest challenges lie on the S-LCA method, i.e. how to relate qualitative impacts to the functional unit and how to manage plenty of indicators on social impact. |
| 88 | [88] | Review article | Life Cycle Assessment: Past, Present, and Future | N | - | - | - | - | The analysis of the recent, current and future development of LCA as an assessment tool. | In the future, LCSA will be tha major assessment that will be used for assessing sustainability of a product or policy. LCSA itself is seen as | The main challenge is how to structure, select, and achieve and channel the practicality of the various disciplinary models to different life |

| # | Artic-les | Area | Title | Functional Unit | | Life cycle impact assessment | | | Methodology | Main results | Challenges |
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| | | | | | | | | | | an approach rather a model. | cycle sustainability questions |
| 89 | [89] | Review article | Application of Life Cycle Sustainability Assessment and Socio-Eco-Efficiency Analysis in Comprehensive Evaluation of Sustainable Development | N | - | - | - | - | The analysis of current state and methods used in the LCSA was conducted. | A comprehensive and integrative assessment is needed for strengthen the method in order to assess the complexity of sustainability issue. | How to integrate three methods in LCSA remains a significant challenge |
| 90 | [90] | Natural hard floor covering | Life Cycle Sustainability Dashboard | N | Not mentioned | Embodied energy, GWP, HTP, POP, AP, EP | Extraction costs, manufac-turing costs, finishing costs, waste disposal costs, electricity costs, revenues | Employ-ment, number of accidents percentage of child labor labor hours per week | The LCSA was performed and LCSD was tested through a case study. | LCSD is used to present an innovative, applicable and practicable comparison methodology for assessing sustainability performance | The LCSA was performed and LCSD was tested through a case study. |

| # | Artic-les | Area | Title | Functional Unit | | Life cycle impact assessment | | | Methodology | Main results | Challenges |
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| 91 | [91] | Theoreti-cal article | From LCA to Life Cycle Sustainability Assessment : concept, practice and future directions | - | - | - | - | - | The current state of each methods in LCSA was discussed and analysed | The development of concept, practice and future directions of LCSA was presented. Some key points are:<br>- The normativity elements in LCSA and the aspects of inter- and intra-generational equity;<br>- The assessment scale<br>- The time horizon<br>- The stakeholders involvement | LCSA was criticized due to the fact that it prevents a complete understanding of the mutual interdependencies of the three domains of sustainability. |
| 92 | [92] | Theoreti-cal article | Progress in sustainability science : lessons learnt from current methodologies for sustainability assessment : Part 1 | - | - | - | - | - | The review lies on the ontological, epistemological and methodological aspects of sustainability in the science context. A meta-review of recent studies on sustainability assessment was also conducted. | Some key features for the improvement of robust sustainability assessment were presented. | Positive impacts should be more promoted by the life cycle-based methodologies so they will not only focus on alternative comparison and avoiding negative impacts. |
| 93 | [93] | Theoreti-cal article | Workshop on life cycle sustainability assessment: the state of the art and research needs - November 26, 2012, Copenhagen, Denmark | - | - | - | - | - | The review happened around the state of the art, the summary of workshop, and research needs on LCSA. | The main results of the workshops presented were about the farmework, the operationalising of LCSA, sustainability assessment of technologies and ontology, epistemology and methodology of LCSA. | How to effectively present the LCSA result, how to apply LCSA into real application and how to involve stakeholders in the process are the primary challenges discussed in the workshop. |
| 94 | [94] | Theoreti-cal article | Life cycle sustainability assessment | - | - | - | - | - | It was short address of editor of IJLCA on the | The growing interest of sustainability issue, approach, inherent | How to deal with different level of maturity between three |

| # | Artic-les | Area | Title | Functional Unit | | Life cycle impact assessment | | | Methodology | Main results | Challenges |
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| | | | | | | | | | recent developments of LCSA | transdisciplinary nature of sustainability science, and the importance of integration between methods are the main idea addressed. | methods, with scenario modeling, with consistent integration and with normative positions (values) and empirical knowledge within LCSA are the main challenges mentioned. |
| 95 | [95] | Theoretical article | From LCA to Sustainability Assessment | - | - | - | - | - | Three methods representing three pillars of sustainability was carefully analysed in terms of its state of the art and current development and its potency to integrate in one assessment such LCSA. | The capability of LCA to quantify environmental impacts must be supplemented by economic (LCC) and social (S-LCA) aspects. | How to keep the balance between the desired scientific accuracy and practical feasibility remains a main challenge. |
| 96 | [96] | Theoretical article | Is there a place for culture in life cycle sustainability assessment? | - | - | - | - | - | A literature review on the definition of culture and culture involvement in LCA, LCSA and S-LCA as well as some key points to address when assessing the integration of culture in LCA, S-LCA and LCSA was conducted. | A positive benefit of considering culture within LCSA has been seen as a greater resonance of LCSA results with stakeholders. The integration of culture in LCSA could potentially help to protect communities and their diversity. | The main challenges are the lack of recognition in decision-making processes due to culture is often seen as intangible norm, understanding when ‘culture’ should be differentiate from ‘social’ also remains, the data gathering, and the diversity of cultures between stakeholders at different scales from local community, regional, to nation. |

| # | Artic-les | Area | Title | Functional Unit | | Life cycle impact assessment | | | Methodology | Main results | Challenges |
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| 97 | [97] | Theoreti-cal article | From a critical review to a conceptual framework for integrating the criticality of resources into Life Cycle Sustainability Assessment | - | - | - | - | - | Review was done by looking at the resource as an area of protection (AoP) in sustainability study. This article also reviewed all of recent criticality assessment studies. | LCA does not capture sufficiently resource criticality assessment even if it is highly important in sustainability aspect. An approach by Graedel et al. (2012) was proposed to evaluate the criticality of resources. | The main challenges lie on a need of a competition factor to evaluate resource depletion by involving resource recycling, substitutability and user adaptation to depletion. The geopolitical supply distribution aspect of resources criticality also need to be considered in LCSA framework. |
| 98 | [98] | Methodo-logical article | Towards application of life cycle sustainability analysis Revue de Métallurgie Towards application of life cycle sustainability | - | Not clearly mentioned | - | - | - | The methodology proposed was consisted of five steps: system description, scenarios, indicators and tools, application of tools, and interpretation of results. This study focuses on the first step: system description. | A general scheme and themes of the system concerned in an LCSA study that need to be addressed were presented. Also, practical approach to conduct and illustrate system description was presented. | - |
| 99 | [99] | Methodo-logical article | Enhancing the practical implementation of life cycle sustainability assessment e proposal of a Tiered approach | - | Not clearly mentioned | - | - | - | Tiered approach was develop to enhance the implementation of indicators and to robust the indicator selection process. | The structure for the tiered approach was presented from sustainability footprint, best practice and comprehensive assessment in order to to improve sustainability assessment towards a more holistic approach away from single aspect assessments. | The new method proposed still does not solve the challenge in the interpretation stage. |

| # | Artic-les | Area | Title | Functional Unit | | Life cycle impact assessment | | | Methodology | Main results | Challenges |
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| 100 | [100] | Review article | A transdisciplinary review of the role of economics in life cycle sustainability assessment | - | - | - | - | - | The review covered the transdisciplinary framework of sustainability assessment, the role of economic values in LCA and economic concepts in ecological economics. A two-stage approach for economic values application in LCSA was proposed. | This paper questioned the reliance of LCA on utilitarianism and valuation using willingness to pay. It also questioned the claim of ELCC as the economic dimension of LCSA. | The current definition of environmental LCC addresses some of the challenges in ontological and epistemological aspect. Existing monetisation and the values of the policy maker need to be accounted to confirm its suitability with sustainability. |
| 101 | [101] | Review article | Life Cycle Sustainability Assessment: What Is It and What Are Its Challenges? | - | - | - | - | - | This study reviews on two main questions: which definition(s) do researchers in the academia adopt and what challenges do they experience | The review on the case or methodological study was presented. The references were categorised on three groups: study on broadening the impacts, broadening the analysis and deepening the analysis. | The lack of (proper and quantitative) S-LCA indicators, the need for practical (case study) examples, dynamic approach and scenario evaluations, how to interpret LCSA results, how to address uncertainties as well as with value choices, the subjectivity (weighting methods), how to deal with benefits in S-LCA, how to avoid double counting, and how to incorporate different perspectives (producer, customer, societal) on costs in LCC, etc. |

| # | Artic-les | Area | Title | Functional Unit | | Life cycle impact assessment | | | Methodology | Main results | Challenges |
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| 102 | [102] | Review article | Systems Thinking for Life Cycle Sustainability Assessment | - | - | - | - | - | Bibliometric analysis was carried out in LCSA studies from 2000 to 2017 based on the broadening indicators category, the broadening scope category and the deepening category. The role of system thinking was also discussed. | The results pointed out that LCSA framework could be advanced in these areas (1) regional and global level LCSA models using multi-region input-output analysis (2) dealing with uncertainties in MCDA indicators weighting; and (3) integration of system dynamics modeling to deal with causal relationships of the indicators. | Envisaging the sustainability mechanisms, understanding further parts of the complex systems, and the links to intended sustainability goals were the main challenges mentioned. |
| 103 | [103] | Review article | Life cycle tools combined with multi-criteria and participatorymethods for agricultural sustainability: Insights from a systematic and critical review | - | - | - | - | - | A systematic and review was done for these parameters: which multi-criterial and/or participatory methods have been linked with LC tools; how is the methodological relationships; how is the involvement of stakeholders; and which synergies have been reached by integrating the methods. | Results of the critical review of the state of the art on LC studies integrating MCDA in agricultural sustainability was presented along with their methodological issues and participative purposes. The discussion lies on the advantages of approaches combination. | The future research proposed was should LCSA is needed to be apply in seperate LC assessement or not considering the communicability of results, usability of specific specialized expertise and use of separate data. |
| 104 | [104] | Editorial article | Charting the Future of Life Cycle Sustainability Assessment | N | - | - | - | - | - | Some issues were mentioned, i.e., :<br>- challenges on broadening of impacts while keeping a comprehensive approach<br>- the communication of | Some priorities must be given to advance LCSA, i.e. which areas should be identified as main priority to be maintained and how to address the interrelationships of those and furthermore |

| # | Artic-les | Area | Title | Functional Unit | | Life cycle impact assessment | | | Methodology | Main results | Challenges |
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| | | | | | | | | | | LCSA results to policy makers applying weighting concept and addressing the value choices<br>- the incorpartion of technological, economic, and political mechanisms at different levels of analysis by integrating LCA with other types of models<br>- the development of appropriate, quantitative and practical approaches for S-LCA | how to integrate both impacts and benefits within LCSA (Schaubroeck and Rugani 2017). To this date, the trend seems to be focus on the prioritization of impacts versus broadening of impacts. |
| 105 | [105] | Review article | Life cycle sustainability assessment of biofuels | N | - | - | - | - | - | The main results deliberate the considerations when applying LCA in biomass to biofuel conversion routes in first-, second-, third- and fourth-generation biofuels as well as address key findings of LCA studies in biofuel production, i.e., on energy corps, solid biofuels upgrade, biofuel thermochemical pretreatment or overall impact of biofuel production | The main challenges presented were mainly main challenges for biofuel sustainability, not challenges related to LCSA application. |

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| 106 | [106] | Hydrogen produc-tion | Life cycle sustainability decision-support framework for ranking of hydrogen production pathways under uncertainties: An interval multi-criteria decision making approach | N | - | GWP, AP | Production cost | Social acceptabi-lity, maturity | LCSA was combined with MCDM called improved decision-making trial and evaluation laboratory (DEMATEL). The updated version of DEMATEL method was used to identify the weights of the criteria. The interval of EDAS (Evaluation based on Distance from Average Solution) was also developed for ranking the alternatives for hydrogen production. | The comparison matrix for identifying the relative influences of maturity, energy efficiency, and exergy efficiency on production cost was presented. The average solution of each indicator, the sum weighted positive & negative distance and the integrated priorities of the four alternative pathways for hydrogen production were elaborated. | The recommended multi-criteria decision making method does not provide numerous actors to takepart in identifying and ranking the alternatives. |
| 107 | [107] | High-density polyethy-lene (HDPE) | Life Cycle Sustainability Assessment for Sustainability Improvements: A Case Study of High-Density Polyethylene Production in Alberta, Canada | Y | the production of 1,000 kg of HDPE at Dow Chemical Canada facility | GHG emission (carbon dioxyde and methane) | Costs based on the raw material, energy and labour | Results were taken from Hannouf and Assefa 2017 | the strong sustainability model and the Driver–Pressure–State–Impact–Response (DPSIR) framework were employed | LCC results were shown interestingly by from three different perspectives (NG producer, petroleum producer and HDPE producer) and by cost category. Interpretation LCSA results were also presented along with the integrated solution-oriented approach. The latter includes developing sustainability improvement proposals for the background and foreground processes | Interpreting the interdependences between the three assessment results is a challenge, particularly moving from comparative assessment approach to solution-oriented approach |

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| 108 | [108] | Transpor-tation fuel | Developing Life Cycle Sustainability Assessment methodology by applying values-based sustainability weighting - tested on biomass based and fossil transportation fuels | N | - | GWP, water and non-renewable energy consump-tion | Production and transport-tation cost | Direct and indirect job | E-LCA was done from well-to-tank and tank-to-wheel while S-LCA consdiered both positive and negative impacts. | The LCSA was weighted based on the sustainability pillars that are focused differently from the values of the stakeholder (Egalitarian, Hierarchist, and Individualist) | The interpretation of LCC results to sustainable development concept remain a challenge. For S-LCA, uncertainty, quality and reability of data used are still questionable because database used in this study is typically slef-reported. For LCA, a challenge to include indirect effect (i.e. indirect land use change) remains exist |

# Annex B

Supplementary Material for:

Life Cycle Assessment and Life Cycle Costing of Multistorey Building: Attributional and Consequential Perspectives

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# 1. Marginal technology identification

## 1.1. Wood

*Already presented in main article.*

## 1.2. Steel

*What time horizon does the study apply to?*

The temporality of this study is long-term.

*Does the change only affect specific processes or markets?*

It is forecasted that more wooden hybrid multistory buildings will be constructed in the future. Thus, it will affect the increase of the other complementary materials needed as well [109].

*What is the trend in the volume of the affected market?*

A growing trend in reinforcing production and consumption of rebars has been observed over the past five years (1.7%) as narrated by Azarijafari [110] and it is estimated that this rise will continue in the future.

*Is there potential for an increase or reduction in production capacity?*

To date, Labrador Trough in the province of Labrador and Northern Quebec is the largest geological source of iron in Canada. Such mines account for almost all of Canada's iron ore mine. Although steel demand is increasing, local production has declined since 2010 and the government is forced to import [111]. Protectionist legislation and increase of foreign import resulted in a substantial drop in exports (-6.1%), while imports recorded an unprecedented 16.4% growth in 2014 [112].

*Is the technology the most or least preferred?*

It is expected that the affected technology will be "blast furnace with carbon capture and storage and top gas recycling" later than 2040 as it is the newest technology supplier to be developed in the future to meet the demand in the years to come [113]. The five top importers are predicted to be similar: China, South Korea, India, Brazil and Turkey [114] with China as the strongest candidate [115].

## 1.3. Concrete

*What time horizon does the study apply to?*

The temporal window of this study is long-term.

*Does the change only affect specific processes or markets?*

Wood will be used more in hybrid multistory buildings in the Québec. As one of the main building materials in hybrid multistory building, the demand for concrete is therefore expected to increase as well [116].

*What is the trend in the volume of the affected market?*

According to IBISWorld study, concrete ready-mixed industry in Canada has shown steady growth of 4.4% percent over the past five years [117]. This growth is projected to continue at a rate of 1.6 per cent over the next five years, gaining from improved services and transport infrastructure construction [118].

*Is there potential for an increase or reduction in production capacity?*

Concrete production technology in Quebec focuses on wet mixing plants where water is mixed with cemented materials and aggregates in the plant instead of drying water into the truck mixer. Since more than 75% of the concrete cost of production comes from the purchase of materials, less attention is paid to technological development and cost optimisation [119].

*Is the technology the most or least preferred?*

Total cement plant production capacity in Quebec is 3.9 Mt per year, and Quebec uses just 1.9 Mt of cement produced [120]. About 70.3% of current production capacity is used locally. Given the impact of a marginal increase in cement demand, the short-term scenario relies on one of the current cement suppliers, while the latest provider would presumably be built later in the long-term scenario, which will be the impacted one.

Coal, natural gas, oil (e.g. residual / heavy fuel oil) and alternative sources such as biomass are included in the clinker production. There is no coal mine in Quebec and only 1% of the production energy consumed comes from coal provided by Central Appalachian mines such as those in New York and Pennsylvania in the U.S [121]. Coal's retail price is determined by the distribution of coal production and shipping to Quebec, making it difficult to be the main supplier in the future. The use of heavy fuel oils is also dramatically declining owing to Quebec government's new banning programme on high-sulfur crude [122]. Natural gas, tyre-derived fuels (TDFs) and biomass are widely used in this business. Natural gas as fuel for cement industry clinker production is not uncommon practise [123]. Therefore, despite the inability of infratructure production to use TDFs and biomass to satisfy rising demand in the future, it is safe to assume that natural gas is long-term projected as unconstrained fuel for calcination cycle.

### 1.4. Gravel

*What time horizon does the study apply to?*

The temporal scope of this study is long-term.

*Does the change only affect specific processes or markets?*

As one of important material in building construction, the increasing of hybrid building indirectly will affect the increase of gravel demand as well.

*What is the trend in the volume of the affected market?*

The sand and gravel industry in Quebec have been steady for approximately 15 years and national aggregate mining industries generate an average of 30 Mt aggregates per year [124] from Azarijafari [125]. Quebec's primary use of sand and gravel (55%) is road construction and building. The increasing penetration of wood use in hybrid building will affect other complementary materials as well, like aggregate.

*Is there potential for an increase or reduction in production capacity?*

The increasing demand of aggregates in the future is anticipated by over 300 aggregate mines available in Quebec and across the country.

*Is the technology the most or least preferred?*

A feature affecting quality and aggregate functionality is their surface texture. Particularly, in concrete mixtures, sand particle form plays an important role in concrete cement material to meet workability and desired hardened properties. Natural aggregates are commonly used in traditional and high-performance concrete mixtures as a lower binder volume is required to achieve the optimal workability and mechanical properties of the mixture relative to crushed aggregates. By using crushed aggregates instead of natural aggregates, water demand will increase when 6 to 9 kg/$m^3$ and sand content by 2 to 3% in the mixtures. Thus, it is predicted that crushed aggregate will be the future long-term marginal technology.

### 1.5.Brick

*What time horizon does the study apply to?*

The temporal scope of this study is long-term. It is forecasted that more wooden multistory buildings will be constructed in the future.

*Does the change only affect specific processes or markets?*

The building market in Québec is predicted to use more wood in their multistory buildings in the future. This will affect the brick market as well since it is one of the primary materials used in hybrid wood-concrete multistory buildings.

*What is the trend in the volume of the affected market?*

Clay brick production is projected to increase in the next few years in line with the growth of residential building in the construction sector. According to the IBIS database, the annual growth of clay brick manufacturing in Canada was 3% between 2013 and 2018 [126].

*Is there potential for an increase or reduction in production capacity?*

Five primary clay and shale mining plants that produce bricks from a quarry in Eastern Canada are located in La Prairie, Brampton, Burlington, Ottawa, and Streetsville [127]. The last four plants operate in Ontario, where three of them (Burlington, Ottawa, and Streetsville) are under production by Hanson Building Materials America (HBMA), who are the largest brick producers nationally. However, no information on the ratio of capacity to production is available.

In the province of Québec, clay soils can be found in the more developed parts of the territory, in particular in the St. Lawrence Valley, the Ottawa Valley, and the Saguenay – Lac-Saint-Jean region [128]. Currently, the majority of the demand for bricks in Québec is solely fulfilled by the Brampton plant, with resources from the St. Lawrence Valley. Thus, there is potential for plants in neighbouring provinces, like Ontario, to provide the increasing demand (if any) in the future.

*Is the technology the most or least preferred?*

According to Natural Resources Canada, the best brick for insulating housing is clay brick [129]. In terms of technological constraints, there is not much variation. Thus, the preference will come down to the most economic price and shortest transportation distance.

According to Dumont [130] and Venta [131], HBMA is considered the largest brick manufacturer and is categorized as E industry or large industry with 200-499 employees while Brampton is medium or C (50-99 employees). With an increasing demand for brick within the next ten years in Québec, the brick plants in Ontario, specifically the Brampton and Burlington plants, could meet this demand.

### 1.6.Gypsum

*What time horizon does the study apply to?*

The temporal period of this study is long-term (10-15 years).

*Does the change only affect specific processes or markets?*

Wood will be used more in hybrid multistory buildings in the Québec residential market. Demand for gypsum, as one of the main building materials, is therefore predicted to increase as well.

*What is the trend in the volume of the affected market?*

No precise data are available regarding the volume of gypsum in the market. However, the manufacturing intensity ratio (or increase rate) has been consistently positive over the past six years [132].

Other data indicate that, in general, gypsum production in Canada has decreased. However, this does not mean that gypsum is not going to be used in the long-term; it is still being used but in smaller quantities.

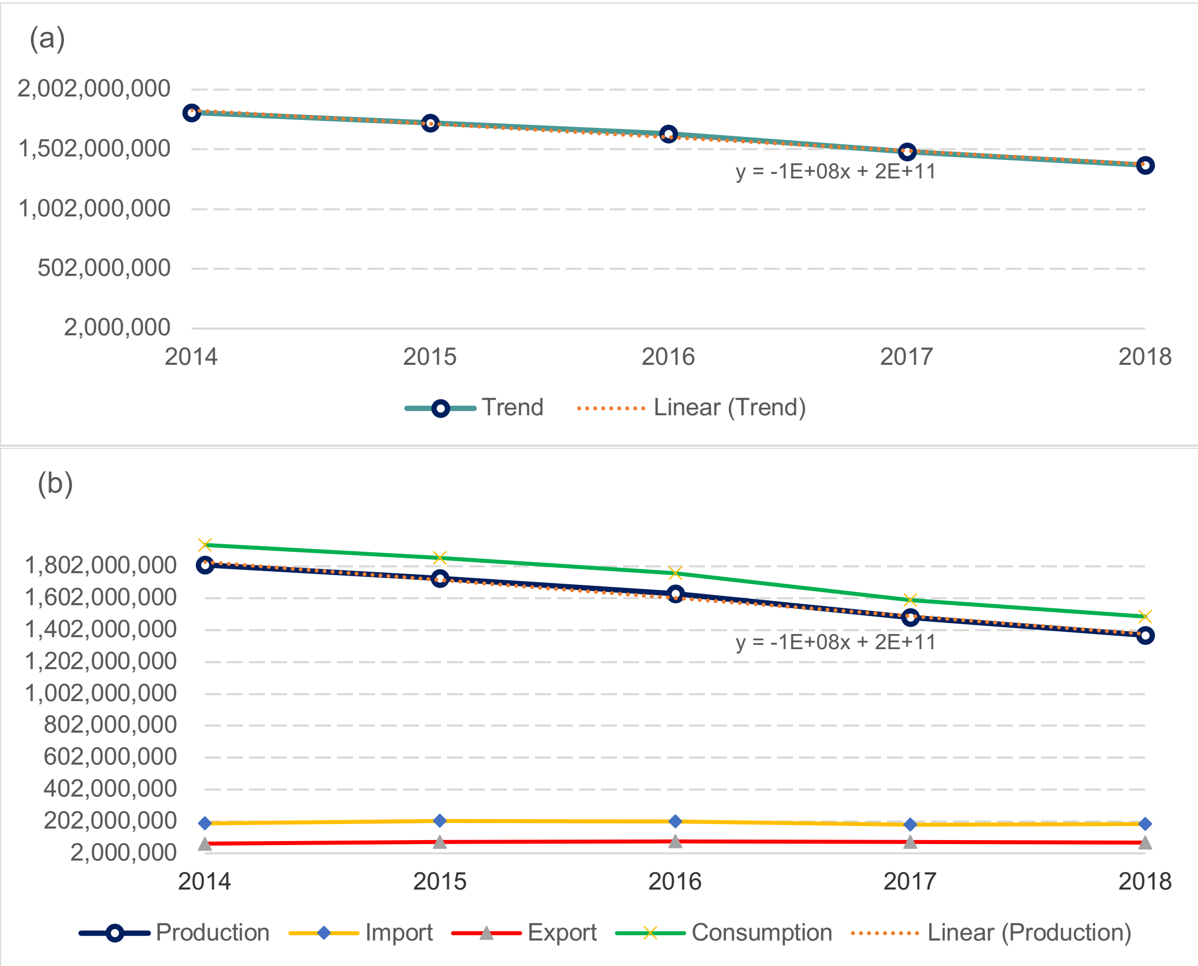


Figure 2 (a) Gypsum production in Canada (in metric tons); (b) Gypsum production, export, import, and consumption in Canada (in metric tons) [133].

*Is there potential for an increase or decrease in production capacity?*

The two main gypsum production plants in Québec are located in Montreal and are owned by CGC Inc. and Domtar Inc. The former also owns another gypsum manufacturing plant in St. Jerome. No information is available regarding capacity constraints for either plant, however, the affected technology can be assessed from a technological perspective.

Gypsum production does not have much variation. Two minor differences can be seen, in the quantity or composition of the raw materials and the type of kettle used. The raw materials differ in the proportions of stucco, paper, water, and perlite used. Different types of kettle have energy efficiencies ranging from 55 to 90% (batch = 50%, continuous = 65%, continuous with submerged combustion = 75%, conical = 90%).

The energy used for drying gypsum material is the major cost in gypsum board production (around 18% of the total direct manufacturing costs). The average gypsum manufacturing technology is batch kettle, however, this technology has low energy efficiency and, thus, is not the preferred type. Another major cost is transportation. If in the future the nearest plant cannot fulfill the gypsum demand in the Québec market, then neighboring markets such as Ontario or the US will fulfill demand.

*Is the technology the most or least preferred?*

Considering the energy costs of production and transportation costs, the most affected supplier is potentially gypsum produced with conical kettle technology from Ontario (Hagersville, Caledonia and Mississauga) or from Montreal [134].

1.7. Aluminum

*What time horizon does the study apply to?*

The temporal coverage of this study is long-term.

*Does the change only affect specific processes or markets?*

It is assumed that the demand for aluminum is likely to increase since one of the major applications of aluminum is in construction following the increasing demand of hybrid multistory building.

*What is the trend in the volume of the affected market?*

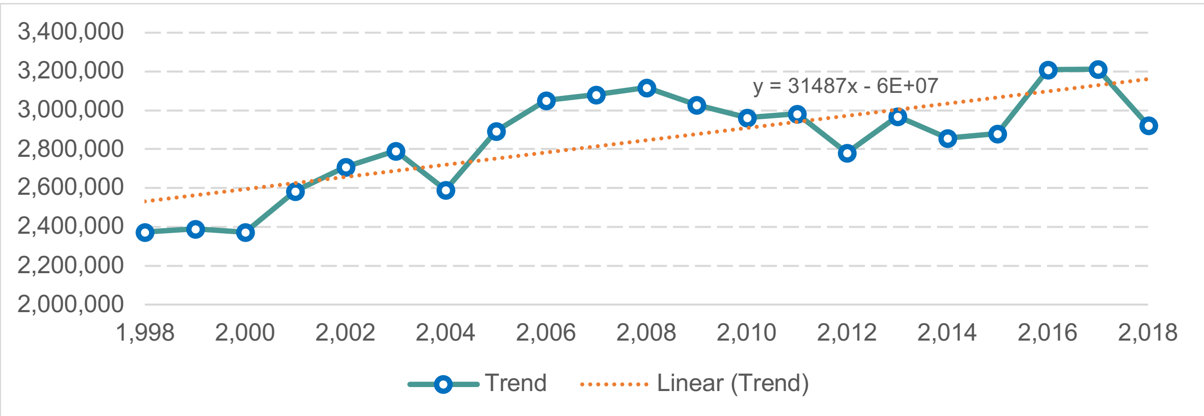


Figure 3 Aluminum production in Canada (in metric tons) [135]

The trend of aluminium production in Canada is increasing. There are eleven aluminum smelter plants in Canada, with ten of them located in Québec. Four plants that have production capacity of >400 tons per year are Sept-Iles, in Saguenay–Lac-Saint-Jean, Kitimat, and Bécancour [136].

*Is there potential for an increase or reduction in production capacity?*

The production constraints of aluminum are unknown. However, given the number of aluminum plants and the fact that aluminum is a highly recyclable material, there is the potential to meet the demand for aluminum through an increase in production capacity. In other words, there are no obvious production constraints in terms of the availability of raw materials, or other factors. All plants are presumably unconstrained or fully elastic. [137]

*Is the technology the most or least preferred?*

Among the unconstrained suppliers/technologies, the most sensitive/flexible to a change in demand is the most competitive, which can be seen from the production cost per unit. In aluminum production, electricity or energy is the key to cheaper production costs. Since most of the aluminum production plants are located in Québec where electricity prices are low, this factor can be disregarded. The second key point is the location of the plant [138].

However, despite the fact that aluminum is highly recyclable and its suppliers are mostly unconstrained, it is worth-mentioning that aluminum is indeed a global product. Previous statistics show that Canada imported quite amount of aluminum from other countries such as China or USA [139]. The lower price is the ultimate reason to import from abroad. This fact seems remain similar for next couple years, especially of China being the top suppliers over the past years.

# 2. Inventory Analysis

## 2.1. LCA Inventory Analysis

### 2.1.1. Attributional approach

Material production phase

*Already presented in main article.*

Use phase

Table 1 Use phase

| Dataset | Unit process[2] | Unit | Amount |
|---|---|---|---|
| **Electricity** | Electricity, low voltage {CA-QC} \| electricity voltage transformation from medium to low voltage \| Cut-off, U | kWh | 101,604,600 |

[2] The unit processes used in the use phase are from ecoinvent dataset while the quantity of electricity is from CAN-Quest software (the assumption made is available in the next section)

Table 2 Input parameters of CAN-Quest

| **Code analysis:** | **NECB 2011** |
|---|---|
| **Building type:** | Mixed use (retail space and condo) |
| **Location:** | Quebec Region A (Montreal) |
| **Utilities and rates:** | Electricity and gas rate 2 |
| **Season definitions:** | Typical use of throughout year |
| **General shell information** | |
| **Building are:** | 10000 m2 |
| **Number of floors** | 8 |
| **Shell multiplier:** | 1 |
| **Building footprint** | |
| **Footprint shape:** | Rectangle |
| **Zoning pattern:** | Perimeter / core (4.57 m) |
| **Building orientation:** | East |
| **Floor to floor** | 3.7 m |
| **Floor to cell** | 2.7 m |

| **Building envelope construction** | |
|---|---|
| ***Roof surface*** | |
| **Construction:** | Wood adv. frame > 60.96 cm |
| **Exterior finish:** | Wood/plywood |
| **Exterior insulation:** | 5.08 cm polyurethane R-12 |
| **Additional insulation:** | None |
| ***Above grade walls*** | |
| **Construction:** | Wood frame 2x6, 60.96 cm |
| **Exterior finish:** | Wood/plywood |
| **Exterior insulation:** | 5.08 cm polyurethane R-12 |
| **Additional insulation:** | none |
| **Interior insulation:** | 2.54 cm polyurethane (R-6) |
| ***Ground floor*** | |
| **Exposure:** | Earth contact |
| **Interior finish:** | Vinyl tile |
| **Construction:** | 15.24 cm Concrete |
| **External insulation:** | no perimeter insulation |
| ***Infiltration:*** | Peri:192.959 L/s-m$^2$ (ext-wall) |
| | Core: 5.078 L/s-m$^2$ (floor) |

| Building interior construction | |
|---|---|
| **Ceilings** | |
| **Int finish** | Lay-in acoustic tile |
| **Batt insulation** | none |
| **Vertical walls** | |
| **Wall type** | Frame |
| **Batt insulation** | R-13 |
| ***Floors*** | |
| **Int finish** | Vynil tyle |
| **Rigid insulation** | 5.08 cm polyurethane (R-12) |
| **Construction** | 10.16 cm concrete |
| **Concrete cap** | 1.212.7 cm LW concrete |
| **Exterior doors** | |
| **Door type** | Glass |
| **Door dimension** | |
| **Ht (m)** | 2,1 |
| **Wd (m)** | 1,8 |
| **Construction** | Triple Clr |
| **Glass category and type** | Triple Clr 0.318 cm, 0.635 cm air |
| **Frame type** | Aluminium w/o Brk |
| **Frame wd (cm)** | 7,6 |
| **Exterior windows** | |
| **Glass category and type** | Triple Clr 0.318 cm, 0.635 cm air |
| **Frame type** | Aluminium w/o Brk |
| **Frame wd (cm)** | 3,3 |
| **Glass category and type** | Triple Clr 0.318 cm, 1.27 cm air |
| **Frame type** | Aluminium w/o Brk |
| **Frame wd (cm)** | 3,3 |
| **Window dimensions, positions** | **an**d quantities |
| **Window Ht (m)** | 1,59 |
| **Sill Ht (m)** | 0,91 |
| **% window** | |
| **South** | 0 |
| **North** | 23,3 |
| **West** | 0 |
| **East** | 0 |

| | |
|---|---|
| **Percent area** | **12,50%** |
| **Design max occup (m2 per pers)** | 30 |
| **Design ventilation (L/s/pers)** | 35,51 |
| **Assign to which floors)** | 1 |
| **Dwelling** | |
| **Percent area** | 87,50% |
| **Design max occup (m2 per pers)** | 59,9 |
| **Design ventilation (L/s/pers)** | 20,7 |
| **Assign to which floors)** | 2 to 8 |
| **Occupancy profiles by season** | |
| **Entire season** | EL1 Occup profile (S1) |
| | |
| **Exterior enduses (not contributing to space loads)** | |
| **Exterior lighting** | |
| **Domestic hot water** | |
| **Interior Lighting Loads and Profiles** | |
| **Retail -sales (W/m2)** | 18 |
| **Dwelling (W/m2)** | 5 |
| **Office equipment loads and profiles (source: A Methodology for Defining Electricity Demand in Energy Simulations Referred to the Italian Context)** | |
| **Retail - sales (W/m2)** | 5 |
| **Dwelling (W/m2)** | 5 |
| **Cooking loads and profiles** | |
| **Retail - sales (W/m2)** | 10 |
| **Dwelling (W/m2)** | 5 |
| **Self-contained refrig** | |
| **Retail - sales (W/m2)** | 10 |
| **Dwelling (W/m2)** | 5 |
| **Misc equipment** | |
| **Retail - sales (W/m2)** | 2,5 |
| **Dwelling (W/m2)** | 5 |
| **Process loads** | |
| **Retail - sales (W/m2)** | 10 |
| **Dwelling (W/m2)** | 5 |
| **Motors and air compresison** | |
| **Retail - sales (W/m2)** | 10 |
| **Dwelling (W/m2)** | 5 |
| **Exterior lighting (W/m2)** | 10 |

| | | | |
|---|---|---|---|
| **HVAC System** | | | |
| **System type name:** | HVAC System 1 | | |
| **Cooling source** | DX Coils | | |
| **Heating sources** | DX Coils (Heating Pump) | | |
| **Heating pump Src** | Air | | |
| **System type** | Split system single zone heat pump | | |
| **System per area** | System per Shell | | |
| **return air path** | Ducted | | |
| **System assignment to thermal zone** | Building envelope and loads 1 | | |
| **Seasonal thermostat setpoints** | | | |
| **Occupied** | Cool | 24,4 | |
| | Heat | 21,1 | |
| **Unoccupied** | Cool | 27,8 | |
| | Heat | 32,2 | |
| **Design temperatures** | indoor | Cooling | 23,9 |
| | | heating | 22,2 |
| | supply | Cooling | 12,8 |
| | | heating | 32,2 |
| **Air flows** | Minimum design flow | 2,54 | L/s-m2 |
| | VAV minimum flow | 100% | |

| **Packaged HVAC equipment** | | |
|---|---|---|
| **Cooling** | | |
| **Typical unit size** | 135-240 kBtuh or 11.25-20 kW | |
| **Efficiency** | EER | |
| | 8,5 | |
| **Heating** | | |
| **Efficiency** | COP | |
| | 2,9 | |
| **Supply fans** | | |
| **Power & Mtr eff** | 249 | Pascal \| High |
| **Fan type** | variable speed druve | |

| **Non Residential Domestic Water Heating** | | |
|---|---|---|
| **Heating fuel** | Natural gas | |
| **Heating type** | Storage | |
| **Hot water use** | 3,79 | l/pers/day |
| **Input rating** | -0,553 | kW |
| **energy factor** | 0,6208 | |
| **Storage tank** | | |
| **tank capacity** | -2 | L |
| **Insulation R value** | 2,1 | m2K/W |
| **Water temperature** | | |
| **Supply water** | 57,2 | C |

| **Non Residential Domestic Water Heating** | | |
|---|---|---|
| **Heating fuel** | Natural gas | |
| **Heating type** | Storage | |
| **Hot water use** | 3,79 | l/pers/day |
| **Input rating** | 10,609 | kW |
| **energy factor** | 0,598 | |
| **Storage tank** | | |
| **tank capacity** | 44 | L |
| **Insulation R value** | 2,1 | m2K/W |
| **Water temperature** | | |
| **Supply water** | 43,3 | C |
| **Process flow** | 9,7 | liter per hour |

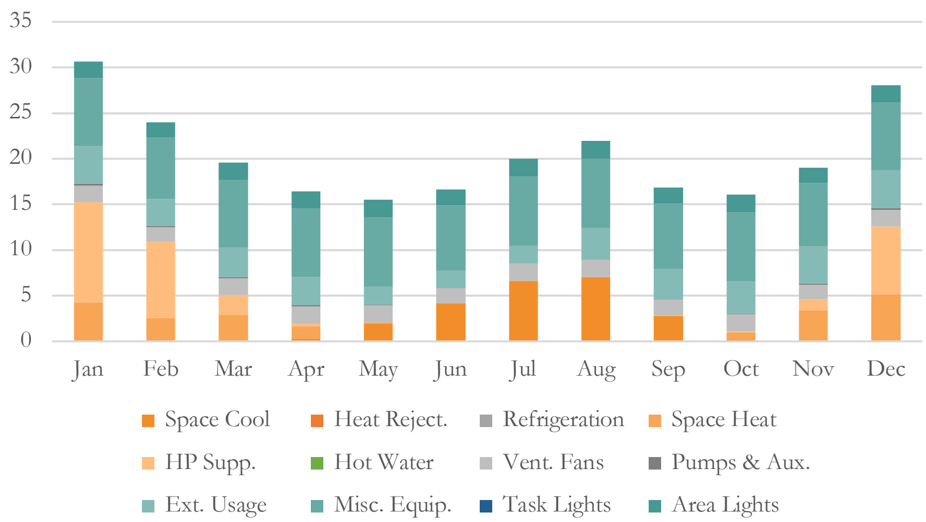


Figure 4. Electricity consumption (kWh)

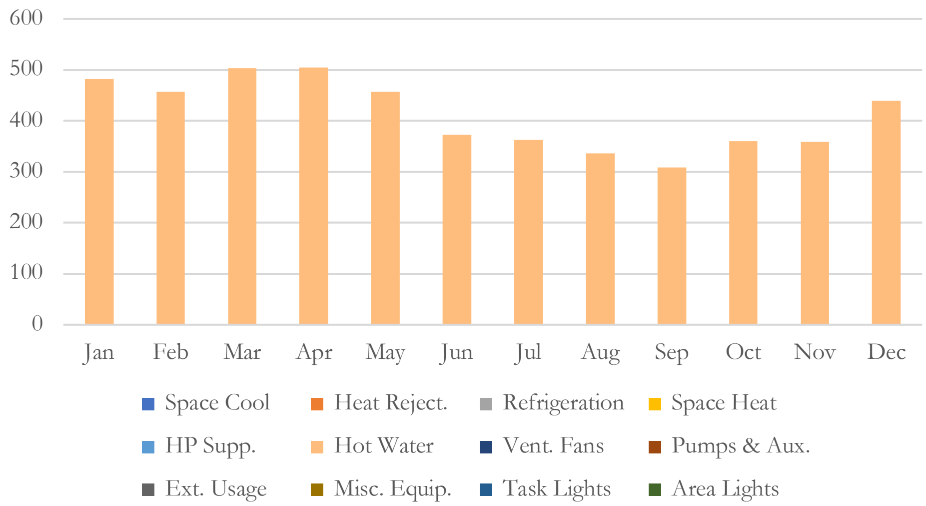


Figure 5. Natural gas consumption (MBTu)

End of life

Table 3. End of life

| Dataset | Name in ecoinvent | Unit | Amount |
|---|---|---|---|
| **Diesel** | Diesel, burned in diesel-electric generating set, 18.5kW {GLO}\| market for \| Cut-off, U | MJ | 1,100 |
| **Transport** | Transport, freight, lorry >32 metric ton, EURO4 {GLO} \| market \| Cut-off, U | tkm | 3,035,364 |
| **Transport** | Transport, freight, lorry >32 metric ton, EURO4 {GLO} \| market \| Cut-off, U | tkm | 910,938 |
| **Emission to air** | | | |
| **Suspended solids, unspecified** | | kg | 30.21 |
| **Particulates, >10mm** | | kg | 9.06 |
| **Particulates, >2.5 mm and < 10mm** | | kg | 0.91 |
| **Carbon monoxide, fossil** | | kg | 5.5 |
| **Nitrogen oxides** | | kg | 8.25 |

### 2.1.2. Consequential Approach

Material production phase

Table 4. Laminated timber production

| Dataset | Unit process | Unit | Amount |
|---|---|---|---|
| **Wood (anhydrous black spruce)** | Sawnwood, board, softwood, raw, dried (u=20%) {CA-QC}\| Conseq, U | $m^3$ | 0.93 |
| **Isocyanates (adhesive)** | Methylene diphenyldiisocyanate {GLO}\| methylene diphenyldiisocyanate production \| Conseq, U | kg | 6.44 |
| **Diesel (agriculture)** | Diesel, burned in building machine {GLO}\| processing \| Conseq, U | MJ | 574.35 |
| **Biomass fuel (ovendry) for heat** | Methanol, from biomass {RoW}\| methanol production, from synthetic gas \| Conseq, U | kg | 20.00 |
| **Oil for fuel** | Petrol, low-sulfur {RoW}\| production \| Conseq, U | kg | 0.05 |
| **Liquefied petroleum gas** | Liquefied petroleum gas {RoW}\| petroleum refinery operation \| Conseq, U | kg | 1.40 |
| **Polyurethane** | Polyurethane, rigid foam {RoW}\| production, Conseq, U | kg | 0.46 |
| **Transport, freight, lorry > 32 metric ton, EURO4** | Transport, freight, lorry > 32 metric ton, EURO4 {RoW}\|Conseq, U | tkm | 400.00 |
| **Electricity for static machine** | Electricity, medium voltage {CA-QC}\| electricity voltage transformation from high to medium voltage \| Conseq, U | kWh | 114.00 |

Table 5. Concrete production

| Dataset | Unit process | Unit | Amount |
|---|---|---|---|
| **Input from Technosphere** | | | |
| **Cement, Portland** | Cement {CA-QC}\| cement production, Portland \| Conseq, U | kg | 343.6 |
| **Tap water** | Tap water {CA-QC}\| tap water production, conventional with biological treatment \| Conseq, U | kg | 206.94 |
| **Sand** | Sand for hybrid building {CA-QC}\| gravel and quarry operation \| Conseq, U (see Table) | kg | 859 |
| **Gravel** | Gravel, crushed for hybrid building {CA-QC}\| production \| Conseq, U (see Table) | kg | 960.05 |
| **Chemical** | Chemical, organic {GLO}\| market for \| Conseq, U | kg | 1.1 |
| **Fatty alcohol** | Fatty alcohol {GLO}\| market for \| Conseq, U | kg | 0.12 |

| | | | |
|---|---|---|---|
| **Transport** | Transport, freight, lorry >32 metric ton, EURO4 {GLO}\| market for \| Conseq, U | kgkm | 41734.90 |
| **Factory** | Concrete mixing factory {GLO}\| market for \| Conseq, U | unit | 0.000000457 |
| **Rubber** | Synthetic rubber {GLO}\| market for \| Conseq, U | kg | 0.00713 |
| **Lubricating oil** | Lubricating oil {GLO}\| market for \| Conseq, U | kg | 0.0119 |
| **Steel** | Steel for hybrid building {CA-QC}\| Steel production \| Conseq, U (see Table 4) | kg | 0.0238 |
| **Electricity** | Electricity, medium voltage {CA-QC}\| market for \| Conseq, U | kWh | 4.114 |
| **Heat** | Heat, district or industrial, natural gas {CA-QC}\| market for \| Conseq, U | MJ | 10.632 |
| **Diesel** | Diesel, burned in building machine {GLO}\| market for \| Conseq, U | MJ | 15.643 |
| **By-product/Waste to Environment** | | | |
| **Water/m$^3$** | | m$^3$ | 0.0061412 |
| **Copper** | | kg | 3.09E-09 |
| **Oils, unspecified** | | kg | 1.55E-08 |
| **Chlorides, unspecified** | | kg | 1.55E-08 |
| **Iron** | | kg | 2.32E-07 |
| **Suspended solids, unspecified** | | kg | 4.64E-07 |
| **By-product/Waste from Technosphere** | | | |
| **Waste concrete {RoW}\| market for waste concrete \| Conseq, U** | | kg | -24.5 |
| **Wastewater from concrete production {RoW}\| market for wastewater from concrete production \| Conseq, U** | | m$^3$ | -0.0348 |

Table 6. Concrete production

| Dataset | Unit process | Unit | Amount |
|---|---|---|---|
| **Input from Technosphere** | | | |
| **burnt shale** | Brunt shale {GLO}\| market for \| Conseq, U | kg | 0.002 |
| **cement factory** | Cement factory {GLO}\| market for \| Conseq, U | unit | 5.36E-11 |
| **clinker with natural gas as a fuel (see Table 3)** | Clinker {CA-QC}\| production \| Conseq, U | kg | 0.83 |
| **electricity, medium voltage** | Electricity, medium voltage {CA-QC}\| market for \| Conseq, U | kWh | 0.0542 |
| **ethylene glycol** | Ethylene glycol {GLO}\| market for \| Conseq, U | kg | 0.00021 |
| **gypsum, mineral** | Gypsum, mineral {GLO}\| market for \| Conseq, U | kg | 0.05 |
| **limestone, crushed, for mill** | Limestone, crushed {RoW}\| market for \| Conseq, U | kg | 0.12 |
| **steel, low-alloyed** | Steel, low-alloyed {CA-QC}\| market for \| Conseq, U | kg | 0.00011 |

Table 7. Clinker production

| Dataset | Unit process | Unit | Amount |
|---|---|---|---|
| **ammonia, liquid** | ammonia, liquid | kg | 0.000908 |
| **bauxite** | bauxite | kg | 0.00012 |
| **cement factory** | cement factory | unit | 6.27E-12 |
| **clay** | clay | kg | 0.196 |
| **diesel, low-sulfur** | diesel, low-sulfur | kg | 0 |
| **electricity, medium voltage** | electricity, medium voltage | kWh | 0.107 |
| **hard coal** | hard coal | kg | 0.0971 |
| **industrial machine, heavy, unspecified** | industrial machine, heavy, unspecified | kg | 3.76E-05 |
| **inert waste, for final disposal** | inert waste, for final disposal | kg | -0.007652 |

| | | | |
|---|---|---|---|
| **iron ore, crude ore, 46% Fe** | iron ore, crude ore, 46% Fe | kg | 0.0109 |
| **lime, hydrated, loose weight** | lime, hydrated, loose weight | kg | 0.00392 |
| **limestone, crushed, for mill** | limestone, crushed, for mill | kg | 1.402 |
| **liquefied petroleum gas** | liquefied petroleum gas | kg | 0 |
| **lubricating oil** | lubricating oil | kg | 4.71E-05 |
| **municipal solid waste** | municipal solid waste | kg | -0.000045 |
| **natural gas, high pressure** | natural gas, high pressure | m3 | 9.16E-02 |
| **petrol, unleaded** | petrol, unleaded | kg | 0 |
| **petroleum coke** | petroleum coke | kg | 0 |
| **refractory, basic, packed** | refractory, basic, packed | kg | 0.00019 |
| **refractory, fireclay, packed** | refractory, fireclay, packed | kg | 8.21E-05 |
| **refractory, high aluminium oxide, packed** | refractory, high aluminium oxide, packed | kg | 0.000137 |
| **sand** | sand | kg | 0.0978 |
| **steel, chromium steel 18/8, hot rolled** | steel, chromium steel 18/8, hot rolled | kg | 5.86E-05 |

Table 8. Steel production

| Dataset | Unit process | Unit | Amount |
|---|---|---|---|
| **Input from Nature** | | | |
| **Oxygen** | | kg | 0.11 |
| **Nitrogen** | | $m^2$ | 0.06 |
| **Iron ore** | | kg | 0.18 |
| **Limestone/lime** | | kg | 0.03 |
| **Coal/Coke** | | kg | 1.61 |
| **Steam** | | MJ | 0.05 |
| **Input from Technosphere** | | | |
| **Oil/Petrol** | Petrol, low-sulfur {CN}\| production \| Conseq, U | kg | 0.03 |
| **Natural gas** | Natural gas, high pressure {CN}\| market for \| Conseq, U | kg | 0.002 |
| **Process water** | Water {CN}\| production \| Conseq, U | kg | 0.02 |
| **Land transport** | Transport, freight, lorry >32 metric ton, EURO4 {GLO}\| market for \| Conseq, U | tkm | 4,5 |
| **Sea transport** | Transport, freight, sea transoceanic ship {GLO}\| market for \| Conseq, U | tkm | 8,5 |
| **Electricity** | | kWh | 0.075 |
| **Output** | | | |
| **Emissions to air** | | | |
| **Aluminium, fume or dust** | | kg | 0.029602 |
| **PM10** | | kg | 0.000019 |
| **SO2** | | kg | 0.000179 |
| **NOx** | | kg | 0.000002 |
| **CO** | | kg | 0.04 |
| **Cr** | | kg | 0.000000007 |
| **Mn** | | kg | 0.0000001 |
| **Ni** | | kg | 0.000000006 |
| **Pb** | | kg | 0.0000001 |
| **Zn** | | kg | 0.0000001 |
| **Hg** | | kg | 0.00000000013 |
| **As** | | kg | 0.00000000025 |
| **Cd** | | kg | 0.00000000014 |
| **H2S** | | kg | 0.000179 |
| **Hydrocarbons** | | kg | 0.000230 |
| **Cyanide compounds** | | kg | 0.000001 |

| | | | |
|---|---|---|---|
| **Ammonia** | | kg | 0.000035 |
| **Fluoranthene** | | kg | 0.000001 |
| **Carbon dioxide** | | kg | 0.65 |
| **Hydrogen** | | kg | 0.00425 |
| **Mn** | | kg | 0.0000001 |
| **Emissions to water** | | | |
| **Water** | | m3 | 0.00357 |
| **Pb** | | kg | 0.0000000042 |
| **Cr** | | kg | 0.0000000045 |
| **Cu** | | kg | 0.0000000058 |
| **Zn** | | kg | 0.0000000290 |
| **Cd** | | kg | 0.0000000002 |
| **Ni** | | kg | 0.0000000060 |
| **Fe** | | kg | 0.0000013 |
| **Cl** | | kg | 0.0002710 |
| **AOX** | | kg | 0.0000380 |
| **Suspended solids** | | kg | 0.0000728 |
| **DOC** | | kg | 0.0000059 |
| **TOC** | | kg | 0.0000072 |
| **COD** | | kg | 0.0000205 |
| **HC** | | kg | 0.0000002 |

Table 9. Inventory of marginal shale brick production in one kg

| Dataset | Unit process | Unit | Amount |
|---|---|---|---|
| **bentonite** | Bentonite {GLO}\| market for \| Conseq, U | kg | 0.00156 |
| **brick production facility** | Brick production facility {RoW}\| brick production facility construction \| Conseq, U | unit | 1.99e-10 |
| **chemical, inorganic** | Chemical, inorganic {GLO}\| market for chemicals, inorganic \| Conseq, U | kg | 7.65e-05 |
| **chemical, organic** | Chemical, organic {GLO}\| market for \| Conseq, U | kg | 0.000569 |
| **diesel, burned in building machine** | Diesel, burned in building machine {GLO}\| market for \| Conseq, U | MJ | 0.031 |
| **electricity, medium voltage** | Electricity, medium voltage {CA-ON}\| market for \| Conseq, U | kWh | 0.086 |
| **frit, for ceramic tile** | Frit, for ceramic tile {GLO}\| market for \| Conseq, U | kg | 0.000257 |
| **heat, district or industrial, natural gas** | Heat, district or industrial, natural gas {RoW}\| market for \| Conseq, U | MJ | 2.18 |
| **kaolin** | Kaolin {GLO}\| market for \| Conseq, U | kg | 1.27e-05 |
| **lime, packed** | Lime, packed {RoW}\| market for lime, packed \| Conseq, U | kg | 0.00275 |
| **lubricating oil** | Lubricating oil {GLO}\| market for \| Conseq, U | kg | 8.44e-05 |
| **manganese** | Manganese {GLO}\| market for \| Conseq, U | kg | 0.00246 |
| **propane, burned in building machine** | Propane, burned in building machine {GLO}\| market for \| Conseq, U | MJ | 0.00242 |
| **sand** | Sand {RoW}\| gravel and quarry operation \| Conseq, U | kg | 0.0116 |
| **shale** | Shale {RoW}\| shale quarry operation \| Conseq, U | kg | 1.05 |
| **sheet rolling, chromium steel** | Sheet rolling, chromium steel {GLO}\| market for \| Conseq, U | kg | 1.57e-07 |
| **solvent, organic** | Solvent, organic {GLO}\| market for \| Conseq, U | kg | 1.15e-05 |
| **steel, low-alloyed** | Solvent, organic {GLO}\| market for \| Conseq, U | kg | 1.57e-07 |
| **tap water** | Tap water {RoW}\| market for \| Conseq, U | kg | 0.00149 |
| **transport, freight, lorry** | Transport, freight, lorry >32 metric ton, EURO4 {GLO}\| market for \| Conseq, U | tkm | 0.6 |
| **Inputs from technosphere, wastes*** | | | |
| **spent solvent mixture** | | kg | -1.15e-05 |
| **waste mineral oil** | | kg | -3.87e-05 |
| **Emissions to air** | | | |

| | | | |
|---|---|---|---|
| **Water** | | m3 | 1.49e-06 |

[1] modified from ecoinvent by changing the production from Ontario

Table 8 Inventory of marginal aluminium production in one kilogram

| Dataset | Unit process | Unit | Amount |
|---|---|---|---|
| **aluminium casting facility** | Aluminium casting facility {GLO}\| market for \| Conseq, U | unit | 1.54E-10 |
| **aluminium, primary, ingot** | Aluminium, primary, ingot {RoW}\| market for \| Conseq, U | kg | 0.583 |
| **copper** | Copper {GLO}\| market for \| Conseq, U | kg | 0.033 |
| **diesel, burned in diesel-electric generating set, 10MW** | Diesel, burned in diesel-electric generating set {GLO}\| market for \| Conseq, U | MJ | 0.0341 |
| **electricity, medium voltage** | Electricity, medium voltage {CA-QC}\| market for \| Conseq, U | kWh | 3.06 |
| **ethylene glycol** | Ethylene glycol {GLO}\| market for \| Conseq, U | kg | 1.94E-07 |
| **heat, district or industrial, natural gas** | Heat, district or industrial, natural gas {CA-QC}\| market for \| Conseq, U | MJ | 1.01 |
| **lithium chloride** | Lithium chloride {GLO}\| market for \| Conseq, U | kg | 0.00167 |
| **lubricating oil** | Lubricating oil {GLO}\| market for \| Conseq, U | kg | 0.00115 |
| **magnesium** | Magnesium {GLO}\| market for \| Conseq, U | kg | 0.002 |
| **potassium chloride, as K2O** | Potassium chloride, as K2O {GLO}\| market for \| Conseq, U | kg | 0.00167 |
| **refractory, basic, packed** | Refractory, basic, packed {GLO}\| market for \| Conseq, U | kg | 3.00E-09 |
| **silver** | Silver {GLO}\| market for \| Conseq, U | kg | 0.003 |
| **sodium hydroxide, without water, in 50% solution state** | Sodium hydroxide, without water, in 50% solution state {GLO}\| market for \| Conseq, U | kg | 1.82E-05 |
| **sodium hypochlorite, without water, in 15% solution state** | Sodium hypochlorite, without water, in 15% solution state {GLO}\| market for \| Conseq, U | kg | 4.94E-05 |
| **tap water** | Tap water {CA-QC}\| market for \| Conseq, U | kg | 1.45 |
| **titanium, primary** | Titanium, primary {GLO}\| market for \| Conseq, U | kg | 0.003 |
| **zirconium oxide** | Zirconium oxide {GLO}\| market for \| Conseq, U | kg | 0.0011 |
| **transport, freight, lorry** | Transport, freight, lorry >32 metric ton, EURO4 {GLO}\| market for \| Conseq, U | tkm | 4.50 |
| **transport, freight, sea** | Transport, freight, sea, transoceanic ship {GLO}\| market for \| Conseq, U | tkm | 8.50 |
| **Inputs from technosphere, credit for by-products*** | | | |
| **iron scrap, unsorted** | Heat, district or industrial, natural gas {CA-QC}\| market for \| Conseq, U | kg | -5.25E-06 |
| **Inputs from technosphere, wastes**** | | | |
| **aluminium scrap, new** | Aluminium scrap, new {RoW}\| market for \| Conseq, U | kg | 0.396 |
| **blast furnace slag** | Blast furnace slag {CA-QC}\| cement production, alternative constituents 6-20% \| Conseq, U | kg | -0.13 |
| **hazardous waste, for underground deposit** | Hazardous waste, for underground deposit {GLO}\| market for \| Conseq, U | kg | -0.00859 |
| **inert waste** | Inert waste {RoW}\| market for inert waste \| Conseq, U | kg | -0.000978 |
| **refractory spent pot liner from Al electrolysis** | Refractory spent pot liner from Al electrolysis {GLO}\| market for \| Conseq, U | kg | -3.00E-09 |
| **sludge, pig iron production** | Sludge, pig iron production {RoW}\| market for sludge, pig iron production \| Conseq, U | kg | -3.53E-06 |
| **spent antifreezer liquid** | Spent antifreezer liquid {GLO}\| market for \| Conseq, U | kg | -1.94E-07 |

| | | | |
|---|---|---|---|
| **waste mineral oil** | Waste mineral oil {RoW}\| market for waste mineral oil \| Conseq, U | kg | -0.00115 |
| **wastewater, average** | Wastewater, average {RoW}\| market for wastewater, average \| Conseq, U | m3 | -0.00137 |
| **Emissions to air** | | | |
| **Water** | | m3 | 7.35E-05 |

Table 9 Inventory of marginal gypsum fibreboard production in one kg[1]

| Dataset | Unit process | Unit | Amount |
|---|---|---|---|
| **Inputs from technosphere** | | | |
| **alkylbenzene sulfonate, linear, petrochemical** | Alkylbenzene sulfonate, linear, petrochemical {GLO}\| market for \| Conseq, U | kg | 9.68E-06 |
| **electricity, medium voltage** | Electricity, medium voltage {CA-QC}\| market for \| Conseq, U | kWh | 0.052861111 |
| **heat, district or industrial, other than natural gas 1.13 MJ** | Heat, district or industrial, other than natural gas {CA-QC}\| market for \| Conseq, U | MJ | 1.1305 |
| **potato starch** | Potato starch {GLO}\| market for \| Conseq, U | kg | 0.0029 |
| **silicone product** | Silicone product {GLO}\| market for \| Conseq, U | kg | 0.000129 |
| **stucco** | Stucco {GLO}\| market for \| Conseq, U | kg | 0.71 |
| **tap water** | Tap water {CH}\| market for \| Conseq, U | kg | 0.318 |
| **wooden board factory, organic bonded boards** | Wooden board factory, organic bonded boards {GLO}\| market for \| Conseq, U | unit | 1.67e-11 |
| **transport, freight, lorry** | Transport, freight, lorry >32 metric ton, EURO4 {GLO}\| market for \| Conseq, U | tkm | 0.0536 |
| **Inputs from technosphere, wastes*** | | | |
| **waste paper, sorted** | | kg | 0.15 |
| **Inputs from environment** | | | |
| **Water, unspecified natural origin** | | m3 | 0.000159 |
| **Emissions to air** | | | |
| **Water** | | m3 | 0.000281 |
| **Emissions to water** | | | |
| **Water** | | m3 | 0.000196 |

[1] modified from ecoinvent by changing the energy efficiency and production from Quebec

Use phase

Table 12. Use phase (consequential)

| Dataset | Unit process[1] | Unit | Amount |
|---|---|---|---|
| **Electricity** | Electricity, low voltage {CA-QC} \| electricity voltage transformation from medium to low voltage \| Conseq, U | kWh | 101,604,600 |

[1] The unit processes used in the use phase are from ecoinvent dataset while the quantity of electricity is from CAN-Quest software (the assumption made is available in the next section)

End of life

Table 13 End of life (consequential)

| Dataset | Unit process[1] | Unit | Amount |
|---|---|---|---|
| **Oriented strand board** | Oriented strand board {CA-QC} \| Conseq, U | $m^3$ | -1481 |
| **Steel** | Steel production {CN} \| Conseq, U | kg | -6,928,117 |
| **Aluminium** | Aluminium production {CN} \| Conseq, U | kg | -45,198 |

| | | | |
|---|---|---|---|
| **Gypsum** | Gypsum fibreboard {CA-QC} \| Conseq, U | kg | -112,373 |
| **Gravel** | Gravel production {CA-QC} \| Conseq, U | kg | -1,261,804 |
| **Diesel** | Diesel, burned in diesel-electric generating set, 18.5kW {GLO}\| market for \| Cut-off, U | MJ | 1,100 |
| **Transport** | Transport, freight, lorry >32 metric ton, EURO4 {GLO} \| market \| Cut-off, U | tkm | 3,035,364 |
| **Transport** | Transport, freight, lorry >32 metric ton, EURO4 {GLO} \| market \| Cut-off, U | tkm | 910,938 |

[1] The unit processes used in the use phase are from ecoinvent dataset while the quantity of electricity is from CAN-Quest software (the assumption made is available in the next section)

Table 14. Material recycling and collection rate

| | Material | Recycling (%) | Collection rate (%) |
|---|---|---|---|
| **1** | Wood | 80 | 50 |
| **2** | Concrete | 70 | 90 |
| **3** | Steel | 70 | 50 |
| **4** | Aluminium | 95 | 51 |
| **5** | Gravel | 90 | 90 |
| **6** | Brick | 50 | 90 |
| **7** | Gypsum | 95 | 50 |

Source: ATHENA and Yeheyis, 2013

## 2.2.LCC Inventory Analysis

### 2.2.1. **Attributional Approach**

Table 15. Attributional life cycle costing

| Activity (process) | Product (1) | Year | Physical amount (2) | | Price (3) | | Monetary amount in $ (4) | Monetary amount discounted to 2019 |
|---|---|---|---|---|---|---|---|---|
| | | | | | | | | |
| **Production phase** | | | | | | | | |
| **Engineering design** | Design of building | 2019 | 1.00 | package | 86,339.92 | $/ pckg | 86,339.92 | 86,339.92 |
| **Site work** | Site work | 2019 | 1.00 | package | 445,513.97 | $/ pckg | 445,513.97 | 445,513.97 |
| **Building construction** | Constructed laminated timber | 2019 | 3,704.25 | $m^3$ | 1,129.85 | $/ $m^3$ | 4,185,260.46 | 4,185,260.46 |
| | Bare material | | | $m^3$ | 734.24 | $/ $m^3$ | 2,719,808.52 | 2,719,808.52 |
| | Bare labour | | | $m^3$ | 128.19 | $/ $m^3$ | 474,837.73 | 474,837.73 |
| | Bare equipment | | | $m^3$ | 28.53 | $/ $m^3$ | 105,698.85 | 105,698.85 |
| | Bare total (indexed) | | | $m^3$ | 926.60 | $/ $m^3$ | 3,432,358.90 | 3,432,358.90 |
| | Total Incl O&P | | | $m^3$ | 1,129.85 | $/ $m^3$ | 4,185,260.46 | 4,185,260.46 |
| | Constructed ready-mix concrete | 2019 | 2,316.33 | $m^3$ | 278.82 | $/ $m^3$ | 645,828.71 | 645,828.71 |
| | Bare material | | | $m^3$ | 233.71 | $/ $m^3$ | 541,337.90 | 541,337.90 |
| | Bare labour | | | $m^3$ | 29.35 | $/ $m^3$ | 67,981.97 | 67,981.97 |
| | Bare equipment | | | $m^3$ | 0.76 | $/ $m^3$ | 1,762.50 | 1,762.50 |
| | Bare total (indexed) | | | $m^3$ | 285.94 | $/ $m^3$ | 662,330.70 | 662,330.70 |
| | Total Incl O&P | | | $m^3$ | 278.82 | $/ $m^3$ | 645,828.71 | 645,828.71 |
| | Constructed brick | 2019 | 2,682.96 | $m^2$ | 205.44 | $/ $m^2$ | 551,195.35 | 551,195.35 |
| | Bare material | | | $m^2$ | 51.09 | $/ $m^2$ | 137,120.83 | 137,120.83 |
| | Bare labour | | | $m^2$ | 97.29 | $/ $m^2$ | 261,210.36 | 261,210.36 |
| | Bare equipment | | | $m^2$ | | $/ $m^2$ | - | - |
| | Bare total (indexed) | | | $m^2$ | 148.38 | $/ $m^2$ | 398,679.03 | 398,679.03 |
| | Total Incl O&P | | | $m^2$ | 205.44 | $/ $m^2$ | 551,195.35 | 552,222.57 |
| | Constructed aluminium | 2019 | 901.80 | $m^2$ | 1,168.53 | $/ $m^2$ | 1,053,775.85 | 1,053,775.85 |
| | Bare material | | | $m^2$ | 907.65 | $/ $m^2$ | 819,421.91 | 819,421.91 |
| | Bare labour | | | $m^2$ | 109.79 | $/ $m^2$ | 99,225.49 | 99,225.49 |
| | Bare equipment | | | $m^2$ | - | $/ $m^2$ | - | - |
| | Bare total (indexed) | | | $m^2$ | 1,017.43 | $/ $m^2$ | 921,589.91 | 921,589.91 |
| | Total Incl O&P | | | $m^2$ | 1,168.53 | $/ $m^2$ | 1,053,775.85 | 1,059,618.47 |
| | Constructed steel | 2019 | 1,979,460.00 | kg | 2.48 | $/ kg | 4,910,117.83 | 4,910,117.83 |
| | Bare material | | | kg | 1.32 | $/ kg | 2,618,587.39 | 2,618,587.39 |
| | Bare labour | | | kg | 0.47 | $/ kg | 935,978.71 | 935,978.71 |
| | Bare equipment | | | kg | 0.26 | $/ kg | 512,098.95 | 512,098.95 |
| | Bare total (indexed) | | | kg | 2.06 | $/ kg | 4,070,973.58 | 4,070,973.58 |
| | Total Incl O&P | | | kg | 2.48 | $/ kg | 4,910,130.23 | 4,910,130.23 |
| | Constructed gypsum | 2019 | 236,575.88 | kg | 0.53 | $/ kg | 124,721.62 | 124,721.62 |
| | Bare material | | | kg | 0.11 | $/ kg | 26,744.54 | 26,744.54 |
| | Bare labour | | | kg | 0.26 | $/ kg | 62,232.76 | 62,232.76 |
| | Bare equipment | | | kg | - | $/ kg | - | - |
| | Bare total (indexed) | | | kg | 0.38 | $/ kg | 89,235.33 | 89,235.33 |
| | Total Incl O&P | | | kg | 0.53 | $/ kg | 124,724.26 | 124,724.26 |
| **Finishing work** | Finishing work | 2019 | 1.00 | package | 1,683,628.39 | $/ pckg | 1,683,628.39 | 1,683,628.39 |
| **Plumbing work** | Plumbing work | 2019 | 1.00 | package | 1,174,222.88 | $/ pckg | 1,174,222.88 | 1,174,222.88 |
| **Mechanical and electrical work** | Mechanical and electrical work | 2019 | 1.00 | package | 3,798,956.37 | $/ pckg | 3,798,956.37 | 3,798,956.37 |
| **Use phase** | | | | | | | | |
| **Use phase** | Electricity consumption 2019 | 2019 | 1,693,410.00 | kWh | 0.09 | $/ kWh | 152,406.90 | 152,406.90 |
| | Electricity consumption 2020 | 2020 | 1,693,410.00 | kWh | 0.09 | $/ kWh | 154,540.60 | 150,039.41 |
| | Electricity consumption 2021 | 2021 | 1,693,410.00 | kWh | 0.09 | $/ kWh | 156,704.16 | 147,708.70 |
| | Electricity consumption 2022 | 2022 | 1,693,410.00 | kWh | 0.09 | $/ kWh | 158,898.02 | 145,414.20 |
| | Electricity consumption 2023 | 2023 | 1,693,410.00 | kWh | 0.10 | $/ kWh | 161,122.60 | 143,155.34 |
| | Electricity consumption 2024 | 2024 | 1,693,410.00 | kWh | 0.10 | $/ kWh | 163,378.31 | 140,931.57 |
| | Electricity consumption 2025 | 2025 | 1,693,410.00 | kWh | 0.10 | $/ kWh | 165,665.61 | 138,742.34 |
| | Electricity consumption 2026 | 2026 | 1,693,410.00 | kWh | 0.10 | $/ kWh | 167,984.93 | 136,587.12 |
| | Electricity consumption 2027 | 2027 | 1,693,410.00 | kWh | 0.10 | $/ kWh | 170,336.72 | 134,465.38 |
| | Electricity consumption 2028 | 2028 | 1,693,410.00 | kWh | 0.10 | $/ kWh | 172,721.43 | 132,376.59 |
| | Electricity consumption 2029 | 2029 | 1,693,410.00 | kWh | 0.10 | $/ kWh | 175,139.53 | 130,320.26 |
| | Electricity consumption 2030 | 2030 | 1,693,410.00 | kWh | 0.10 | $/ kWh | 177,591.48 | 128,295.87 |
| | Electricity consumption 2031 | 2031 | 1,693,410.00 | kWh | 0.11 | $/ kWh | 180,077.76 | 126,302.92 |
| | Electricity consumption 2032 | 2032 | 1,693,410.00 | kWh | 0.11 | $/ kWh | 182,598.85 | 124,340.93 |
| | Electricity consumption 2033 | 2033 | 1,693,410.00 | kWh | 0.11 | $/ kWh | 185,155.24 | 122,409.42 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Electricity consumption 2034 | 2034 | 1,693,410.00 | kWh | 0.11 | $/ kWh | 187,747.41 | 120,507.92 |
| | Electricity consumption 2035 | 2035 | 1,693,410.00 | kWh | 0.11 | $/ kWh | 190,375.87 | 118,635.95 |
| | Electricity consumption 2036 | 2036 | 1,693,410.00 | kWh | 0.11 | $/ kWh | 193,041.14 | 116,793.06 |
| | Electricity consumption 2037 | 2037 | 1,693,410.00 | kWh | 0.12 | $/ kWh | 195,743.71 | 114,978.80 |
| | Electricity consumption 2038 | 2038 | 1,693,410.00 | kWh | 0.12 | $/ kWh | 198,484.12 | 113,192.72 |
| | Electricity consumption 2039 | 2039 | 1,693,410.00 | kWh | 0.12 | $/ kWh | 201,262.90 | 111,434.39 |
| | Electricity consumption 2040 | 2040 | 1,693,410.00 | kWh | 0.12 | $/ kWh | 204,080.58 | 109,703.37 |
| | Electricity consumption 2041 | 2041 | 1,693,410.00 | kWh | 0.12 | $/ kWh | 206,937.71 | 107,999.24 |
| | Electricity consumption 2042 | 2042 | 1,693,410.00 | kWh | 0.12 | $/ kWh | 209,834.84 | 106,321.58 |
| | Electricity consumption 2043 | 2043 | 1,693,410.00 | kWh | 0.13 | $/ kWh | 212,772.53 | 104,669.98 |
| | Electricity consumption 2044 | 2044 | 1,693,410.00 | kWh | 0.13 | $/ kWh | 215,751.34 | 103,044.04 |
| | Electricity consumption 2045 | 2045 | 1,693,410.00 | kWh | 0.13 | $/ kWh | 218,771.86 | 101,443.36 |
| | Electricity consumption 2046 | 2046 | 1,693,410.00 | kWh | 0.13 | $/ kWh | 221,834.67 | 99,867.54 |
| | Electricity consumption 2047 | 2047 | 1,693,410.00 | kWh | 0.13 | $/ kWh | 224,940.35 | 98,316.20 |
| | Electricity consumption 2048 | 2048 | 1,693,410.00 | kWh | 0.13 | $/ kWh | 228,089.52 | 96,788.96 |
| | Electricity consumption 2049 | 2049 | 1,693,410.00 | kWh | 0.14 | $/ kWh | 231,282.77 | 95,285.44 |
| | Electricity consumption 2050 | 2050 | 1,693,410.00 | kWh | 0.14 | $/ kWh | 234,520.73 | 93,805.28 |
| | Electricity consumption 2051 | 2051 | 1,693,410.00 | kWh | 0.14 | $/ kWh | 237,804.02 | 92,348.11 |
| | Electricity consumption 2052 | 2052 | 1,693,410.00 | kWh | 0.14 | $/ kWh | 241,133.27 | 90,913.57 |
| | Electricity consumption 2053 | 2053 | 1,693,410.00 | kWh | 0.14 | $/ kWh | 244,509.14 | 89,501.32 |
| | Electricity consumption 2054 | 2054 | 1,693,410.00 | kWh | 0.15 | $/ kWh | 247,932.27 | 88,111.01 |
| | Electricity consumption 2055 | 2055 | 1,693,410.00 | kWh | 0.15 | $/ kWh | 251,403.32 | 86,742.30 |
| | Electricity consumption 2056 | 2056 | 1,693,410.00 | kWh | 0.15 | $/ kWh | 254,922.97 | 85,394.84 |
| | Electricity consumption 2057 | 2057 | 1,693,410.00 | kWh | 0.15 | $/ kWh | 258,491.89 | 84,068.32 |
| | Electricity consumption 2058 | 2058 | 1,693,410.00 | kWh | 0.15 | $/ kWh | 262,110.77 | 82,762.41 |
| | Electricity consumption 2059 | 2059 | 1,693,410.00 | kWh | 0.16 | $/ kWh | 265,780.33 | 81,476.78 |
| | Electricity consumption 2060 | 2060 | 1,693,410.00 | kWh | 0.16 | $/ kWh | 269,501.25 | 80,211.12 |
| | Electricity consumption 2061 | 2061 | 1,693,410.00 | kWh | 0.16 | $/ kWh | 273,274.27 | 78,965.12 |
| | Electricity consumption 2062 | 2062 | 1,693,410.00 | kWh | 0.16 | $/ kWh | 277,100.11 | 77,738.48 |
| | Electricity consumption 2063 | 2063 | 1,693,410.00 | kWh | 0.17 | $/ kWh | 280,979.51 | 76,530.89 |
| | Electricity consumption 2064 | 2064 | 1,693,410.00 | kWh | 0.17 | $/ kWh | 284,913.22 | 75,342.06 |
| | Electricity consumption 2065 | 2065 | 1,693,410.00 | kWh | 0.17 | $/ kWh | 288,902.01 | 74,171.70 |
| | Electricity consumption 2066 | 2066 | 1,693,410.00 | kWh | 0.17 | $/ kWh | 292,946.64 | 73,019.52 |
| | Electricity consumption 2067 | 2067 | 1,693,410.00 | kWh | 0.18 | $/ kWh | 297,047.89 | 71,885.23 |
| | Electricity consumption 2068 | 2068 | 1,693,410.00 | kWh | 0.18 | $/ kWh | 301,206.56 | 70,768.57 |
| | Electricity consumption 2069 | 2069 | 1,693,410.00 | kWh | 0.18 | $/ kWh | 305,423.45 | 69,669.25 |
| | Electricity consumption 2070 | 2070 | 1,693,410.00 | kWh | 0.18 | $/ kWh | 309,699.38 | 68,587.01 |
| | Electricity consumption 2071 | 2071 | 1,693,410.00 | kWh | 0.19 | $/ kWh | 314,035.17 | 67,521.58 |
| | Electricity consumption 2072 | 2072 | 1,693,410.00 | kWh | 0.19 | $/ kWh | 318,431.66 | 66,472.70 |
| | Electricity consumption 2073 | 2073 | 1,693,410.00 | kWh | 0.19 | $/ kWh | 322,889.71 | 65,440.12 |
| | Electricity consumption 2074 | 2074 | 1,693,410.00 | kWh | 0.19 | $/ kWh | 327,410.16 | 64,423.57 |
| | Electricity consumption 2075 | 2075 | 1,693,410.00 | kWh | 0.20 | $/ kWh | 331,993.90 | 63,422.82 |
| | Electricity consumption 2076 | 2076 | 1,693,410.00 | kWh | 0.20 | $/ kWh | 336,641.82 | 62,437.61 |
| | Electricity consumption 2077 | 2077 | 1,693,410.00 | kWh | 0.20 | $/ kWh | 341,354.80 | 61,467.70 |
| | Electricity consumption 2078 | 2078 | 1,693,410.00 | kWh | 0.20 | $/ kWh | 346,133.77 | 60,512.87 |
| **End of life phase** | | | | | | | | |
| **Demolition or deconstruction** | End of life laminated timber | 2079 | 3,704.25 | $m^3$ | 1,504.12 | $/ $m^3$ | 5,571,629.83 | 974,060.65 |
| | End of life ready-mix concrete | 2079 | 2,316.33 | $m^3$ | 739.93 | $/ $m^3$ | 1,713,920.00 | 299,636.21 |
| | End of life brick | 2079 | 2,682.96 | $m^2$ | 205.21 | $/ $m^2$ | 550,573.15 | 96,254.00 |
| | End of life aluminium | 2079 | 12.27 | $m^3$ | 866.08 | $/ $m^3$ | 10,631.05 | 1,858.57 |
| | End of life steel | 2079 | 1,979,460.00 | kg | 0.111 | $/ kg | 219,791.36 | 38,425.04 |
| | End of life gypsum | 2079 | 236,575.88 | kg | 0.30 | $/ kg | 71,549.40 | 12,508.63 |

## 2.2.2. Consequential Approach

Table 16. Consequential life cycle costing

| Activity (process) | Product (1) | Year | Physical amount (2) | | Price (3) | | Monetary amount in $ (4) | Monetary amount discounted to 2019 |
|---|---|---|---|---|---|---|---|---|
| | | | | | | | | |
| **Production phase** | | | | | | | | |
| **Engineering design** | Design of building | 2030 | 1.00 | pckg | 93,419.56 | $/ pckg | 93,419.56 | 67,488.27 |
| **Site work** | Site work | 2030 | 1.00 | pckg | 482,044.91 | $/ pckg | 482,044.91 | 348,239.50 |
| **Building construction** | Constructed laminated timber from Quebec | 2030 | 3,704.25 | $m^3$ | 1,968.02 | $/ $m^3$ | 7,290,040.46 | 5,266,480.34 |
| | Bare material | | 3,704.25 | $m^3$ | 1,278.93 | $/ $m^3$ | 4,737,462.42 | 3,422,443.65 |
| | Bare labour | | 3,704.25 | $m^3$ | 304.57 | $/ $m^3$ | 1,128,196.97 | 815,033.50 |
| | Bare equipment | | 3,704.25 | $m^3$ | 49.70 | $/ $m^3$ | 184,110.14 | 133,005.08 |
| | Bare total | | 3,704.25 | $m^3$ | 1,698.52 | $/ $m^3$ | 6,291,760.32 | 4,545,301.52 |
| | Total Incl O&P | | 3,704.25 | $m^3$ | 1,968.02 | $/ $m^3$ | 7,290,040.46 | 5,266,480.34 |
| | Constructed ready-mix concrete from Quebec | 2030 | 2,316.33 | $m^3$ | 344.81 | $/ $m^3$ | 798,687.48 | 576,988.83 |
| | Bare material | | 2,316.33 | $m^3$ | 289.02 | $/ $m^3$ | 669,465.14 | 483,635.86 |
| | Bare labour | | 2,316.33 | $m^3$ | 67.05 | $/ $m^3$ | 155,310.25 | 112,199.43 |
| | Bare equipment | | 2,316.33 | $m^3$ | 0.94 | $/ $m^3$ | 2,179.65 | 1,574.63 |
| | Bare total | | 2,316.33 | $m^3$ | 388.07 | $/ $m^3$ | 898,900.13 | 649,384.58 |
| | Total Incl O&P | | 2,316.33 | $m^3$ | 344.81 | $/ $m^3$ | 798,687.48 | 576,988.83 |
| | Constructed brick from Ontario | 2030 | 2,682.96 | $m^2$ | 342.64 | $/ $m^2$ | 919,281.77 | 664,108.71 |
| | Bare material | | 2,682.96 | $m^2$ | 85.21 | $/ $m^2$ | 228,604.46 | 165,148.73 |
| | Bare labour | | 2,682.96 | $m^2$ | 229.62 | $/ $m^2$ | 616,060.49 | 445,055.21 |
| | Bare equipment | | 2,682.96 | $m^2$ | | $/ $m^2$ | - | - |
| | Bare total | | 2,682.96 | $m^2$ | 247.46 | $/ $m^2$ | 663,925.72 | 479,634.07 |
| | Total Incl O&P | | 2,682.96 | $m^2$ | 342.64 | $/ $m^2$ | 919,281.77 | 664,108.71 |
| | Constructed aluminium (from Chinese supplier) | 2030 | 901.80 | $m^2$ | 574.65 | $/ $m^2$ | 518,220.78 | 374,373.72 |
| | Bare material | | 901.80 | $m^2$ | 207.33 | $/ $m^2$ | 186,974.14 | 135,074.10 |
| | Bare labour | | 901.80 | $m^2$ | 250.82 | $/ $m^2$ | 226,186.94 | 163,402.26 |
| | Bare equipment | | 901.80 | $m^2$ | | $/ $m^2$ | - | - |
| | Bare total | | 901.80 | $m^2$ | 458.15 | $/ $m^2$ | 413,161.08 | 298,476.36 |
| | Total Incl O&P | | 901.80 | $m^2$ | 574.65 | $/ $m^2$ | 518,220.78 | 374,373.72 |
| | Constructed steel (from Chinese supplier) | 2030 | 1,979,460.00 | kg | 1.90 | $/ kg | 3,756,170.30 | 2,713,537.34 |
| | Bare material | | 1,979,460.00 | kg | 0.17 | $/ kg | 333,766.65 | 241,120.13 |
| | Bare labour | | 1,979,460.00 | kg | 1.08 | $/ kg | 2,138,316.07 | 1,544,765.03 |
| | Bare equipment | | 1,979,460.00 | kg | 0.26 | $/ kg | 512,098.18 | 369,950.62 |
| | Bare total | | 1,979,460.00 | kg | 1.51 | $/ kg | 2,984,180.90 | 2,155,835.78 |
| | Total Incl O&P | | 1,979,460.00 | kg | 1.90 | $/ kg | 3,756,170.30 | 2,713,537.34 |
| | Constructed gypsum from Ontario | 2030 | 236,575.88 | kg | 1.08 | $/ kg | 255,284.40 | 184,422.88 |
| | Bare material | | 236,575.88 | kg | 0.23 | $/ kg | 54,941.64 | 39,691.01 |
| | Bare labour | | 236,575.88 | kg | 0.62 | $/ kg | 147,381.42 | 106,471.47 |
| | Bare equipment | | 236,575.88 | kg | - | $/ kg | - | - |
| | Bare total | | 236,575.88 | kg | 0.77 | $/ kg | 182,583.84 | 131,902.45 |
| | Total Incl O&P | | 236,575.88 | kg | 1.08 | $/ kg | 255,284.40 | 184,422.88 |
| **Finishing work** | Finishing work | 2030 | 1.00 | pckg | 1,821,681.34 | $/ pckg | 1,821,681.34 | 1,316,021.36 |
| **Plumbing work** | Plumbing work | 2030 | 1.00 | pckg | 1,270,505.96 | $/ pckg | 1,270,505.96 | 917,840.54 |
| **Mechanical and electrical work** | Mechanical and electrical work | 2030 | 1.00 | pckg | 4,203,880.02 | $/ pckg | 4,203,880.02 | 3,036,972.37 |
| **Use phase** | | | | | | | | |
| **Use phase** | Electricity consumption 2019 | 2030 | 1,693,410.00 | kWh | 0.10 | $/ kWh | 177,591.48 | 128,295.87 |
| | Electricity consumption 2020 | 2031 | 1,693,410.00 | kWh | 0.11 | $/ kWh | 180,077.76 | 126,302.92 |
| | Electricity consumption 2021 | 2032 | 1,693,410.00 | kWh | 0.11 | $/ kWh | 182,598.85 | 124,340.93 |
| | Electricity consumption 2022 | 2033 | 1,693,410.00 | kWh | 0.11 | $/ kWh | 185,155.24 | 122,409.42 |
| | Electricity consumption 2023 | 2034 | 1,693,410.00 | kWh | 0.11 | $/ kWh | 187,747.41 | 120,507.92 |
| | Electricity consumption 2024 | 2035 | 1,693,410.00 | kWh | 0.11 | $/ kWh | 190,375.87 | 118,635.95 |
| | Electricity consumption 2025 | 2036 | 1,693,410.00 | kWh | 0.11 | $/ kWh | 193,041.14 | 116,793.06 |
| | Electricity consumption 2026 | 2037 | 1,693,410.00 | kWh | 0.12 | $/ kWh | 195,743.71 | 114,978.80 |
| | Electricity consumption 2027 | 2038 | 1,693,410.00 | kWh | 0.12 | $/ kWh | 198,484.12 | 113,192.72 |
| | Electricity consumption 2028 | 2039 | 1,693,410.00 | kWh | 0.12 | $/ kWh | 201,262.90 | 111,434.39 |
| | Electricity consumption 2029 | 2040 | 1,693,410.00 | kWh | 0.12 | $/ kWh | 204,080.58 | 109,703.37 |
| | Electricity consumption 2030 | 2041 | 1,693,410.00 | kWh | 0.12 | $/ kWh | 206,937.71 | 107,999.24 |
| | Electricity consumption 2031 | 2042 | 1,693,410.00 | kWh | 0.12 | $/ kWh | 209,834.84 | 106,321.58 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Electricity consumption 2032 | 2043 | 1,693,410.00 | kWh | 0.13 | $/ kWh | 212,772.53 | 104,669.98 |
| | Electricity consumption 2033 | 2044 | 1,693,410.00 | kWh | 0.13 | $/ kWh | 215,751.34 | 103,044.04 |
| | Electricity consumption 2034 | 2045 | 1,693,410.00 | kWh | 0.13 | $/ kWh | 218,771.86 | 101,443.36 |
| | Electricity consumption 2035 | 2046 | 1,693,410.00 | kWh | 0.13 | $/ kWh | 221,834.67 | 99,867.54 |
| | Electricity consumption 2036 | 2047 | 1,693,410.00 | kWh | 0.13 | $/ kWh | 224,940.35 | 98,316.20 |
| | Electricity consumption 2037 | 2048 | 1,693,410.00 | kWh | 0.13 | $/ kWh | 228,089.52 | 96,788.96 |
| | Electricity consumption 2038 | 2049 | 1,693,410.00 | kWh | 0.14 | $/ kWh | 231,282.77 | 95,285.44 |
| | Electricity consumption 2039 | 2050 | 1,693,410.00 | kWh | 0.14 | $/ kWh | 234,520.73 | 93,805.28 |
| | Electricity consumption 2040 | 2051 | 1,693,410.00 | kWh | 0.14 | $/ kWh | 237,804.02 | 92,348.11 |
| | Electricity consumption 2041 | 2052 | 1,693,410.00 | kWh | 0.14 | $/ kWh | 241,133.27 | 90,913.57 |
| | Electricity consumption 2042 | 2053 | 1,693,410.00 | kWh | 0.14 | $/ kWh | 244,509.14 | 89,501.32 |
| | Electricity consumption 2043 | 2054 | 1,693,410.00 | kWh | 0.15 | $/ kWh | 247,932.27 | 88,111.01 |
| | Electricity consumption 2044 | 2055 | 1,693,410.00 | kWh | 0.15 | $/ kWh | 251,403.32 | 86,742.30 |
| | Electricity consumption 2045 | 2056 | 1,693,410.00 | kWh | 0.15 | $/ kWh | 254,922.97 | 85,394.84 |
| | Electricity consumption 2046 | 2057 | 1,693,410.00 | kWh | 0.15 | $/ kWh | 258,491.89 | 84,068.32 |
| | Electricity consumption 2047 | 2058 | 1,693,410.00 | kWh | 0.15 | $/ kWh | 262,110.77 | 82,762.41 |
| | Electricity consumption 2048 | 2059 | 1,693,410.00 | kWh | 0.16 | $/ kWh | 265,780.33 | 81,476.78 |
| | Electricity consumption 2049 | 2060 | 1,693,410.00 | kWh | 0.16 | $/ kWh | 269,501.25 | 80,211.12 |
| | Electricity consumption 2050 | 2061 | 1,693,410.00 | kWh | 0.16 | $/ kWh | 273,274.27 | 78,965.12 |
| | Electricity consumption 2051 | 2062 | 1,693,410.00 | kWh | 0.16 | $/ kWh | 277,100.11 | 77,738.48 |
| | Electricity consumption 2052 | 2063 | 1,693,410.00 | kWh | 0.17 | $/ kWh | 280,979.51 | 76,530.89 |
| | Electricity consumption 2053 | 2064 | 1,693,410.00 | kWh | 0.17 | $/ kWh | 284,913.22 | 75,342.06 |
| | Electricity consumption 2054 | 2065 | 1,693,410.00 | kWh | 0.17 | $/ kWh | 288,902.01 | 74,171.70 |
| | Electricity consumption 2055 | 2066 | 1,693,410.00 | kWh | 0.17 | $/ kWh | 292,946.64 | 73,019.52 |
| | Electricity consumption 2056 | 2067 | 1,693,410.00 | kWh | 0.18 | $/ kWh | 297,047.89 | 71,885.23 |
| | Electricity consumption 2057 | 2068 | 1,693,410.00 | kWh | 0.18 | $/ kWh | 301,206.56 | 70,768.57 |
| | Electricity consumption 2058 | 2069 | 1,693,410.00 | kWh | 0.18 | $/ kWh | 305,423.45 | 69,669.25 |
| | Electricity consumption 2059 | 2070 | 1,693,410.00 | kWh | 0.18 | $/ kWh | 309,699.38 | 68,587.01 |
| | Electricity consumption 2060 | 2071 | 1,693,410.00 | kWh | 0.19 | $/ kWh | 314,035.17 | 67,521.58 |
| | Electricity consumption 2061 | 2072 | 1,693,410.00 | kWh | 0.19 | $/ kWh | 318,431.66 | 66,472.70 |
| | Electricity consumption 2062 | 2073 | 1,693,410.00 | kWh | 0.19 | $/ kWh | 322,889.71 | 65,440.12 |
| | Electricity consumption 2063 | 2074 | 1,693,410.00 | kWh | 0.19 | $/ kWh | 327,410.16 | 64,423.57 |
| | Electricity consumption 2064 | 2075 | 1,693,410.00 | kWh | 0.20 | $/ kWh | 331,993.90 | 63,422.82 |
| | Electricity consumption 2065 | 2076 | 1,693,410.00 | kWh | 0.20 | $/ kWh | 336,641.82 | 62,437.61 |
| | Electricity consumption 2066 | 2077 | 1,693,410.00 | kWh | 0.20 | $/ kWh | 341,354.80 | 61,467.70 |
| | Electricity consumption 2067 | 2078 | 1,693,410.00 | kWh | 0.20 | $/ kWh | 346,133.77 | 60,512.87 |
| | Electricity consumption 2068 | 2079 | 1,693,410.00 | kWh | 0.21 | $/ kWh | 350,979.64 | 59,572.86 |
| | Electricity consumption 2069 | 2080 | 1,693,410.00 | kWh | 0.21 | $/ kWh | 355,893.36 | 58,647.46 |
| | Electricity consumption 2070 | 2081 | 1,693,410.00 | kWh | 0.21 | $/ kWh | 360,875.87 | 57,736.43 |
| | Electricity consumption 2071 | 2082 | 1,693,410.00 | kWh | 0.22 | $/ kWh | 365,928.13 | 56,839.55 |
| | Electricity consumption 2072 | 2083 | 1,693,410.00 | kWh | 0.22 | $/ kWh | 371,051.12 | 55,956.61 |
| | Electricity consumption 2073 | 2084 | 1,693,410.00 | kWh | 0.22 | $/ kWh | 376,245.84 | 55,087.38 |
| | Electricity consumption 2074 | 2085 | 1,693,410.00 | kWh | 0.23 | $/ kWh | 381,513.28 | 54,231.65 |
| | Electricity consumption 2075 | 2086 | 1,693,410.00 | kWh | 0.23 | $/ kWh | 386,854.47 | 53,389.22 |
| | Electricity consumption 2076 | 2087 | 1,693,410.00 | kWh | 0.23 | $/ kWh | 392,270.43 | 52,559.87 |
| | Electricity consumption 2077 | 2088 | 1,693,410.00 | kWh | 0.23 | $/ kWh | 397,762.21 | 51,743.41 |
| | Electricity consumption 2078 | 2089 | 1,693,410.00 | kWh | 0.24 | $/ kWh | 403,330.88 | 50,939.63 |
| **End of life phase** | | | | | | | | |
| **Demolition or deconstruction** | End of life laminated timber | 2079 | 3,704.25 | $m^3$ | 3,053.88 | $/ $m^3$ | 11,312,320.8 | 1,428,716.25 |
| | End of life ready-mix concrete | 2079 | 2,316.33 | $m^3$ | 1,502.31 | $/ $m^3$ | 3,479,845.84 | 439,495.34 |
| | End of life brick | 2079 | 2,682.96 | $m^2$ | 416.65 | $/ $m^2$ | 1,117,852.45 | 141,181.81 |
| | End of life aluminium | 2079 | 12.27 | $m^3$ | 1,758.44 | $/ $m^3$ | 21,584.69 | 2,726.09 |
| | End of life steel | 2079 | 1,979,460.00 | kg | 0.23 | $/ kg | 446,251.90 | 56,360.44 |
| | End of life gypsum | 2079 | 236,575.88 | kg | 0.58 | $/ kg | 136,211.75 | 17,203.18 |
| **Avoided cost** | Wood | 2079 | -1,481.70 | $m^3$ | 1,968.84 | $/ $m^3$ | -2,917,230.9 | -3,684,385.64 |
| | Gravel from concrete | 2079 | -3,502,290.96 | kg | 0.24 | $/ kg | -824,155.71 | -104,088.69 |
| | Steel | 2079 | -692,811.00 | kg | 26.35 | $/ kg | -18,253,642 | -2,305,386.79 |
| | Aluminium | 2079 | -436.92 | $m^2$ | 32,859.08 | $/ $m^2$ | -14,356,859 | -1,813,233.49 |
| | Gravel from brick | 2079 | -4,342.83 | kg | 0.24 | $/ kg | -1,021.95 | -129.07 |
| | Gypsum | 2079 | -112,373.54 | kg | 7.94 | $/ kg | -892,341.68 | -112,700.40 |

Example of calculation

**Attributional approach**

Material Production Cost

To calculate the cost in the material production phase, two equations are used: the first equation accounts for the production cost of each material, and the second one calculates the sum of these costs for all materials.

The cost calculations are divided into four categories: material, labor, equipment and overhead profit (O&P).

*Construction cost of each material=(bare material i + bare labor i + bare equipment i + O&P cost i) *city index*

*Total production cost = engineering design cost + site work cost +* $\sum$ *construction cost of each material + finishing cost + plumbing cost + mechanical and electrical cost*

Use-Phase Cost

To quantify the use phase cost, one main accounting equation of the present value (PV) is used with three examples on how to calculate the electricity cost.

*Total use cost = present value (PV) of* $\sum$ *use cost* $_{year\ n}$

$= PV\ of\ use\ cost_{year\ n} + PV\ of\ use\ cost_{year\ n+1\ discounted\ to\ year\ n}$

$+ PV\ of\ use\ cost_{year\ n+2\ discounted\ to\ year\ n} + \ldots. +$

$PV\ of\ use\ cost_{year\ t\ discounted\ to\ year\ n}$

In year n (when i=0),

$Electricity\ cost\ per\ kWh_{year\ n} = electricity\ cost\ per\ kWh_{year\ n} * (1+inflation\ rate)^{t}$

$Use\ cost_{year\ n} = electricity\ cost\ per\ kWh_{n} * annual\ electricity\ consumption$

$PV\ Use\ cost_{year\ n} = use\ cost_{year\ t}/(1+r)^{t}$

In year n+1 (when t=1),

$Electricity\ cost\ per\ kWh_{year\ n+1} = electricity\ cost\ per\ kWh_{year\ n} * (1+inflation\ rate)^{t}$

$Use\ cost_{year\ n+1} = electricity\ cost\ per\ kWh_{n+1} * annual\ electricity\ consumption$

$PV\ Use\ cost_{year\ n} = use\ cost_{year\ t}/(1+r)^{t}$

In year n+2 (when t=2)

$Electricity\ cost\ per\ kWh_{year\ n+2} = electricity\ cost\ per\ kWh_{year\ n} * (1+inflation\ rate)^{t}$

$Use\ cost_{year\ n+2} = electricity\ cost\ per\ kWh_{n+2} * annual\ electricity\ consumption$

$PV\ Use\ cost_{year\ n} = use\ cost_{year\ t}/(1+r)^{t}$

In the economic assessment, the future price is estimated based on the price increase rate according to Statistic Canada and Hydro-Quebec.

End of life Cost

The total end of life cost of building materials is calculated by the sum of end oflife cost of each material.

To calculate the end of life cost of building materials, similar to the previous section, the PV accounting model is used.

*End of life cost of each material=PV (bare material i + bare labor i + bare equipment i + O&P cost i)*

*Total end of life cost = PV* $\sum$ *end of life cost of each material*

***Example in material production***

*Construction cost of each material=(bare material i + bare labor i + bare equipment i + O&P cost i)*city index*

*Total production cost = engineering design cost + site work cost +* $\sum$ *construction cost of each material + finishing cost + plumbing cost + mechanical and electrical cost*

*Construction cost of laminated timber= ((734.24 $/ m3*3,704.25 m3) + (128.19 $/ m3*3,704.25 m3) + (28.53 $/ m3*3,704.25 m3) +(0.0527*$/ m3*3,704.25 m3))*1.04 = 1,129.85$*

*Total production cost = 86,339.92+ 445,513.97 + (4,185,260.46 + 645,828.71 + 551,195.35 + 1,053,775.85 + 4,910,117.83 + 124,721.62) + 1,683,628.39 + 1,174,222.88 + 3,798,956.37*

***Example in use phase***

In year 1,

Electricity cost per $kWh_{year\ n}$ = electricity cost per $kWh_{year\ n}$ * $(1+inflation\ rate)^t$

Use $cost_{year\ n}$ = electricity cost per $kWh_n$ * annual electricity consumption

PV Use $cost_{year\ n}$ = use $cost_{year\ t}/(1+r)^t$

Electricity cost per $kWh_{year\ 2019}$ = electricity cost per $kWh_{year\ 2019}$ * $(1+inflation\ rate)^t$

=0.09*($(1+0.014)^0$)

=0.09$/kWh

Use $cost_{year\ 2019}$ = electricity cost per $kWh_{2019}$ * annual electricity consumption

=0.09 $/kWh*1,693,410.00 kWh

=152,406.90$

PV Use $cost_{year\ 2019}$ = use $cost_{year\ 2019}/(1+r)^t$

=152,406.90$/$(1+0.03)^0$

=152,406.90$

In year 2,

Electricity cost per $kWh_{year\ 2020}$ = electricity cost per $kWh_{year\ n}$ * $(1+inflation\ rate)^t$

=0.09*($(1+0.014)^1$)

=0.092$/kWh

Use $cost_{year\ 2020}$ = electricity cost per $kWh_{2020}$ * annual electricity consumption

=0.092 $/kWh*1,693,410.00 kWh

=154,540.60$

PV Use $cost_{year\ 2019}$ = use $cost_{year\ 2020}/(1+r)^t$

=154,540.60$/$(1+0.03)^1$

= 150,039.41$

***Example in end of life cost***

In the end of life (year 2079)

End of life cost in 2079 = End of life $cost_{year\ 2019}$ * $(1+inflation\ rate)^t$ x City index

= 31$/ cubic meter x ($(1+0.0665)^{59}$)*City index

= 1,504.12 $/ cubic meter

Total end of life cost in 2079 = 1,504.12 $/ cubic meter x 3,704.25 cubic meter

= 5,571,629.83 $

PV in 2019 = End of life $cost_{year\ t}/(1+r)^t$

= 5,571,629.83 $/($(1+0.03)^{59}$)

= 974,060.65 $

**Consequential approach**

In the consequential assessment, the calculation is based on the cost of future marginal technology. Most of the future costs used in this study are available from the outlook and forecast sections of the IMF and OECD database for 2030. These future costs are then discounted to present value (PV) of the current year (2019) at a 3% discounting rate. Secondly, these future costs are then forecasted back based on different increasing rates; for example, the market growth material cost was obtained from the Canadian building trend analysis [140]. The calculation details are provided in the Appendix B Supplementary Material section of this article.

Material Production Cost

To calculate the current value of future cost of marginal technology, the present value (PV) is used.

*Total production cost = present value (PV) of ∑ production cost in future $_{year\ n}$*

*= PV of material cost$_{year\ n}$ + PV of labor cost$_{year\ n}$ + PV of equipment cost$_{year\ n}$ + .... + PV of other cost$_{year\ n}$*

*= (Material cost$_{year\ n}$ / $(1+r)^t$) + (Labor cost$_{year\ n}$ / $(1+r)^t$)*

*+ (Equipment cost$_{yearn}$ / $(1+r)^t$) + .... + (Other cost$_{year\ n}$ / $(1+r)^t$)*

The future cost of the material, labor, equipment or other can be obtained from national, regional or global database such as IMF and OECD.

[1] If not available, they are forecasted with specific increase rates from the year of available data to 2030

*Material cost$_{year\ m}$ = Material cost$_{current\ year}$ x ((1+ inflation rate)$^t$) x city index*

*Labor cost$_{year\ m}$ = Labor cost$_{current\ year}$ x ((1+ inflation rate)$^t$) x city index*

*Equipment cost$_{year\ m}$ = Equipment cost$_{current\ year}$ x ((1+ inflation rate)$^t$) x city index*

*Total production cost*

*= PV of material cost$_{year\ m}$ + PV of labor cost$_{year\ m}$ + PV of equipment cost$_{year\ m}$ + .... + PV of other cost$_{year\ m}$*

*= (Material cost$_{year\ m}$ / $(1+r)^t$) + (Labor cost$_{year\ m}$ / $(1+r)^t$)*

*+ (Equipment cost $_{year\ m}$ / $(1+r)^t$) + .... + (Other cost$_{year\ m}$ / $(1+r)^t$)*

Use-Phase Cost

The calculation method for use phase for consequential is similar with attributional one. The only difference is the time frame for consequential is prospective from 2030 to 60 years onwards. The annual increasing rate of electricity cost used is 1,4% according to Hydro-Quebec. All the future price from 2030 to 2070 is then discounted to present value with 3% annual rate.

*<u>If data of future costs are available,</u>*

*Use cost*

*= Present value (PV) of ∑ Use cost in future $_{year\ n}$*

*= PV of Use cost$_{year\ n\ in\ future}$ + PV of Use cost$_{year\ n+1\ in\ future}$ + PV of Use cost$_{year\ n+2\ in\ future}$ + .... + PV of Use cost$_{year\ t\ in\ future}$*

*Use cost$_{year\ n}$ = electricity cost per kWh$_n$ * annual electricity consumption*

If not available,

*Electricity cost per kWh$_{future}$= electricity cost per kWh$_{year\ n}$ * (1+inflation rate) $^t$*

*In year 1*

*Electricity cost per kWh$_{year\ 2030}$= electricity cost per kWh$_{year\ (current)}$ * (1+inflation rate) $^t$*

*In year 2*

*Electricity cost per* $kWh_{year\ 2031}$ *= electricity cost per* $kWh_{year\ (current)}$ ** (1+inflation rate)* $^{t}$

*Use* $cost_{year\ 2030}$ *= electricity cost per* $kWh_{year\ 2030}$ ** annual electricity consumption*
*PV with discounted rate = r*
$PV_{2019} = \text{Use } cost_{year\ 2030} / (1+r)^{t})$
*Use* $cost_{year\ 2031}$ *= electricity cost per* $kWh_{year\ 2031}$ ** annual electricity consumption*
*PV with discounted rate = r*
$PV_{2019} = \text{Use } cost_{year\ 2031} / (1+r)^{t})$

End of life
The calculation model used here is similar to the attributional one. The difference lies on the quantification of benefits of re-selling building waste materials generated after reaching their end of life.
*Total end of life cost =* $PV \sum end\ of\ life$ *cost of each material ……………………..(2)*
$=PV \sum end\ of\ life$ *cost of material per* $unit_{future}$ *x Unit*
$=PV \sum end\ of\ life$ *cost of* $material_{future}$
$= \sum end\ of\ life$ *cost of each* $material_{future}/(1+r)^{t})$

If data of future costs are not available
*End of life cost of material per unit in future = End of life* $cost_{year\ 2019}$ ** (1+inflation rate)* $^{t}$
*Total end of life cost in future = End of life cost of material per unit in future x unit*
*PV in current year = End of life* $cost_{year\ t}/(1+r)^{t}$

Benefits of re-selling building waste materials
*Benefits of re-selling* building waste materials *in future = Benefits of re-selling* building waste materials $_{year\ 2019}$ ** (1+inflation rate)* $^{t}$
*Total benefits in future =* $\sum benefits\ of\ waste\ materials$
*PV benefits in current year = benefits in future* $/(1+r)^{t}$

***Example in material production***
*Total production cost = present value (PV) of* $\sum$ *construction cost in future* $_{year\ n}$

*<u>If data of future costs are available,</u>*
*Total production cost*
*= PV of material* $cost_{year\ n}$ *+ PV of labor* $cost_{year\ n}$ *+ PV of equipment* $cost_{year\ n}$ *+ …. + PV of other* $cost_{year\ n}$
$= (\text{Material } cost_{year\ n} / (1+r)^{t}) + (\text{Labor } cost_{year\ n} / (1+r)^{t})$
$+ (\text{Equipment } cost_{yearn} / (1+r)^{t}) + .... + (\text{Other } cost_{year\ n} / (1+r)^{t})$

*If not, the costs are forecasted to the future and then discounted back to current year for comparison*

*Material* $cost_{year\ m}$ *= Material* $cost_{current\ year}$ *x ((1+ inflation rate)* $^{t}$*) x city index*
*Labor* $cost_{year\ m}$ *= Labor* $cost_{current\ year}$ *x ((1+ inflation rate)* $^{t}$*) x city index*
*Equipment* $cost_{year\ m}$ *= Equipment* $cost_{current\ year}$ *x ((1+ inflation rate)* $^{t}$*) x city index*

*Total production cost*

*= PV of material cost$_{year\ m}$ + PV of labor cost$_{year\ m}$ + PV of equipment cost$_{year\ m}$ + .... + PV of other cost$_{year\ m}$*
*= (Material cost$_{year\ m}$ / $(1+r)^t$) + (Labor cost$_{year\ m}$ / $(1+r)^t$)*
+ (Equipment cost $_{year\ m}$ / $(1+r)^t$) + .... + (Other cost$_{year\ m}$ / $(1+r)^t$)

*For steel (IMF)*
*Steel price in 2030, based on IMF report = 0,17 $/kg*
*Steel needed is 1,979,460.00 kg*
*Steel cost in 2030 = 0,17 $/kg x 1,979,460.00kg = 333,766.65 $*
*Steel cost in 2019*
*= Steel cost in 2030/($(1+0.03)^{11}$)*
*= 333,766.65 $/ ($(1+0.03)^{11}$)*

*For aluminium (OECD)*
*Aluminium price in 2030, based on OECD report = 207.33 $/square meter*
*Aluminium needed is 901.80 square meter*
*Aluminium cost in 2030 = 207.33 $/square meter x 901.80 square meter = 186,974.14 $*

*Aluminium cost in 2019*
*= Aluminium cost in 2030/($(1+0.03)^{11}$*
*= 186,974.14 $/($(1+0.03)^{11}$)*

*If not available, they are forecasted with specific increase rates from the year of available data to 2030*
*= 3,422,443.65 $*
*For wood,*
*Material cost$_{year\ 2030}$ = Material cost$_{year\ 2019}$ x ($(1+0.048)^{11}$) x city index*
*= (734.24 $/ m3*3,704.25 m3) x ($(1+0.048)^{11}$) x 1.04*
*=3,704.25 m3*
*Total material cost year 2030*
*= 3,704.25 m3 x 1,278.93 $/m3*
*= 4,737,462.42$*
*With discounted rate = 0.03*
*= 4,737,462.42$/($(1+0.03)^{11}$)*
*= 3,422,443.65 $*
***Example in use phase***
*Electricity cost per kWh$_{future}$= electricity cost per kWh$_{year\ n}$ * $(1+\text{inflation rate})^t$*
*In year 1*
*Electricity cost per kWh$_{year\ 2030}$= electricity cost per kWh$_{year\ 2019}$ * $(1+\text{inflation rate})^t$*
*= 0.09*($(1+0.014)^{11}$)*
*=0.10 $/kWh*
*Use cost$_{year\ 2030}$ = electricity cost per kWh$_{year}$ 2030 * annual electricity consumption*
*=0.10 $/kWh*1,693,410.00 kWh*
*= 177,591.48$*
*PV with discounted rate = 0.03*
*= 177,591.48$/($(1+0.03)^{11}$)*
*= 128,295.87$*
In year 2
*Electricity cost per kWh$_{year\ 2031}$= electricity cost per kWh$_{year\ 2019}$ * $(1+\text{inflation rate})^t$*
*= 0.09*($(1+0.014)^{12}$)*

*=0.11 \$/kWh*
*Use cost*$_{year\ 2030}$ *= electricity cost per kWh*$_{year}$ *2030 * annual electricity consumption*
*=0.11 \$/kWh*1,693,410.00 kWh*
*= 180,077.76\$*
*PV with discounted rate = 0.03*
$= 180{,}077.76\$/((1+0.03)^{12})$
*= 126,302.92\$*
***Example in end of life cost***
*For wood*
In the end of life (year 2089)
*End of life cost in 2089 = End of life cost*$_{year\ 2019}$ $* (1+\text{inflation rate})^{t}$ *x City index*
$= 31\$/$ *cubic meter x* $((1+0.0665)^{70})$*City index*
*= 3,053.88 \$/ cubic meter*
*Total end of life cost in 2079 = 3,053.88 \$/ cubic meter x 3,704.25 cubic meter*
*= 11,312,320.80 \$*

*PV in 2019 = End of life cost*$_{year\ t}/(1+r)^{t}$
$= 11{,}312{,}320.80\ \$/((1+0.03)^{70})$
*= 1,428,716.25\$*

3. Impact Assessment

3.1. LCA Impact Assessment

### 3.1.1. Attributional approach

Midpoint results

Carcinogens: in terms of process, steel production is the main contributor and makes up for an emission of 5.43E+06 C2H3Cl eq. (90%) of the building's total impact of 6.00E+06 kg C2H3Cl eq. The analysis of the impact at the substance level reveals that hydrocarbons aromatic airborne emissions are responsible of 1.62E+06 kg C2H3Cl eq. (64%). Emissions of benzo(a)pyrene, another aromatic hydrocarbon substance, is the second largest contributor in terms of substance with 5.86E+05 kg C2H3Cl eq. (23%).

Non-carcinogens: dust linked to unalloyed electric arc furnace steel treatment produces 6.94E+05 kg C2H3Cl eq (43%) from a total impact of 1.61E+06 kg C2H3Cl eq. Second contributor is the steel production that makes up an emission of 2.53E+06 kg C2H3Cl eq (19%). The most impactful substances are dioxin to air and arsenic to with emission of 7.28E+05 kg C2H3Cl eq (54%) and 3.88E+05 kg C2H3Cl eq (29%) respectively.

Ozone layer depletion: the coke involved in freight train transportation contributes 3.45E-01 kg CFC-11 eq. (23%) from the total impact of 1.48E+00 kg CFC-11 eq. The most impactful substance is halon methane bromotrifluoro contributing 8.07E-01 kg CFC-11 eq. (54%) which is 34% used in the electricity production from petroleum source.

Land occupation: sawlog and veneer log extraction linked to softwood production occupies 8.37E+06 m2org.arable from a total impact of 8.95E+06 m2org.arable. This contributes around 95% of the total land consumption.

Global warming: quicklime production linked to the cement production is the largest contributor with the emission of 1.03E+06 kg CO2 eq. (6%) of a total impact of 1.74E+07 kg CO2 eq. It is consumed here mainly to produce the concrete for structural component. The clinker production linked also to the cement-making process causes an emission of 1.01E+06 kg CO2 eq. (5.8%) and is the second largest contributor in this category. Fossil Carbon dioxide is the main substance contributing to 2.24E+07 kg CO2 eq. (88.5%).

Non-renewable energy: natural gas linked to the electricity mix production is responsible of 3.81E+07 MJ primary (17.3%) of the total impact of 2.20E+08 MJ primary. The second main cause is hard coal used in the transport processes linked mainly to material production. It contributes to 2.34E+07 MJ primary. It makes up 10.6% of the total emission. In terms of substances, hard coal is the largest contributor with 2.34E+07 MJ primary or 52% from the total impact. The second is crude oil with 5.81E+07 MJ primary

Table 7. Hybrid building contribution analysis (attributional approach) - most impactful processes per midpoint category

| Impact category | Unit | Most impactful processes | Impact | Share | Total |
|---|---|---|---|---|---|
| Carcinogens | kg C2H3Cl eq | Steel, low-alloyed {RoW}\| steel production, electric, low-alloyed | 5.43E+06 | 90% | 6.00E+06 |
| | | Ferrochromium, high-carbon, 68% Cr {GLO}\| production | 6.02 E+05 | 2.3% | |
| Non-carcinogens | kg C2H3Cl eq | Dust, unalloyed electric arc furnace steel {RoW}\| treatment of, residual material landfill | 6.94E+05 | 43% | 1.61E+06 |

| | | | | | |
|---|---|---|---|---|---|
| | | Steel, low-alloyed {CA-QC}\|steel production, electric, low-alloyed | 2.32E+05 | 14.5% | |
| Respiratory inorganics | kg PM2.5 eq | Nickel, 99.5% {RU}\| platinum group metal mine operation | 1.2E+04 | 13% | 8.39E+04 |
| | | Steel, low-alloyed {CA-QC}\|steel production, electric, low-alloyed | 9.13E+03 | 12% | |
| Ionizing radiation | Bq C-14 eq | Tailing, from uranium milling {GLO}\| treatment of | 9.03E+07 | 46% | 1.94E+08 |
| | | Spent nuclear fuel {RoW}\| treatment of, reprocessing | 5.46E+07 | 28% | |
| Ozone layer depletion | kg CFC-11 eq | Transport, pipeline, long distance, natural gas {RoW} | 8.78E-01 | 43% | 2.03E+00 |
| | | Petroleum {RoW}\| petroleum and gas production, on-shore | 2.43E-01 | 12% | |
| Respiratory organics | kg C2H4 eq | Blasting {RoW}\|processing | 2.46E+03 | 22% | 1.10E+04 |
| | | Steel, low-alloyed {CA-QC}\|steel production, electric, low-alloyed | 1.5E+03 | 14% | |
| Aquatic ecotoxicity | kg TEG water | Blasting {RoW}\|processing | 5.09E+09 | 41% | 1.23E+10 |
| | | Blasting {RER}\|processing | 2.51E+09 | 20% | |
| Terrestrial ecotoxicity | kg TEG soil | Blasting {RoW}\|processing | 1.31E+09 | 34% | 3.83E+09 |
| | | Steel, low-alloyed {CA-QC}\|steel production, electric, low-alloyed | 1.01E+09 | 26% | |
| Terrestrial acid/nutria | kg SO2 eq | Blasting {RoW}\|processing | 1.84E+05 | 21% | 8.59E+05 |
| | | Nickel, 99.5% {RU}\| platinum group metal mine operation | 1.54E+05 | 18% | |
| Land occupation | m2org.arable | Sawlog and veneer log, softwood {CA-QC}, softwood forestry | 8.37E+06 | 94% | 8.95E+06 |
| | | Sulfidic tailing, off-site {GLO} | 2.12E+05 | 2.3% | |
| Aquatic acidification | kg SO2 eq | Nickel, 99.5% {RU}\| platinum group metal mine operation | 1.54E+05 | 44% | 3.47E+05 |
| | | Nickel, 99.5% {GLO}\| nickel mine operation | 6.93E+04 | 20% | |
| Aquatic eutrophication | kg PO4 P-lim | Sulfidic tailing, off-site {GLO} | 1.39E+05 | 99% | 1.4E+05 |
| | | Spoil from hard coal mining {GLO} | 6.57E+02 | 0.4% | |
| Global warming | kg CO2 eq | Quicklime, in pieces, loose {RoW}\|production | 1.03E+06 | 6% | 1.74E+07 |
| | | Clinker {RoW}\| production | 1.01E+06 | 5.8% | |
| Non-renewable energy | MJ primary | Natural gas, high pressure {CA-AB}\|natural gas production | 3.81E+07 | 17.3% | 2.20E+08 |
| | | Hard coal {CN}\| hard coal mine operation | 2.34E+07 | 10.6% | |

| | | | | | | |
|---|---|---|---|---|---|---|
| Mineral extraction | MJ surplus | Molybdenite mine operation | {RNA}\|copper | 1.29E+07 | 28% | 4.64E+07 |
| | | Molybdenite mine operation | {RAS}\|copper | 1.06E+07 | 23% | |

Endpoint results

Human health: steel production is the most intensive process in terms of human health with a score of 2.23E+01 DALY (27.8%) from a total score of 8.43E+00 DALY. It is due to metal supply chain involved in steel production such as nickel, ferrochromium and molybdenum. They release high amount of airborne emission such as particulates, hydrocarbon aromatic, sulfur dioxide and nitrogen oxides. The second biggest contribution comes from nickel mine operation. It contributes 8.43E+01 or 10.5% of the total impact to human health.

Ecosystem quality: the blasting process to mine molybdenum needed for steel production is the prime cause of both aquatic and terrestrial ecotoxicity (25.9% or 1.08E+07 out of 4.15E+07 PDF*m2*yr), owing to aluminium release to air during this process. Zinc is the second largest impactful substance that contribute to terrestrial ecotoxicity arising from molybdenum production. The third contributive process of ecosystem quality comes from sawlog and softwood production (22% or 9.12E+06 out of 4.15E+07 PDF*m2*yr).

Climate change: interpretation on this category may also be found in the paragraph on global warming in the previous section. This damage category is equivalent to the global warming impact category in the midpoint section.

Resource: natural gas is the main cause of non-renewable energy extraction used for heat in steel-making process with a score of 3.81E+07 Bq C-14 eq (14.3%) from a total score of 2.67E+08 Bq C-14 eq. Second prime cause of non-renewable energy extraction is petroleum that is used as diesel for fueling natural gas and steel production with a score of 2.34E+07 Bq C-14 eq  or 8.79% from total impact. Molybdenite and nickel are also two substances that contribute most for mineral extraction. It is linked to the mining process of some mineral needed in steel making process.

Table 18. Hybrid building contribution analysis (attributional approach)
- most impactful processes per endpoint category

| Impact category | Unit | Most impactful processes | Impact | Share | Total |
|---|---|---|---|---|---|
| Human health | DALY | Steel, low-alloyed {CA-QC}\| steel production, electric, low-alloyed \| Cut-off, U | 2.23E+01 | 27.8% | 8.01E+01 |
| | | Nickel, 99.5% {RU}\| platinum group metal mine operation, ore with high palladium content \| Cut-off, U | 8.43E+01 | 10.5% | |
| Ecosystem quality | PDF*m2*yr | Blasting {RoW}\| processing \| Cut-off, U | 1.08E+07 | 25.9% | 4.15E+07 |
| | | Sawlog and veneer log, softwood, measured as solid wood under bark {CA-QC}\| softwood forestry, mixed species, boreal forest \| Cut-off, U | 9.12E+06 | 22% | |
| Climate change | kg CO2 eq | Quicklime, in pieces, loose {RoW}\| production \| Cut-off, U | 1.03E+06 | 5.92% | 1.74E+07 |

| | | | | | |
|---|---|---|---|---|---|
| | | Clinker {RoW}\| production \| Cut-off, U | 1.01E+06 | 5.83% | |
| Resource | Bq C-14 eq | Natural gas, high pressure {CA-AB}\| natural gas production \| Cut-off, U | 3.81E+07 | 14.3% | 2.67E+08 |
| | | Petroleum {RoW}\| petroleum and gas production, on-shore \| Cut-off, U | 2.34E+07 | 8.79% | |

### 3.1.2. Consequential approach

Midpoint results

Carcinogens: in terms of process, the natural gas contained in electricity mix imported from Ontario causes the highest share of the impact. It makes up for an emission of 2.10E+05 kg C2H3Cl eq. (53%) of the building's total impact (4.04E+05 kg C2H3Cl eq). The analysis of the impact at the substance level reveals that both hydrocarbons aromatic and dioxin tetra chlorodibenzo airborne emissions are responsible of 3.07E+05 kg C2H3Cl eq. (76%).

Non-carcinogens: natural gas also causes greatest impact in this category. It makes up 54% of total emission (5.90E+05 out of 1.09E+05 kg C2H3Cl eq.). In the substance level, dioxin tetra chlorodibenzo also contributes to the highest impact around 59.8 % (6.64E+05 out of 1.11E+06 kg C2H3Cl eq.)

Respiratory inorganics: heat and transport involved in steel making process in China contribute most to the total impact respectively 29% and 34%, (6.44E+03 and 7.52E+03 out of 3.58E+04 kg PM 2.5 eq). The highest airborne substance out of the entire process are particulates < 2.5 um. It causes 1.19E+04 kg PM 2.5 eq or 33.24% of total respiratory inorganics -related emission.

Ozone layer depletion: natural gas used as electricity mix contributes 1.66 kg CFC-11 eq. (30%) from a total impact of 5.49 kg CFC-11 eq. Second process contributing most is transportation of the natural gas using long distance pipeline. The most impactful substance is halon (methane bromotrifluoro) contributing 3.39 kg CFC-11 eq. (61.52%).

Terrestrial acidification: the most significant process for this category is the transportation for the steel from China. In terms of substances, the nitrogen oxides involved here is mainly present in sea transoceanic freight ship. It causes 5.07E+05 kg SO2 eq. (75.78%) from a total impact of 6.69E+05 kg SO2 eq.

Land occupation: sawlog (softwood) for laminated timber is the main contributor with the land accusation of 7.05E+06 m2.org.arable out of 8.09E+06 m2.org.arable. This contributes around 87% of the total land consumption.

Global warming: electricity production from mostly natural gas in Ontario is the largest contributor with the emission of 2.14E+07 kg CO2 eq. (56%) from the total impact of 3.83E+07 kg CO2 eq. The electricity is mainly used in electricity mix to make the housing warm during cold times. This is part of marginal technology. The freight transportation is the second contributor and the clinker production itself is in the third position. They are respectively responsible for a share of the impacts of 3.91E+06 kg CO2 eq. (10%) and of 1.92E+06 kg CO2 eq. (5%). Fossil carbon dioxide is the main substance contributing to the impact with 3.76E+05 kg CO2 eq. (96%) that are both mainly linked to use phase (electricity generation) and material production (steel making and clinker process).

Non-renewable energy: steel from China used as marginal technology is responsible for the emission of 6.08E+06 MJ primary (58%) of the total impact of 1.06E+07 MJ primary.

Mineral extraction: the copper concentrate used in the electricity production is the main contributor with 2.46E+05 MJ surplus (25%) from a total impact of 9.82E+05 MJ surplus. Second is the ferronickel concentrate from the same source with 2.14E+05 MJ surplus (22%).

Table 19. Hybrid building contribution analysis (consequential approach)
- most impactful processes per midpoint category

| Impact category | Unit | Most impactful processes | Impact | Share | Total |
|---|---|---|---|---|---|
| Carcinogens | kg C2H3Cl eq | Natural gas, high pressure {CA-AB} \| market for | 1.15E+05 | 29% | 3.95E+05 |
| | | Natural gas, high pressure {RoW}\| natural gas production | 9.49 E+04 | 24% | |

| | | | | | |
|---|---|---|---|---|---|
| Non-carcinogens | kg C2H3Cl eq | Natural gas, high pressure {CA-AB} \| market for | 5.90E+05 | 54% | 1.09E+05 |
| Respiratory inorganics | kg PM2.5 eq | Heat, district or industrial, other than natural gas {RoW} | 6.44E+03 | 19% | 3.42E+06 |
| | | Transport, freight, sea, transoceanic ship {GLO} | 5.21E+03 | 15% | |
| Ionizing radiation | Bq C-14 eq | Low level radioactive waste {GLO}\| treatment of | 7.67E+07 | 95% | 8.09E+07 |
| Ozone layer depletion | kg CFC-11 eq | Natural gas, high pressure {CA-AB}\|petroleum and gas production on-shore | 1.66E+00 | 58% | 5.49E+00 |
| | | Transport, pipeline, long distance, natural gas {RoW}\| | 1.33E+00 | 17% | |
| Respiratory organics | kg C2H4 eq | Natural gas, high pressure {CA-AB} \| natural gas production | 2.15E+03 | 15% | 1.42E+04 |
| | | Natural gas, high pressure {CA-AB} \| market for | 2.07E+03 | 11% | |
| Aquatic ecotoxicity | kg TEG water | Drilling waste {CH}\| treatment of, landfarming | 4.64E+08 | 23% | 2.48E+09 |
| | | Wood ash mixture, pure {RoW}\| treatment of wood ash mixture, pure, landfarming | 1.04E+03 | 20% | |
| Terrestrial ecotoxicity | kg TEG soil | Tyre wear emissions, lorry {RoW}\| treatment of | 4.18E+08 | 32% | 1.30E+09 |
| | | Wood ash mixture, pure {RoW}\| treatment of wood ash mixture, pure, landfarming | 1.76E+08 | 14% | |
| Terrestrial acid/nutria | kg SO2 eq | Transport, freight, sea, transoceanic ship {GLO}\| processing | 1.51E+05 | 23% | 6.49E+05 |
| | | Transport, freight, lorry >32 metric ton, EURO4 {RoW}\| transport, freight, lorry >32 metric ton, EURO4 | 9.46E+04 | 15% | |
| Land occupation | m2org.arable | Sawlog and veneer log, softwood, measured as solid wood under bark {CA-QC}\| softwood forestry, mixed species, boreal forest | 7.05E+06 | 87% | 8.09E+06 |
| Aquatic acidification | kg SO2 eq | Transport, freight, sea, transoceanic ship {GLO}\| processing | 3.74E+04 | 24% | 1.54E+05 |
| | | Natural gas, high pressure {CA-AB}\| market for | 1.83E+04 | 12% | |
| Aquatic eutrophication | kg PO4 P-lim | Sulfidic tailing, off-site {GLO}\| treatment of | 2.40E+03 | 48% | 5.03E+03 |
| | | Spoil from lignite mining {GLO}\| treatment of, in surface landfill | 1.04E+03 | 21% | |

| | | | | | |
|---|---|---|---|---|---|
| Global warming | kg CO2 eq | Electricity, high voltage {CA-ON}\| electricity production, natural gas, combined cycle power plant | 2.14E+07 | 56% | 3.83E+07 |
| | | Transport, freight, lorry >32 metric ton, EURO4 {RoW}\| transport, freight, lorry >32 metric ton, EURO4 | 3.91E+06 | 10% | |
| Non-renewable energy | MJ primary | Steel {CN}\| production | 6.09E+08 | 58% | 1.06E+09 |
| | | Natural gas, high pressure {CA-AB}\| natural gas production | 2.94E+08 | 28% | |
| Mineral extraction | MJ surplus | Copper {RoW}\| gold-silver-zinc-lead-copper mine operation and refining | 2.46E+05 | 25% | 9.82E+05 |
| | | Ferronickel, 25% Ni {GLO}\| production | 2.15E+05 | 22% | |

Endpoint results

Human health: heat and power co-generation (other than natural gas) is the process causing the most damage in terms of human health with a score of 4.51E+00 DALY (16%) from a total score of 28.13E+00 DALY. The heat is primarily used for the production of steel in China. Transportation of steel by transoceanic ship is the second largest contributor with 3.68E+00 DALY (13%) and natural gas from electricity mix is third with 3.19E+00 DALY (11%). In terms of substance, particulates < 2.5 um 1.11E+01 DALY (38%) is the largest contributor. The main processes responsible for the emission of that substance are the heat production for steel making and electricity production of importation from Ontario. The nitrogen oxides with 9.09E+00 DALY (31%) is the second largest contributing substance coming mainly from transportation phase of material.

Ecosystem quality: the softwood harvesting and production process causes 7.68E+06 PDF*m2*yr (39%) from a total damage of 1.98E+07 PDF*m2*yr. Tire wire emission from lorry (transportation) is the second largest contributor and is responsible for 3.32E+00 PDF*m2*yr (17%). The substance causing the most damage is forest or land occupation 5.88E+06 PDF*m2*yr (29%) of which 93% comes from the softwood processes. The emission of zinc to soil is the second largest contributory substance with 5.26E+06 PDF*m2*yr (26%).

Climate change: comments on this category may be found in the paragraph on global warming in the previous section. This damage category is equivalent to the global warming impact category in the midpoint section.

Resource: Steel making process in China causes a damage of 6.09E+08 MJ primary (57%) from a total damage of 1.07E+09 MJ primary. It is followed by natural gas at 2.94E+08 MJ primary (27.4%) which is used in the electricity production. In terms of substance, the natural gas with 4.48E+08 MJ (42%) is the main contributor. It is primarily used for electricity production. The hard coal is the second largest contributor with 4.17E+08 MJ primary (38%). The steel making process stage causes 64% of the damage related to the consumption of the hard coal.

Table 20. Hybrid building contribution analysis (consequential approach) - most impactful processes per endpoint category

| Impact category | Unit | Most impactful processes | Impact | Share | Total |
|---|---|---|---|---|---|
| Human health | DALY | Heat, district or industrial, other than natural gas {RoW}\| heat and power co-generation, lignite | 4.51E+00 | 16% | 2.81E+01 |
| | | Transport, freight, sea, transoceanic ship {GLO}\| processing | 3.68E+00 | 13% | |
| Ecosystem quality | PDF*m2*yr | Sawlog and veneer log, softwood, measured as solid wood under bark {CA-QC}\| softwood forestry, mixed species, boreal forest | 7.68E+06 | 39% | 1.98E+07 |
| | | Tyre wear emissions, lorry {RoW}\| treatment of | 3.32E+06 | 17% | |
| Climate change | kg CO2 eq | Electricity, high voltage {CA-ON}\| electricity production, natural gas, combined cycle power plant | 2.14E+07 | 56% | 3.83E+07 |
| | | Transport, freight, lorry >32 metric ton, EURO4 {RoW}\| transport, freight, lorry >32 metric ton, EURO4 | 3.91E+06 | 10% | |
| Resource | Bq C-14 eq | Steel (CN) \| production | 6.08E+08 | 58% | 1.06E+08 |
| | | Natural gas, high pressure {CA-AB}\| natural gas production | 2.93E+08 | 28% | |

Sensitivity analysis
LCA Attributional Result with ReCiPe Method

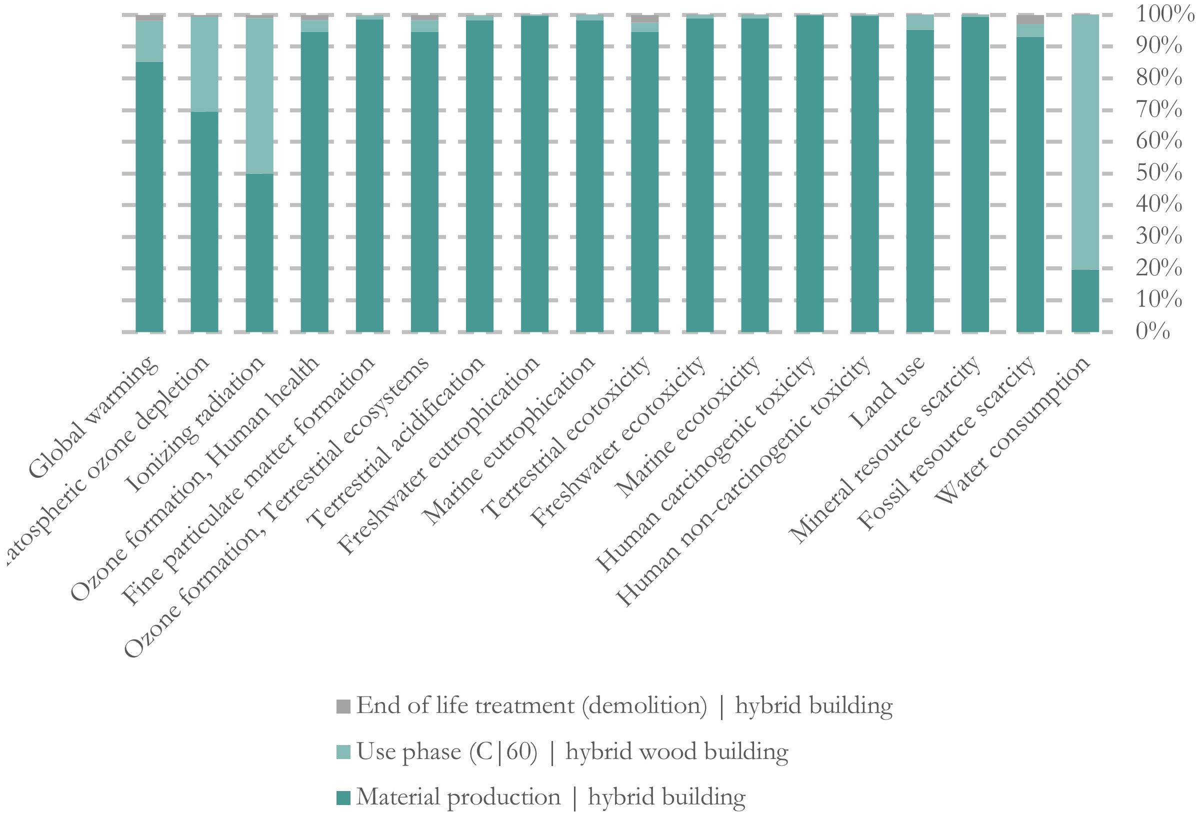


Figure 7. Midpoint results (attributional) - ReCiPe

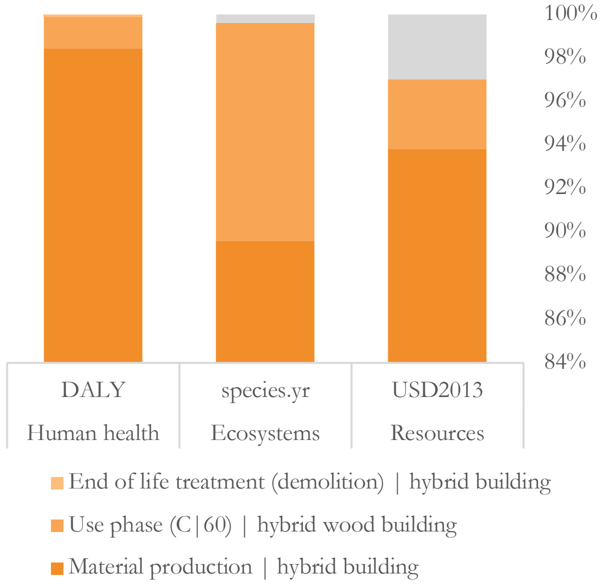


Figure 8 Endpoint result (attributional) - ReCiPe

LCA Consequential Result with ReCiPe Method

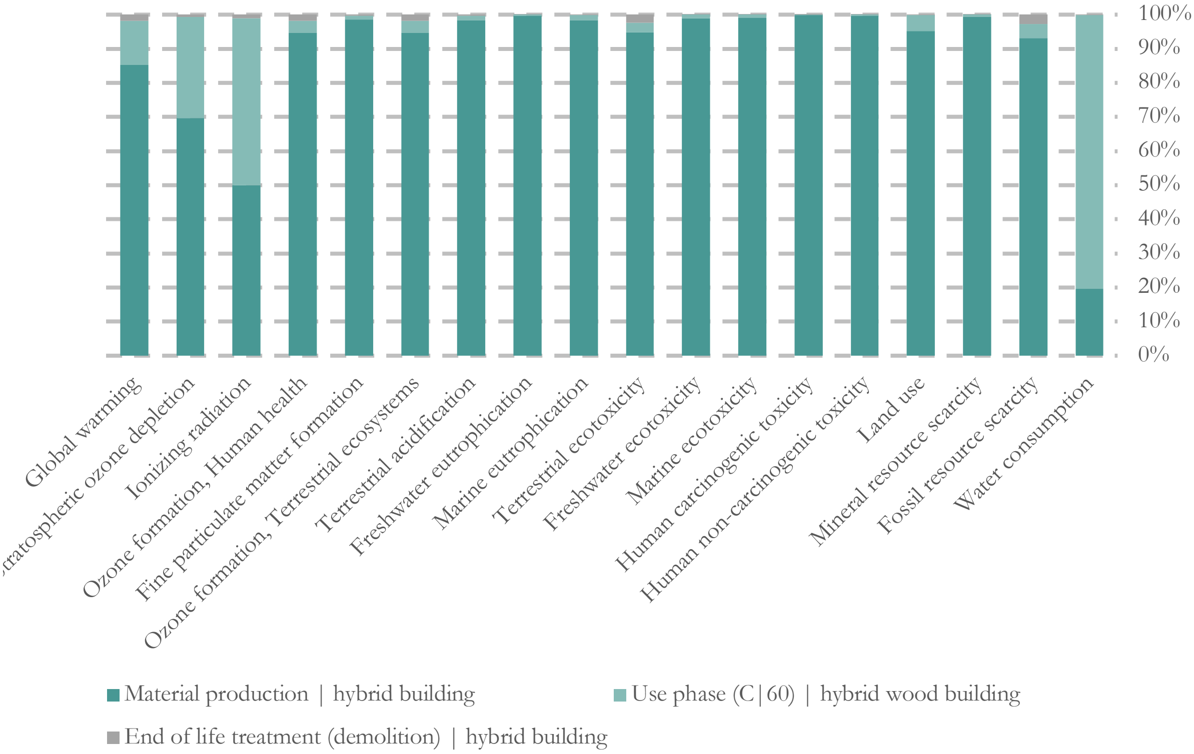


Figure 9 Midpoint results (consequential) - ReCiPe

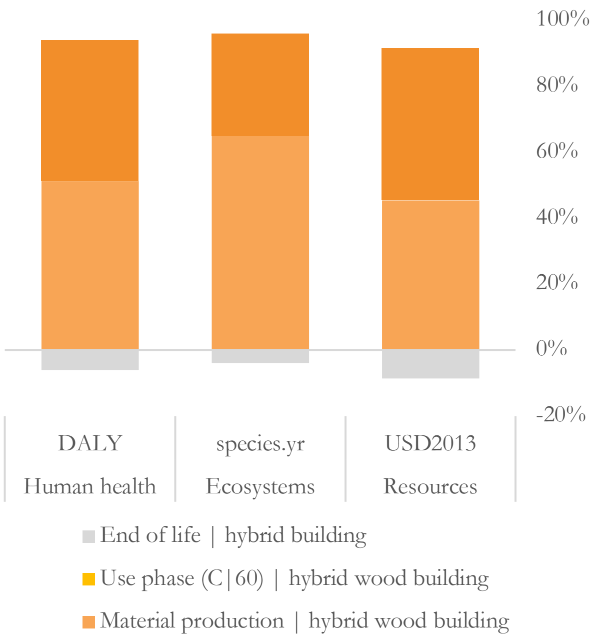


Figure 10 Endpoint consequential - ReCiPe

Similar to the attributional approach, the sensitivity analysis performed using the different impact methods (ReCiPe) generates similar results. Material production was the most impactful phase among the four impact human health categories and the five human toxicity categories. Similar to the IMPACT method, these results were also due to the nonrenewable electricity used in the steel production process, which partly is obtained from Ontario, and the

transcontinental transportation of bulk materials, which adversely impacts human health and climate change.
With steel production as the most impactful activity among the various categories, we performed sensitivity analysis by varying the steel import source between the United States, South Korea, Turkey and Brazil as the top five steel sources relative to China. This revealed that importing steel from Turkey and the USA results in impacts smaller than 49% and 32%, respectively, on human health. Similarly, importing steel from Brazil and Turkey has an impact smaller than 52% on the ecosystem quality, while importing steel from the USA and India has a smaller than 34-38% impact. In terms of global warming, importing steel from the USA, Turkey, Brazil and India results in similar impacts of approximately 32-33%. In terms of resource extraction, importing steel from Turkey and Brazil, India and the USA results in impacts smaller than 29% and 12%, respectively. In general, importing steel from South Korea has a similar impact to importing steel from China.

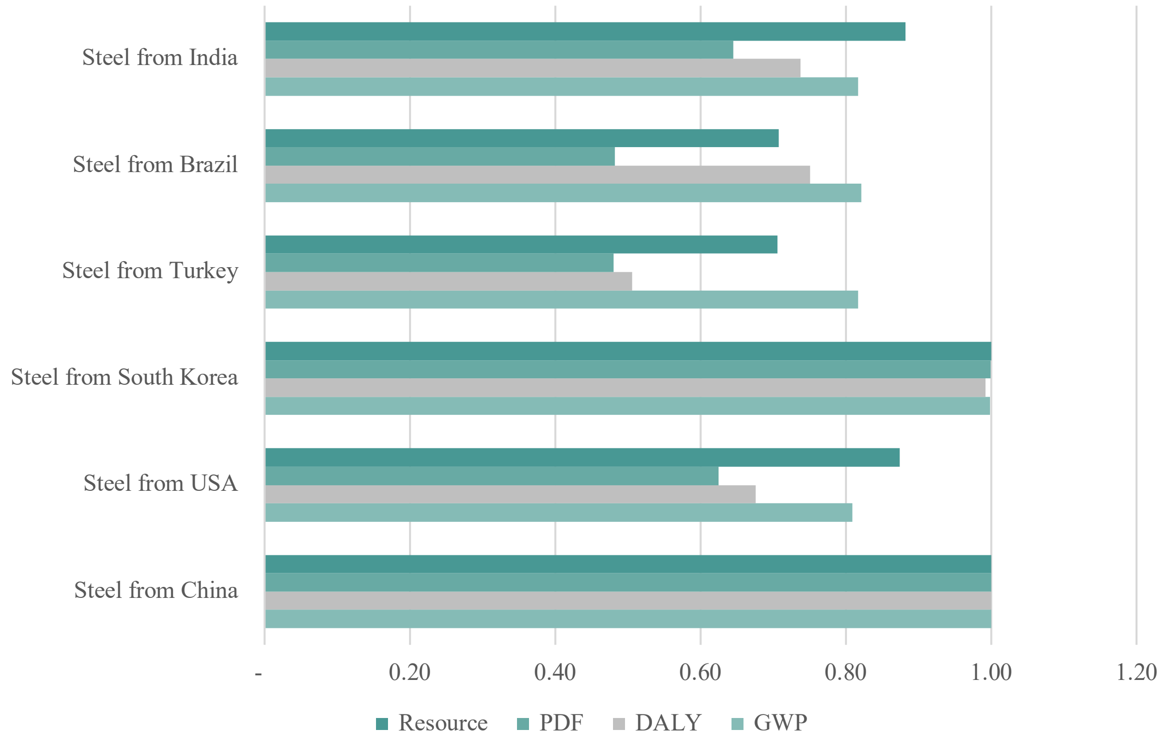


Figure 11 Consequential LCA

## 3.2. LCC Impact Assessment

### 3.2.1. Attributional Approach

Attributional Approach Cashflow by Timeline

Table 21. Timeline of attributional LCC

| Year | Production phase | Use phase | End of life phase |
|---|---|---|---|
| 2019 | 18,659,561 | 152,407 | 0 |
| 2020 | 0 | 154,541 | 0 |
| 2021 | 0 | 156,704 | 0 |
| 2022 | 0 | 158,898 | 0 |
| 2023 | 0 | 161,123 | 0 |
| 2024 | 0 | 163,378 | 0 |
| 2025 | 0 | 165,666 | 0 |
| 2026 | 0 | 167,985 | 0 |
| ...... | 0 | - | 0 |
| 2078 | 0 | 341,355 | 0 |
| 2079 | 0 | 346,134 | 8,138,095 |

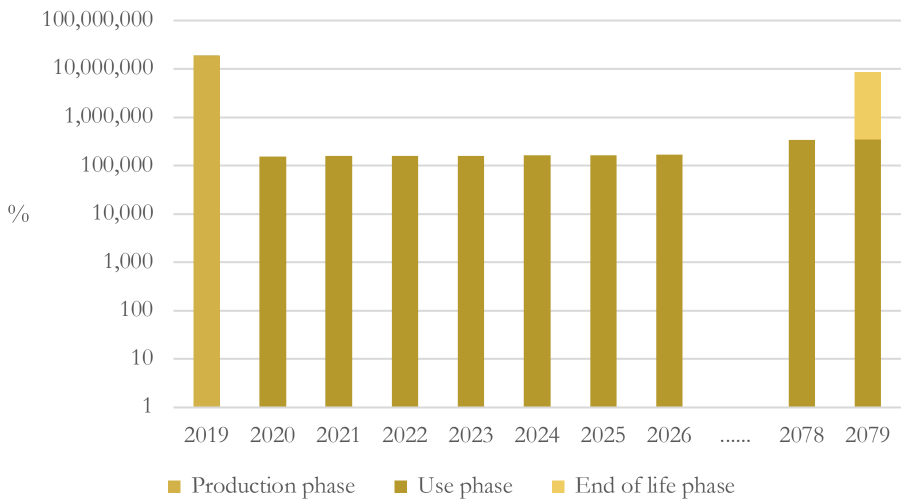


Figure 12 Timeline of Attributional LCC

### 3.2.2. Consequential Approach

Consequential Cashflow by Timeline

Table 22. Timeline of consequential LCC

| Year | Production phase | Use phase | End of life phase |
|---|---|---|---|
| 2030 | 21,409,217 | 177,591 | 0 |
| 2031 | 1 | 180,078 | 0 |
| 2032 | 1 | 182,599 | 0 |
| 2033 | 1 | 185,155 | 0 |
| 2034 | 1 | 187,747 | 0 |
| 2035 | 1 | 190,376 | 0 |
| 2036 | 1 | 193,041 | 0 |
| 2037 | 1 | 195,744 | 0 |
| …… | 0 | 0 | 0 |
| 2088 | 1 | 397,762 | 0 |
| 2089 | 1 | 403,331 | -1,505,203 |

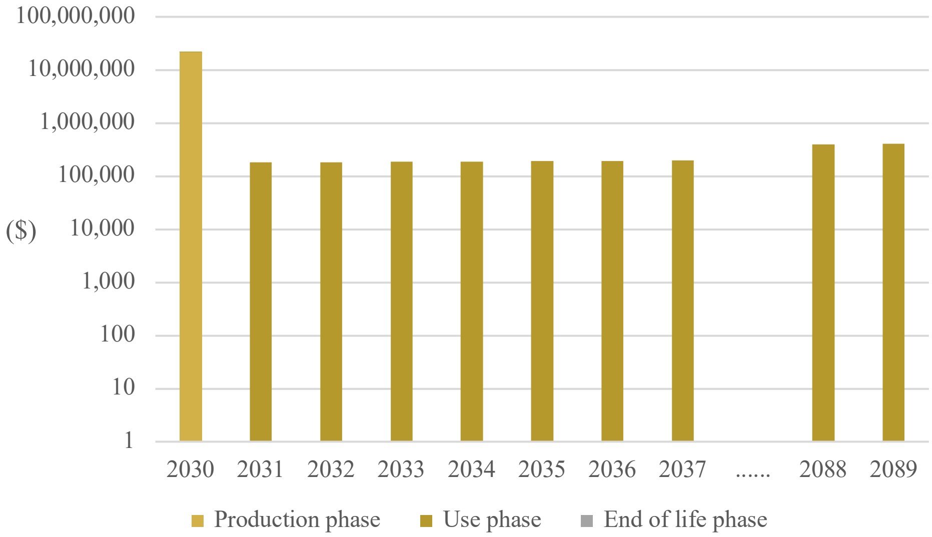


Figure 13 Timeline of Consequential LCA[1]

[1]the end of life cost avoided is negative value (thus it is not shown)

Sensitivity Analysis of LCC
Attributional LCC with Three Scenario (Pessimist, Average and Optimist)

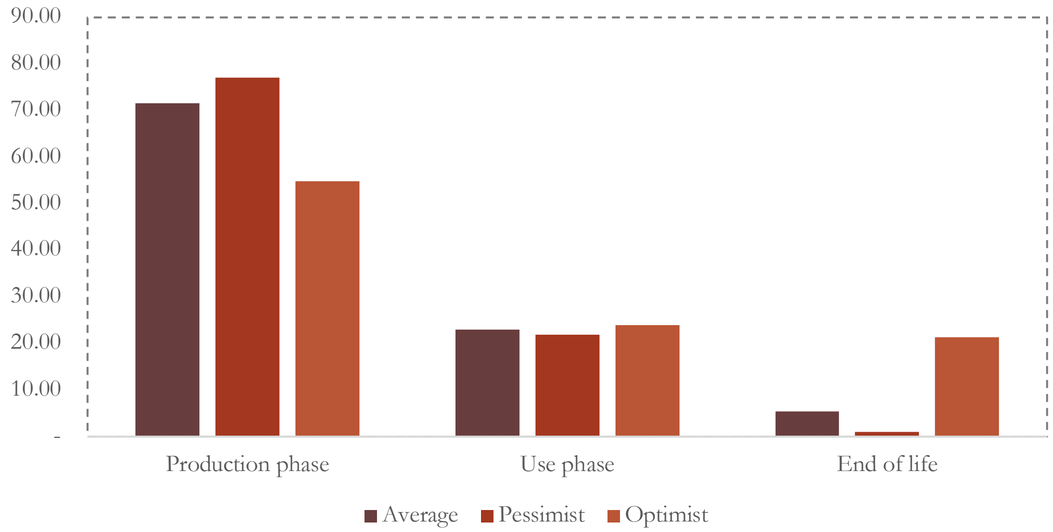


Figure 14. Attributional LCC

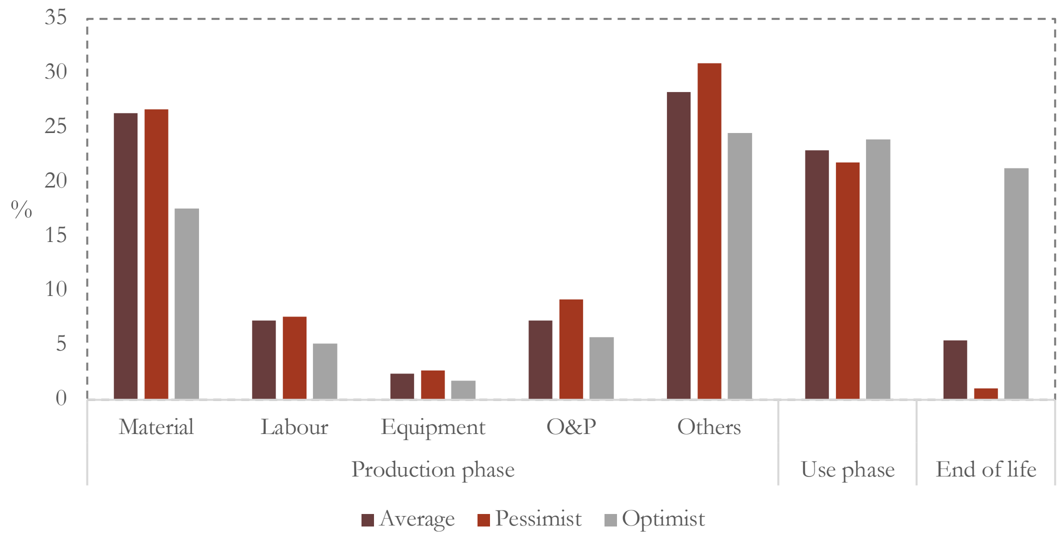


Figure 15. Attributional LCC with material cost breakdown

Consequential LCC with three scenario (Pessimist, Average and Optimist)

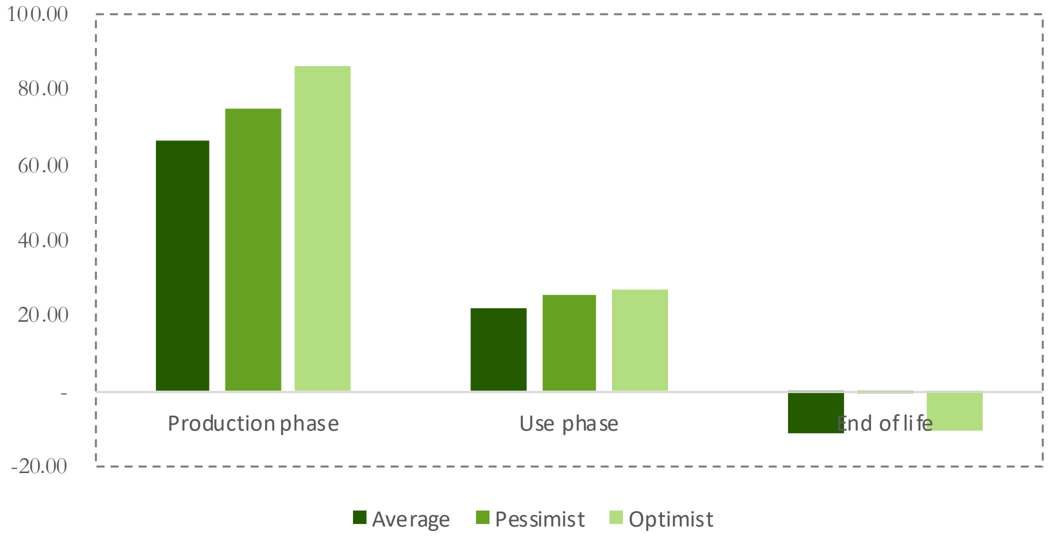


Figure 16. Consequential LCC

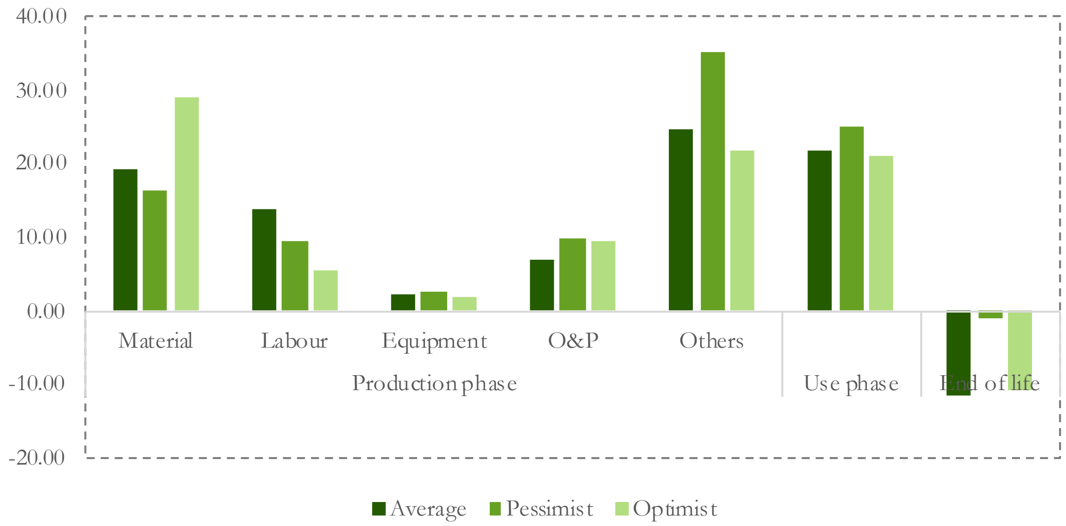


Figure 17. Consequential LCC material cost breakdown

# Annex C

## 1. Inventory for unit process level assessment

The inventory indicator for unit-process level assessment applied in the case study is shown in Table S1.

*Table S1. Inventory data for unit-process level*

| | Activity (process) | Product (1) | Amount (2) | |
|---|---|---|---|---|
| **1** | Production of laminated timber | | | |
| | Economic flows | Manufactured laminated timber | 1.00 | cubic meter |
| | Employability flows | Carpenter | **-0.03** | man-hour |
| **2** | Production of wood joist | | | |
| | Economic flows | Manufactured wood joist | 1.00 | cubic meter |
| | Employability flows | Carpenter | **0.00** | man-hour |
| **3** | Production of plywood panel | | | |
| | Economic flows | Manufactured plywood panel | 1.00 | square meter |
| | Employability flows | Carpenter | **-0.01** | man-hour |
| **4** | Construction of laminated timber | | | |
| | Economic flows | Manufactured laminated timber | -1.00 | cubic meter |
| | | Constructed laminated timber | 1.00 | cubic meter |
| | Employability flows | Carpenter | -1.39 | man-hour |
| | | Equipment operators (crane) | -0.17 | man-hour |
| **5** | Construction of wood joist | | | |
| | Economic flows | Manufactured wood joist | -2.36 | cubic meter |
| | | Constructed wood joist | 2.36 | cubic meter |
| | Employability flows | Carpenter | -8.94 | man-hour |
| **6** | Construction of plywood | | | |
| | Economic flows | Manufactured plywood panel | -2.36 | square meter |
| | | Constructed plywood panel | 2.36 | square meter |
| | Employability flows | Carpenter | -8.94 | man-hour |
| **7** | Construction of normal concrete | | | |
| | Economic flows | Constructed normal concrete | 0.03 | cubic meter |
| | Employability flows | Labor foreman (outside) | -0.06 | man-hour |
| | | Laborers | -0.32 | man-hour |
| | | Cement finisher | -0.06 | man-hour |
| | | Equipment operators (med) | -0.06 | man-hour |
| **8** | Precast concrete construction | | | |
| | Economic flows | Constructed precast concrete | 0.09 | square meter |

| | | | | |
|---|---|---|---|---|
| | Employability flows | Labor foreman (outside) | 0.00 | man-hour |
| | | Laborers | -0.01 | man-hour |
| | | Cement finisher | -0.01 | man-hour |
| | | Equipment operators (med) | 0.00 | man-hour |
| **9** | Constrution of brick | | | |
| | Economic flows | Constructed brick | 0.09 | square meter |
| | Employability flows | Bricklayer | -0.10 | man-hour |
| | | Bricklayer helper | -0.07 | man-hour |
| **10** | Construction of aluminium | | | |
| | Economic flows | Constructed aluminium | 0.09 | square meter |
| | Employability flows | Glaziers | -0.08 | man-hour |
| | | Structural steel worker | -0.002 | man-hour |
| **11** | Construction of building | | | |
| | Economic flows | Constructed laminated timber | -3,704.25 | cubic meter |
| | | Constructed wood joist | -171.63 | cubic meter |
| | | Constructed plywood panel | -8.80 | square meter |
| | | Constructed normal concrete | -299.03 | cubic meter |
| | | Constructed precast concrete | -2,316.33 | square meter |
| | | Constructed brick | -2,682.96 | square meter |
| | | Constructed aluminium | -1,075.99 | square meter |
| | | Constructed Building | 1.00 | stance |
| | Employability flows | Site manager | -0.01 | man-hour |

## 2. Set of question and keyword for company level assessment

The set of questions to ask and keywords used for company level of assessment is presented in Table S1.

*Table S2. Set of question and indicator in company level assessment*

| Category | Sub-category | Indicator | Keywords |
|---|---|---|---|
| Local employment | • The proportion of local workers hired is regarded to be high.<br>• The company adheres to a hiring policy that favors local candidates.<br>• The company adheres to the policy of the use of locally based suppliers. | *Is there any statement of negative violation or any positive statement/evidence on the company's report and website about local hiring?*<br>- *No document can be assessed*<br>- *Yes, there is negative violation evidence*<br>- *No evidence of negative violation*<br>- *No evidence of negative violation and yes, there is positive and extensive statement/evidence* | *Local hiring, local employment* |
| | | *Is there any negative statement on the NGO report or newspaper about issue related to failing of hiring the locals?*<br>- *No document can be assessed*<br>- *Yes, there is negative violation evidence*<br>- *No evidence of negative violation*<br>- *No evidence of negative violation but yes, there is positive and extensive statement/evidence instead* | *Local hiring, local employment* |
| Respect to indigenous people | Ethnic minorities have the right to be protected by the company | *Is there any statement of negative violation or any positive statement/evidence on the company's report and website about protecting indigenous people?*<br>- *No document can be assessed*<br>- *Yes, there is negative violation evidence*<br>- *No evidence of negative violation*<br>- *No evidence of negative violation and yes, there is positive and extensive statement/evidence* | *Respect to indigenous, respect to minorities* |
| | | *Is there any negative statement on the NGO report or newspaper* | *Conflict with indigenous* |

| | | | |
|---|---|---|---|
| | | *about issue related to the company's involvement with indigenous people?*<br>- *No document can be assessed*<br>- *Yes, there is negative violation evidence*<br>- *No evidence of negative violation*<br>- *No evidence of negative violation but yes, there is positive and extensive statement/evidence instead* | |
| Secure living conditions | • There have been a number of legal complaints filed against the organization because of security issues.<br>• The total number of fatalities and injuries attributable to the organization. | *Is there any statement of negative violation or any positive statement/evidence on the company's report and website about dealing with safe and healthy issue on local community?*<br>- *No document can be assessed*<br>- *Yes, there is negative violation evidence*<br>- *No evidence of negative violation*<br>- *No evidence of negative violation and yes, there is positive and extensive statement/evidence* | *Safety, security* |
| | | *Is there any negative statement on the NGO report or newspaper about issue related to the company's safe and healthy of the local community?*<br>- *No document can be assessed*<br>- *Yes, there is negative violation evidence*<br>- *No evidence of negative violation*<br>- *No evidence of negative violation but yes, there is positive and extensive statement/evidence instead* | *Injury, accident* |
| Access to immaterial resources and material resources | • The company develops infrastructure relating to the company that is accessible to and | *Is there any statement of negative violation or any positive statement/evidence on the company's report and website on dealing with material and immaterial resource conflict?*<br>- *No document can be assessed* | *Free from land conflict, land management* |

| | | | |
|---|---|---|---|
| | beneficial to the community.<br>• The company has conducted a risk assessment for potential resource conflicts.<br>• The company has an environmental management system that has been accredited. | - *Yes, there is negative violation evidence*<br>- *No evidence of negative violation*<br>- *No evidence of negative violation and yes, there is positive and extensive statement/evidence* | |
| | | *Is there any negative statement on the NGO report or newspaper about issue related to the company's conflict on immaterial resources and material resources?*<br>- *No document can be assessed*<br>- *Yes, there is negative violation evidence*<br>- *No evidence of negative violation*<br>- *No evidence of negative violation but yes, there is positive and extensive statement/evidence instead* | *Land conflict* |
| Community engagement | The company adheres to its policies regarding community involvement. | *Is there any statement of negative violation or any positive statement/evidence on the company's report and website about community engagement?*<br>- *No document can be assessed*<br>- *Yes, there is negative violation evidence*<br>- *No evidence of negative violation*<br>- *No evidence of negative violation and yes, there is positive and extensive statement/evidence* | *CSR, community development, community engagement* |
| | | *Is there any negative statement on the NGO report or newspaper about issue related to community engagement of the company?*<br>- *No document can be assessed*<br>- *Yes, there is negative violation evidence*<br>- *No evidence of negative violation*<br>- *No evidence of negative violation but yes, there is positive and extensive statement/evidence instead* | *CSR, community development, community engagement* |

| | | | |
|---|---|---|---|
| Child labor | • Children under the legal working age of 15 years old are employed by the company.<br>• The children are hard at work during the night hours. | *Is there any statement of negative violation or any positive statement/evidence on the company's report and website about non-violation of child labor?*<br>- *No document can be assessed*<br>- *Yes, there is negative violation evidence*<br>- *No evidence of negative violation*<br>- *No evidence of negative violation and yes, there is positive and extensive statement/evidence* | *Free from child labor, child, underage* |
| | | *Is there any negative statement on the NGO report or newspaper about issue related to the company's involvement in child labor?*<br>- *No document can be assessed*<br>- *Yes, there is negative violation evidence*<br>- *No evidence of negative violation*<br>- *No evidence of negative violation but yes, there is positive and extensive statement/evidence instead* | *Child labor, underage* |
| Health and Safety | • The company has a clear policy in place for health and safety concerns.<br>• The organization has workplace safety precautions in place, as well as emergency processes. | *Is there any statement of negative violation or any positive statement/evidence on the company's report and website about health and safety?*<br>- *No document can be assessed*<br>- *Yes, there is negative violation evidence*<br>- *No evidence of negative violation*<br>- *No evidence of negative violation and yes, there is positive and extensive statement/evidence* | *Safety, injury, zero accident* |
| | | *Is there any negative statement on the NGO report or newspaper about issue related health and safety?*<br>- *No document can be assessed*<br>- *Yes, there is negative violation evidence* | *Injury, accident* |

| | | | |
|---|---|---|---|
| | | - *No evidence of negative violation*<br>- *No evidence of negative violation but yes, there is positive and extensive statement/evidence instead* | |
| Freedom of association and collective bargaining | Employees are free to form and join labor unions. | *Is there any statement of negative violation or any positive statement/evidence on the company's report and website about worker union?*<br>- *No document can be assessed*<br>- *Yes, there is negative violation evidence*<br>- *No evidence of negative violation*<br>- *No evidence of negative violation and yes, there is positive and extensive statement/evidence* | *Worker union, freedom, association* |
| | | *Is there any negative statement on the NGO report or newspaper about issue related to the company's worker union?*<br>- *No document can be assessed*<br>- *Yes, there is negative violation evidence*<br>- *No evidence of negative violation*<br>- *No evidence of negative violation but yes, there is positive and extensive statement/evidence instead* | *Worker union, freedom, association, worker strike* |
| The employment of forced labor | • The employees came to an agreement on employment terms based on the contracts.<br>• The identification documents of the employees were kept.<br>• Employees have the right to end their job at any time. | *Is there any statement of negative violation or any positive statement/evidence on the company's report and website worker's contract?*<br>- *No document can be assessed*<br>- *Yes, there is negative violation evidence*<br>- *No evidence of negative violation*<br>- *No evidence of negative violation and yes, there is positive and extensive statement/evidence* | *Free from forced labor, contract rule* |
| | | *Is there any negative statement on the NGO report or newspaper* | *Contract, forced labor* |

| | | | |
|---|---|---|---|
| | | *about issue related to the company's worker contract?*<br>- *No document can be assessed*<br>- *Yes, there is negative violation evidence*<br>- *No evidence of negative violation*<br>- *No evidence of negative violation but yes, there is positive and extensive statement/evidence instead* | |
| Equal opportunity and free from discrimination | • The corporation adheres to established standards on equal opportunity.<br>• Men and women are paid at the same rate. | *Is there any statement of negative violation or any positive statement/evidence on the company's report and website about promoting equal opportunity and freedom from discrimination?*<br>- *No document can be assessed*<br>- *Yes, there is negative violation evidence*<br>- *No evidence of negative violation*<br>- *No evidence of negative violation and yes, there is positive and extensive statement/evidence* | *Free from discrimination, equality* |
| | | *Is there any negative statement on the NGO report or newspaper about issue related to the company's involvement in violating equal opportunity and free from discrimination?*<br>- *No document can be assessed*<br>- *Yes, there is negative violation evidence*<br>- *No evidence of negative violation*<br>- *No evidence of negative violation but yes, there is positive and extensive statement/evidence instead* | *Discrimination, equality* |
| Fair Salary | Is the corporation employing the lowest paid employees when compared to the minimum wage or not? | *Is there any statement of negative violation or any positive statement/evidence on the company's report and website about salary plan?*<br>- *No document can be assessed* | *Salary, wage, paid, contract* |

| | | | |
|---|---|---|---|
| | | - *Yes, there is negative violation evidence*<br>- *No evidence of negative violation*<br>- *No evidence of negative violation and yes, there is positive and extensive statement/evidence* | |
| | | *Is there any negative statement on the NGO report or newspaper about issue related to the company's worker salary compared to the minimum wage?*<br>- *No document can be assessed*<br>- *Yes, there is negative violation evidence*<br>- *No evidence of negative violation*<br>- *No evidence of negative violation but there is positive and extensive statement/evidence instead* | *Unpaid, salary, wage, minimum wage, contract* |
| Decent hours of work | • Is the average number of hours worked by the company in conformity with the International Labor Organization standard?<br>• Is the number of holidays provided by the company | *Is there any statement of negative violation or any positive statement/evidence on the company's report and website about*<br>the company's working hours and work-life balance?<br>- *No document can be assessed*<br>- *Yes, there is negative violation evidence*<br>- *No evidence of negative violation*<br>- *No evidence of negative violation and yes, there is positive and extensive statement/evidence* | *Working hours, work life balance* |
| | | *Is there any negative statement on the NGO report or newspaper about issue related to the company's working hours?*<br>- *No document can be assessed*<br>- *Yes, there is negative violation evidence*<br>- *No evidence of negative violation*<br>- *No evidence of negative violation but yes, there is positive and extensive* | *Stress, working hours, work life balance* |

| | | | |
|---|---|---|---|
| | | *statement/evidence instead* | |
| Social benefit and security | Has the company ever been in violation of the Social Security Act? | *Is there any statement of negative violation or any positive statement/evidence on the company's report and website on social benefit i.e. insurance, pension, etc?*<br>- *No document can be assessed*<br>- *Yes, there is negative violation evidence*<br>- *No evidence of negative violation*<br>- *No evidence of negative violation and yes, there is positive and extensive statement/evidence* | |
| | | *Is there any negative statement on the NGO report or newspaper about issue related to the company's involvement on violating social security?*<br>- *No document can be assessed*<br>- *Yes, there is negative violation evidence*<br>- *No evidence of negative violation*<br>- *No evidence of negative violation but yes, there is positive and extensive statement/evidence instead* | |
| Corruption | Is the organization committed to preventing corruption?<br>Involvement in corruption and bribery on the part of the company | *Is there any statement of negative violation or any positive statement/evidence on the company's report and website about preventing corruption?*<br>- *No document can be assessed*<br>- *Yes, there is negative violation evidence*<br>- *No evidence of negative violation*<br>- *No evidence of negative violation and yes, there is positive and extensive statement/evidence* | *Free from corruption, transparency* |
| | | *Is there any negative statement on the NGO report or newspaper about issue related to the company's involvement on corruption?* | *corruption* |

| | | | |
|---|---|---|---|
| | | - *No document can be assessed*<br>- *Yes, there is negative violation evidence*<br>- *No evidence of negative violation*<br>- *No evidence of negative violation but yes, there is positive and extensive statement/evidence instead* | |
| Public commitments to sustainability | • Is the corporation required to make its documentation (EIA/SIA reports) available to the public? | *Is there any statement of negative violation or any positive statement/evidence on the company's report and website about promoting and achieving sustainability?*<br>- *No document can be assessed*<br>- *Yes, there is negative violation evidence*<br>- *No evidence of negative violation*<br>- *No evidence of negative violation and yes, there is positive and extensive statement/evidence* | *Sustainability as main goal* |
| | | *Is there any negative statement on the NGO report or newspaper about issue related to the company's non-fulfilment of sustainability targets?*<br>- *No document can be assessed*<br>- *Yes, there is negative violation evidence*<br>- *No evidence of negative violation*<br>- *No evidence of negative violation but yes, there is positive and extensive statement/evidence instead* | *Environmental damage, impact* |
| Contribution to economic development | Is the company making a positive contribution to the economy (via revenue gains, wages paid, and so on)? | *Is there any statement of negative violation or any positive statement/evidence on the company's report and website about contributing to economic development?*<br>- *No document can be assessed*<br>- *Yes, there is negative violation evidence* | *Employment, job creation* |

| | | | |
|---|---|---|---|
| | | - *No evidence of negative violation*<br>- *No evidence of negative violation and yes, there is positive and extensive statement/evidence* | |
| | | *Is there any negative statement on the NGO report or newspaper about issue related to the company's non-fulfilment of economic development?*<br>- *No document can be assessed*<br>- *Yes, there is negative violation evidence*<br>- *No evidence of negative violation*<br>- *No evidence of negative violation but yes, there is positive and extensive statement/evidence instead* | *Employment, loss of job* |
| Technology development | • Is the company a participant in a technology transfer program or with other companies?<br>• Is the company involved in research and development through partnerships?<br>• What percentage of the company's budget is allocated to technology development and technology transfer? | *Is there any statement of negative violation or any positive statement/evidence on the company's report and website about technology development?*<br>- *No document can be assessed*<br>- *Yes, there is negative violation evidence*<br>- *No evidence of negative violation*<br>- *No evidence of negative violation and yes, there is positive and extensive statement/evidence* | *Technology development, innovation* |
| | | *Is there any negative statement on the NGO report or newspaper about issue related to the company's non-fulfilment of technology development?*<br>- *No document can be assessed*<br>- *Yes, there is negative violation evidence*<br>- *No evidence of negative violation*<br>- *No evidence of negative violation but yes, there is positive and extensive statement/evidence instead* | *Fake innovation, fake technology* |

| | | | |
|---|---|---|---|
| Fair competition | • What is the company's anti-competitive behavior policy?<br>• The company's legal proceedings, whether pending or concluded, involving anti-competitive practices and violations of anti-trust laws | *Is there any statement of negative violation or any positive statement/evidence on the company's report and website about fair competition?*<br>- *No document can be assessed*<br>- *Yes, there is negative violation evidence*<br>- *No evidence of negative violation*<br>- *No evidence of negative violation and yes, there is positive and extensive statement/evidence* | *Competition, trust, fair, anti-trust, anti-competitive* |
| | | *Is there any negative statement on the NGO report or newspaper about issue related to the company's involvement on anti-competitive behavior and monopoly practices?*<br>- *No document can be assessed*<br>- *Yes, there is negative violation evidence*<br>- *No evidence of negative violation*<br>- *No evidence of negative violation but there is positive and extensive statement/evidence instead* | *Monopoly, competition, trust, fair, anti-trust, anti-competitive* |
| Promoting CSR | • Environmental and social certifications were held by the company<br>• A CSR report was released by the company<br>• Suppliers were audited for their environmental and social compliance | *Is there any statement of negative violation or any positive statement/evidence on the company's report and website about corporate social responsibility?*<br>- *No document can be assessed*<br>- *Yes, there is negative violation evidence*<br>- *No evidence of negative violation*<br>- *No evidence of negative violation and yes, there is positive and extensive statement/evidence* | *CSR, corporate, social, responsibility, audit* |
| | | *Is there any negative statement on the NGO report or newspaper about issue related to the company's involvement on non-* | *CSR, corporate, social, responsibility, audit* |

| | | |
|---|---|---|
| | *fulfilling corporate social responsibility?*<br>- *No document can be assessed*<br>- *Yes, there is negative violation evidence*<br>- *No evidence of negative violation*<br>- *No evidence of negative violation but there is positive and extensive statement/evidence* | |

# 3. Multilevel analysis with focus on gaps in selected indicators and product life cycle

*The added value of using multilevel analysis is shown through figure 2-5. The* available data in company level indicating how many indicators can be assessed is presented in figure 2. If we add one more level, such sector level, the added value can be seen in figure 3, 4 and 5.

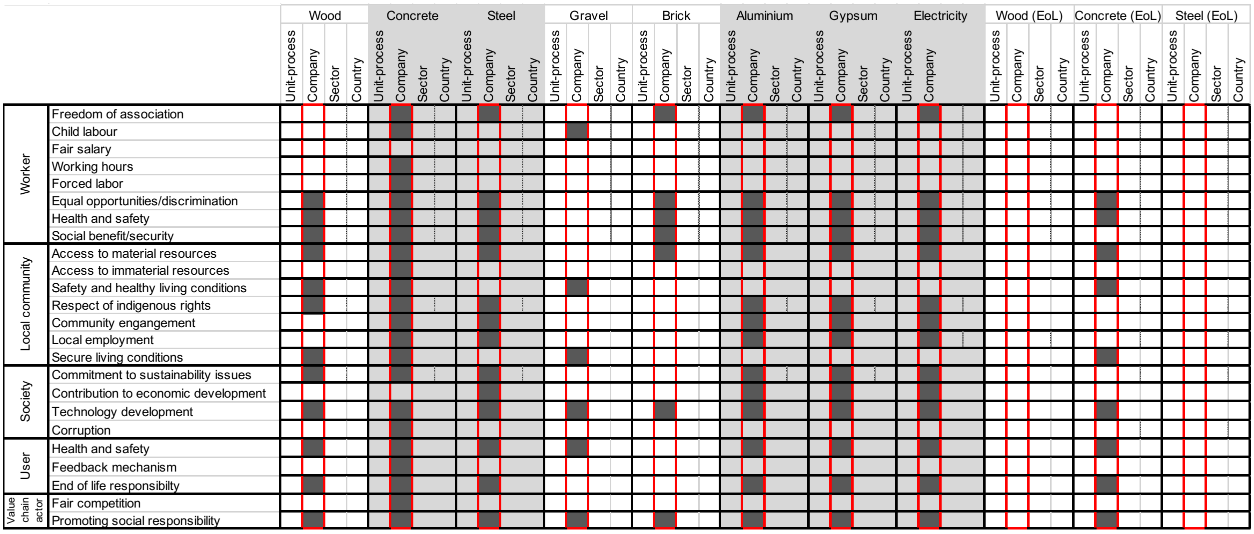


Figure S1. The available data in company level with vertical grey area indicating companies that present more than 12 indicators

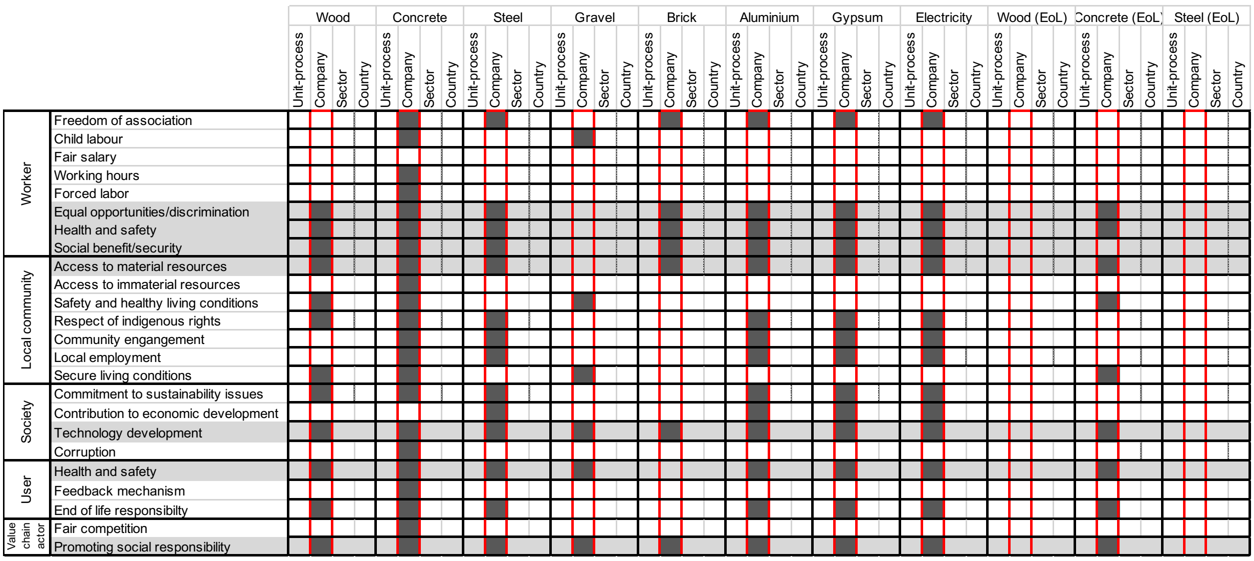


Figure S2. The available data in company level with horizontal grey area indicating how many indicators can be assessed

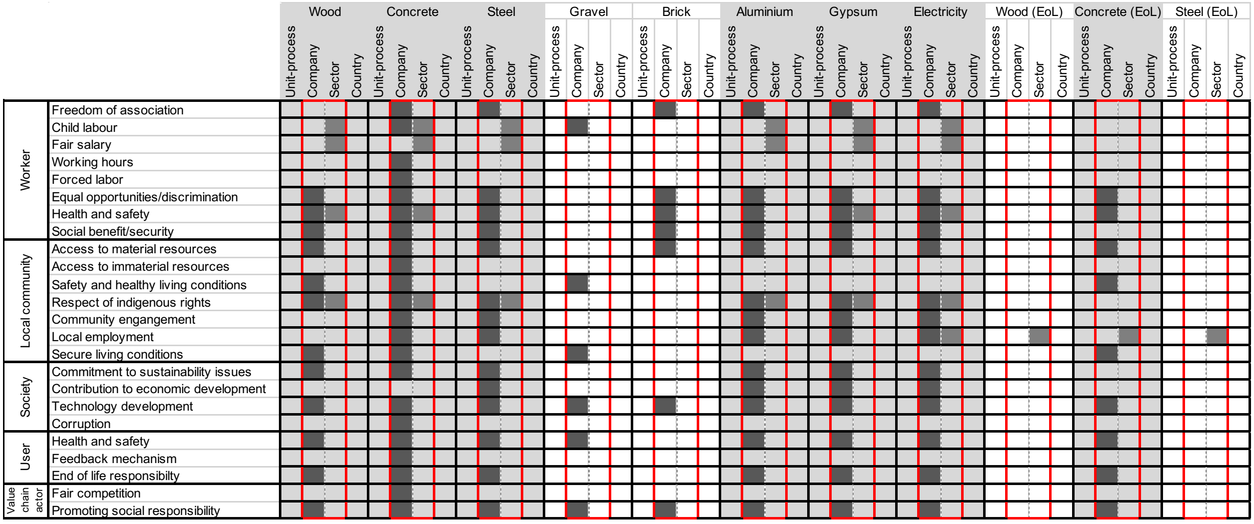


Figure S3. The available data in company and sector level with greater numbers of companies or sectors that present more than 12 indicators

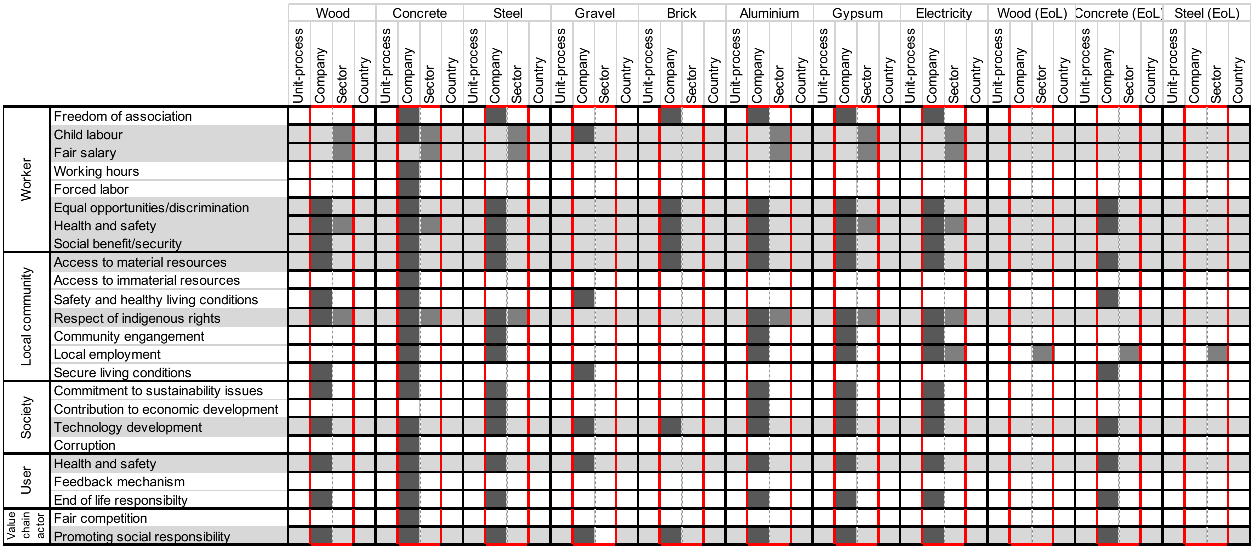


Figure S4. The available data in company and sector level with greater numbers of indicators that can be assessed (grey area)

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