Life cycle assessment and life cycle costing of multistorey building: Attributional and consequential perspectives

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Buildings are accountable for much of the resource consumption and CO_2 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 stake-holders the opportunity to avoid such future consequences.

1. Introduction

The construction sector is the largest polluter in the global economy, representing 23% of the CO_2 emissions worldwide and being a dominant resource consumer [1,2]. It is therefore a keystone for climate change and environmental mitigation [3–6]. 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].

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 [8,9]. 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 [10–12]. 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 [13–15].

Because of their complementary perspectives, several authors argued for the necessity of both approaches [16–18]. For example, Brander et al. (2019) [17] 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

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consequential modelling in a single step that could result in "misleading interpretations" [17]. 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 [19]. Buyle et al. (2018) [19] 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 [19] and Dara et al. [20], 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.

2. Methodology

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 [8,9]. 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 [8, 9]. 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 [21–23].

To apply the marginal technology, it is mandated to use marginal data that reflects marginal environmental burden affected by the technology [24]. 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.

Many different methods are available to identify the marginal technology depending on data availability, starting from complex models such as partial and general equilibrium models [25], rectangular choice-of-technology model [26], trade network analysis [27], causal descriptive models [28], agent modeling [29], game theory [30] and experience curves [31](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 [32] or on the five-step procedure developed by Weidema (2003) [10]. Relying on the limited available data from regional and national statistics and reports, the five-step procedure is adopted in this case study.

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 [33,34].

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 m^2 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).

2.1.1.1. Attributional LCA. Using the attributional approach, the aim is to determine what environmental impact can be attributed to a hybrid

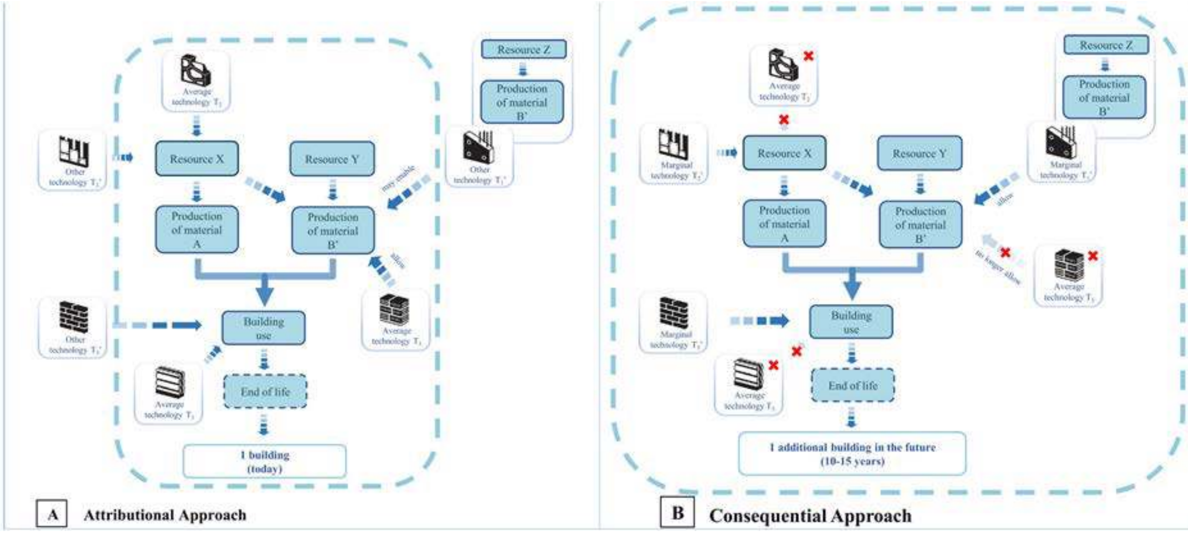

Fig. 1. Illustration of scope analysis.

Table 1
Summary of techniques to identify marginal technology.

Technique	Description
Partial and general equilibrium models [25]	The models can capture the potential effects of policy decisions on supply, demand, price, and resulting product production for one or more economic markets [25].
Trade network analysis [27]	With a regression analysis of historical production patterns for product types across countries, trade network analysis is used to classify clusters of countries traditionally connected in more intensive product exchanges.that ease marginal technology identification under the geographical constraints [27].
Causal descriptive models [28]	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 [28].
Agent based modeling (AGM) [29]	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 [29].
Game theory [30]	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 [30].
Experience curves [31]	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 [31].

Table 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

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).

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. 2B).

One of the main elements in the consequential approach is marginal technology identification. How to conduct marginal technology identification, however, remains unclear [14,35,36]. The absence of consensus stems from the difficulty of the work conducted, which aims to capture all causal connections [24,35]. 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) [10](see Fig. 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.

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

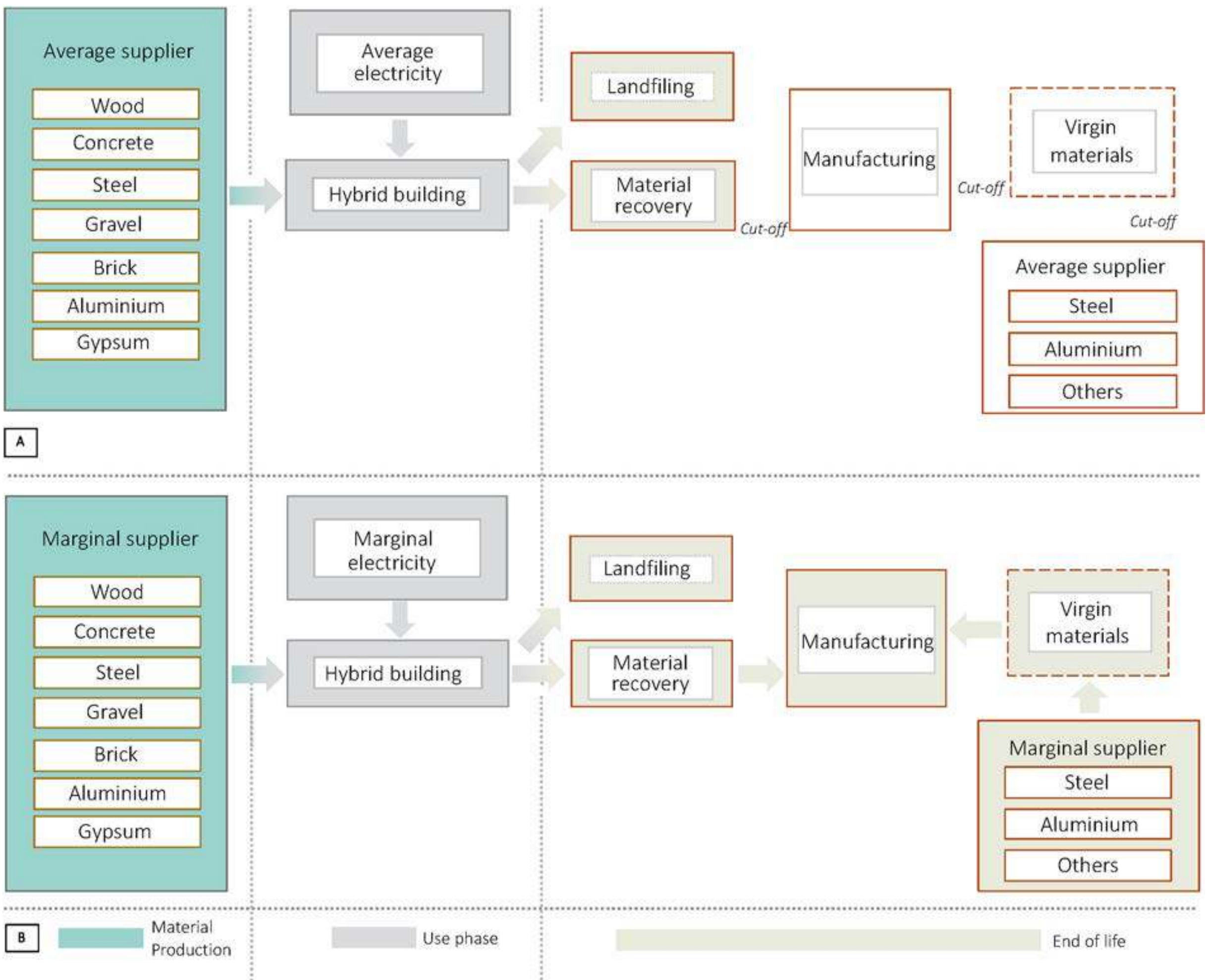

Fig. 2. System boundary of hybrid multistory building in attributional (upper) and consequential assessment (lower) with the dash line means the avoided burdens.

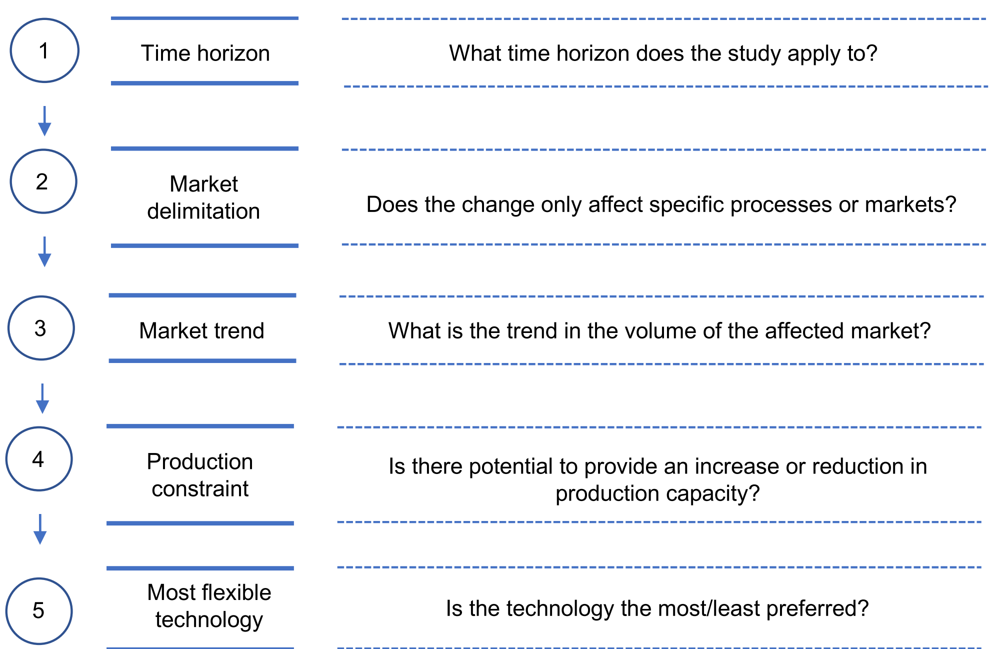

Fig. 3. Identification of the marginal technologies (adapted and modified from Weidema).

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.

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) [10].

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 [36,37], 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% [38–40]. The Food and Agriculture Organization predicted that sawn wood production based on three different IPCC scenarios that also show increasing trends [41]. 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 [20,42–44]. It is predicted that CLT will have better strength properties compared to glulam hardwood [45]. 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 [46].

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 [47]. 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 [48]. 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 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 portions of wind and natural gas

2.1.2. Life cycle inventory (LCI)

2.1.2.1. Attributional LCI

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 Supplementary Material for more details). Calculations were done with Simapro 8.5 and the impact method Impact 2002+ both mid and endpoint categories.

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 [49] and of laminated timber [50–52]. The inventory of concrete production per m^3 is adapted from Ecoinvent for Quebec context [53]. The inventory of steel and aluminum production in Quebec was obtained from Dussault [54,55]. The material inputs and emission data for gypsum and brick are generated from Althaus [56] and Reid [57], respectively. The input and output data of materials and emissions from gravel production are extracted from Lesage [58]. This includes whole manufacturing processes, internal processes (transport, etc.) and infrastructure.

2.1.2.1.2. Use phase – attributional. To model energy consumption

Table 4
Inventory of hybrid multistory building – attributional approach.

Dataset	Unit process[a] {Geographical location} | System model	Unit	Amount
Laminated timber	Laminated timber production {CA-QC} | Cut-off, U	m^3	3,704.25
Concrete	Concrete, 30–32 MPa {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

[a] 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 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.

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.

2.1.2.2. Consequential LCI

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 m^3 is adapted from ecoinvent by changing the marginal cement and clinker production [59, 60]. In the consequential approach, a previous study monitored the marginal technologies for concrete production in Quebec [61], with an additional inventory of cement and clinker production from other sources [60,62].

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 [63–65]. 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.

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 [66,67], especially if availability of data is a major issue [68]. 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 [69,70]. This also includes the electricity production in Quebec, electricity loss due to transmission and the imported electricity.

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.

Table 5
Inventory of hybrid multistory building – consequential approach.

Dataset	Unit process {Geographical location} | System model	Unit	Amount
Laminated timber	Laminated timber production {CA-QC} | Conseq, U	m^3	3,704.25
Concrete	Concrete, 30–32 MPa {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

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.

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 [71], which was the result of its working group describing three different categories of LCC: conventional, environmental and social LCC. While conventional LCC ignores the post-production (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 [72]. 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.

2.2.1. Goal and scope of LCC

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. The consequential analysis aims to assess the economic cost and consequences of constructing more hybrid wood multistory buildings in the long term. 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.

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 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.

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.

2.2.2. LCC inventory data

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 [73]. 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 Supplementary Material.

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

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

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

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).

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

Where u_i 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),

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

Where $PV \sum u_i$ 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.

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).

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

The eo_i represents end of life cost $material_i$ while t is time, eu_i is end of life cost per unit $material_i$, i is inflation rate and u_n 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).

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

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]. The calculation details are provided in the Supplementary Material of this article.

2.2.2.2.1. Material production cost. The total material production cost (Pc_q) 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.

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

Where mcf_i is the material cost year n in future, lcf_i is the labor cost and ecf_i 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).

$$Pc_q = PV \sum$$

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

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).

$$Pc_q = mcf_i + lcf_i + ecf_i \text{ with } mcf_i = mc_i \text{ x } (1+m)^t \text{ x Ci; } lcf_i = lc_i \text{ x } (1+m)^t \text{ x Ci;}$$

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

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.

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

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

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

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).

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

Where el is the electricity cost per $kWh_{year\ n}$ 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.

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).

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

Where eof_i is the end of life cost of $material_i$ 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).

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

Where eu_i is end of life cost per unit material$_i$, i is inflation rate, u_n is unit (volume or area) and C_i 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

$$B = \sum bf_i \text{ with } bf_i = b_i \text{ x } (1+m)^t \text{ x } u_n \text{ x } C_i \quad (14)$$

Where bf_i is the benefits of re-selling building waste material$_i$ in the future, b_i 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.

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.

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).

3.1. LCA results

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.

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).

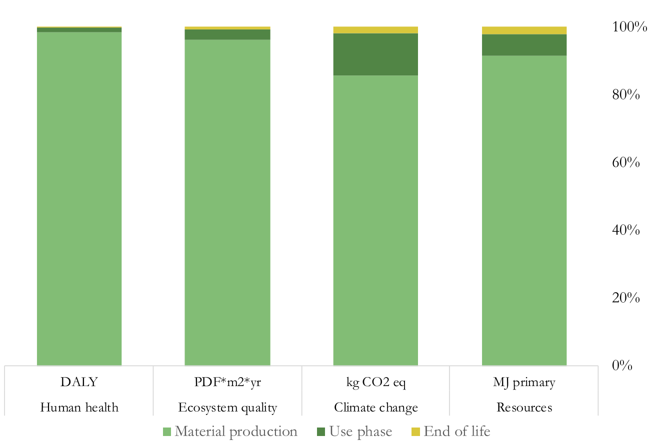

Fig. 4. Contribution analysis of endpoint results with with the attributional approach.

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 Supplementary Material 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.

According to the sensitivity analysis conducted using the different impact methods (ReCiPe) (see Supplementary Material), 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 Impact2002+ 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 [51–56]. 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 [57].

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.

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

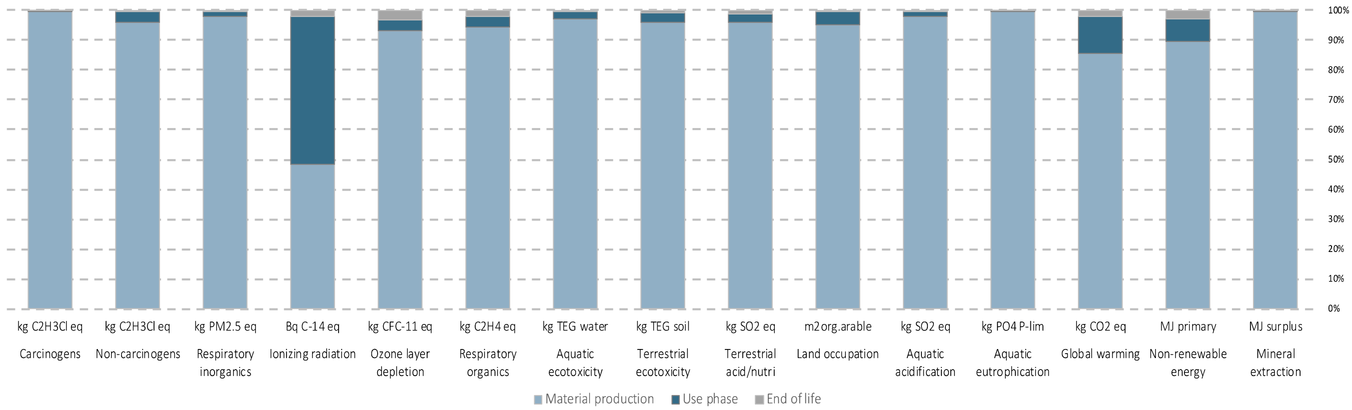

Fig. 5. Midpoint results of life cycle impact of hybrid building with attributional approach (contribution analysis).

Table 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

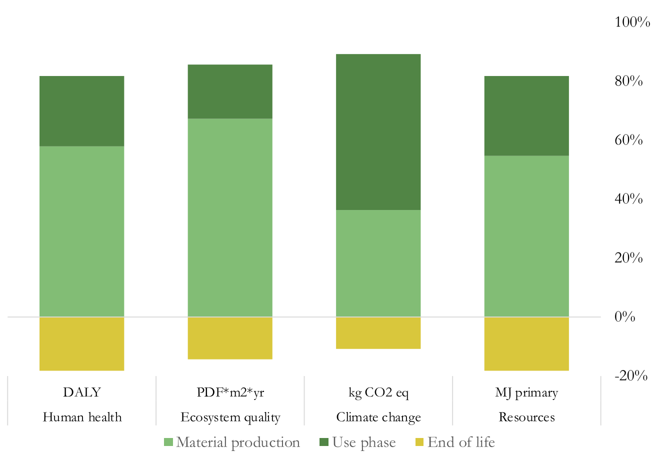

Fig. 6. Contribution analysis of endpoint results with the consequential approach.

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 [76]. 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 [77].

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

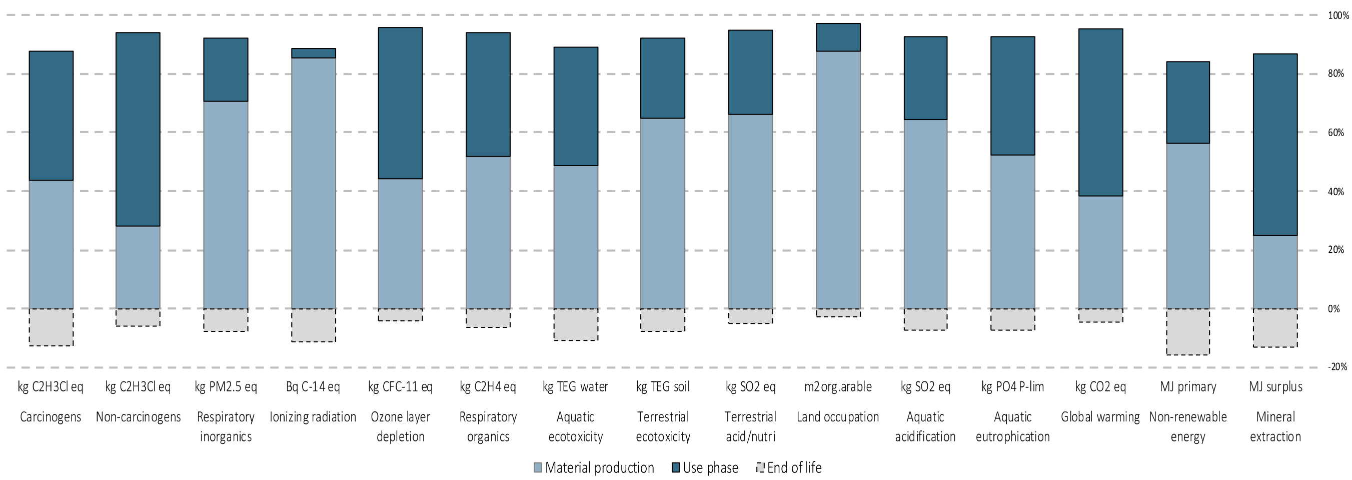

Fig. 7. Midpoint results of life cycle impact of hybrid building with consequential approach (constribution analysis).

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 [78,79]. Also, CLCA is also useful as a decision support during the initial plan while attributional is to know past annual performance of the policy [80].

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 [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.

3.2. LCC results

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.

In the material category, steel and wood have the largest life cycle

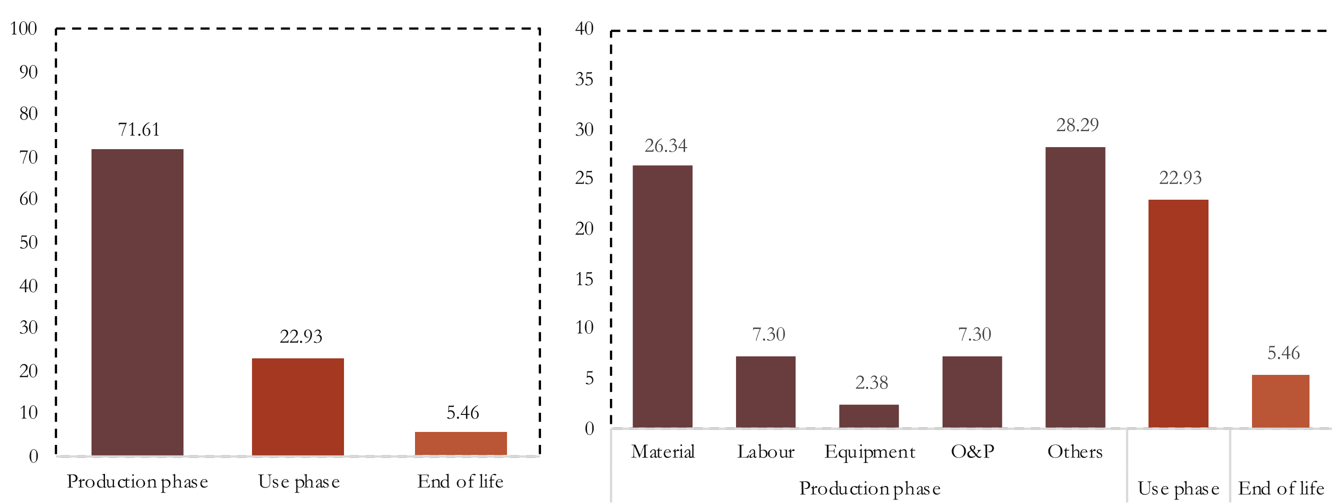

Fig. 8. Attributional LCC

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 Supplementary Material). 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 supplementary material).

3.2.2. Consequential LCC

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

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 Supplementary Material). 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.

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 [82]. The price changes within a country appear to follow their own internally generated increase path without the 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 [83]. 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.

Table 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

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 [84]. 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.

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

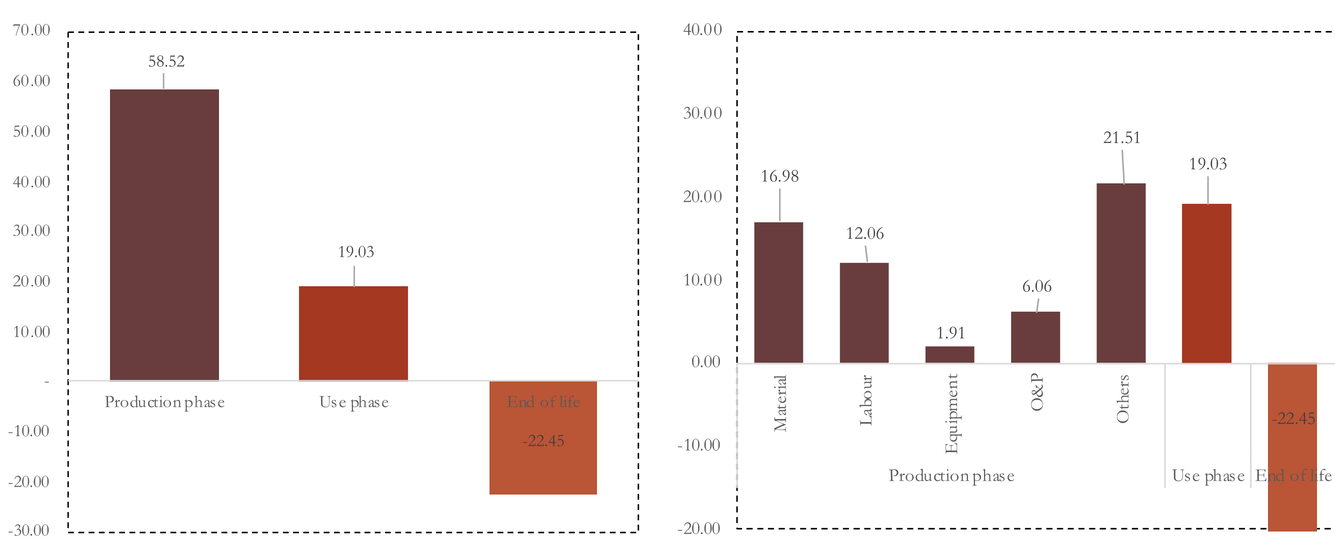

Fig. 9. Consequential LCC

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 dealing 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.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The authors are 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.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.buildenv.2021.107836.

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Nomenclature

Pc_a: total production cost - attributional ($)
e: engineering design cost ($)
s: site work cost ($)
c_i: construction cost of each material ($)
f: finishing cost ($)
pl: plumbing cost ($)
me: mechanical and electrical cost ($)
mc_i: material cost ($)
lc_i: bare labor cost ($)
ec_i: bare equipment cost ($)
o_i: overheard cost ($)
Ci: city index
Pc_q: total production cost - consequential
PV: present value
mcf_i: material $\text{cost}_{\text{year n in future}}$
lcf_i: labor $\text{cost}_{\text{year n in future}}$
ecf_i: equipment $\text{cost}_{\text{year n in future}}$
r: discounting rate
t: time
U: Total use cost ($)
u_i: use cost ($)
el: electricity cost per $\text{kWh}_{\text{year n}}$ ($/kWh)

ec =: annual electricity consumption (kWh)
uf_n: use cost year n in future ($)
E: Total end of life cost of different material
eo_i: end of life cost $material_i$
eu_i: end of life cost per unit $material_i$
eof_i: end of life cost of $material_i$ in future
B: the total benefit
bf_i: the benefits of re-selling building waste $material_i$ in the future
b_i: the benefit of re-selling building waste materials