Consequential impacts of a net-zero carbon design: life cycle assessment of an active building

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Abstract. Life Cycle Assessment (LCA) is becoming the predominant means for determining if a building design meets a carbon emission target. These target values are set to help building designers meet aspirational net-zero carbon targets. Within LCA, there are two modelling frameworks. Attributional LCA (ALCA) assigns a portion of global emissions to a specific product or process. Consequential LCA (CLCA) assesses the impacts from a market’s response to a change in demand for a product or process. A case study building, located in Swansea, UK, has been assessed to investigate the differences between ALCA and CLCA. The case study building employs: a modular off-site construction building fabric; on-site energy generation; and, on-site energy storage – all strategies that may be adopted at large scale to decarbonise the built environment. Based on global warming potential assessed over a 100-year time horizon (GWP100), the total upfront embodied impacts from CLCA are 19% higher than that from ALCA. Three differences exist within the rank order of building elements. The Frame presented the highest contribution to the GWP100 within the CLCA results, whereas External Walls contributed the most within the ALCA results. The differences arise mostly from how electricity production is modelled within attributional and consequential datasets and whether substitution or cut-off are used within the background processes. CLCA can capture the environmental impacts of decisions taken to create a net-zero built environment. However, CLCA should not be directly compared to ALCA without appreciating and recognising how the methods and scopes differ.

Keywords: Building, Life Cycle Assessment, Consequential LCA, Case Study

1. Introduction

Life Cycle Assessment (LCA) has become the predominant means of quantifying the environmental impacts of products and services. The use of life cycle assessment is standardized by ISO 14040 [1] and ISO 14044 [2], with further requirements for the built environment covered by EN 15978 [3]. Within the field of LCA, there are two main modelling approaches, outlined in Sections 1.1 and 1.2 respectively: attributional life cycle assessment (ALCA) and consequential life cycle assessment (CLCA).

As sectors including the built environment pursue low-carbon futures, LCA has been employed as a means of assessing the environmental impacts of industry activities. LCA results are being used to determine if industry initiatives are reducing carbon emissions when compared against standard practice.
These initiatives will result in changes in demands of products and services. The ways in which markets respond to these changes in demand will result in indirect environmental impacts that are not appropriately captured within ALCA results. CLCA is needed to assess the impacts that result from “small-scale, long-term decisions” [4]. The industry shift to a future net-zero built environment reflects the “accumulated trend” of individual design decisions that will lead to long-term changes in the market [4]. However, CLCA is not well understood by industry and has, thus far, been confined to limited applications within the academic realm [5].

The presented work compares the results of a consequential and attributional life cycle assessment of a building. The purpose of this work is less about the results of a specific LCA, but more focused on how the results from the two methods differ when applied to the same building. The remainder of this paper is organized as follows: Section 2 outlines the LCA goal and scope and provides details about the case study building. Section 3 summarises the results for both the attributional and consequential assessments. The results are compared and discussed in Section 4, with the conclusions and further work presented in Section 5.

1.1. Attributional Life Cycle Assessment
Attributional LCA (ALCA) is the current assessment approach within the built environment. ALCA aims to describe the environmental impacts associated with a product or, for the built environment, a building [6]. ALCA looks at a product in isolation to estimate the share of global environmental impacts that can be assigned to it [4–6]. ALCA considers all processes directly linked to the subject of the study [6]. Therefore, ALCA assesses the impacts that result from exchanges of physical properties, energy or services that are required to produce, consume, use and dispose of the object of assessment [5, 6].

Within the built environment, the environmental impacts of materials and building assemblies are commonly described using Environmental Product Declarations (EPDs). EPDs are produced using ALCA to estimate the environmental impacts of a ‘declared unit’ of product based on average processes. They commonly only report single-point values and do not consider the impacts that would result from a change in demand of the product under study [5, 8]. However, building designers commonly use EPDs to inform design decisions and thus change demand for products across the construction industry. This is a misuse of ALCA, as it ignores the consequences from increasing the demand in one product over others [9].

1.2. Consequential Life Cycle Assessment
In the construction sector, consequential LCA (CLCA) has only seen limited application within academic studies focused on the evaluation between specific materials or building assemblies. CLCA considers the marginal processes that are used to meet a change in demand [7]. Whereas ALCA can be used to determine the environmental impact of a product, CLCA would be used to determine the environmental impact associated with a change in demand for that product [6, 7]. Therefore, CLCA takes into account the market responses to the decision to use a product [5, 10].

Outside of the built environment, the benefits of using CLCA to guide policy and decision making have been highlighted by Plevin et al [10], among others, since the mid-2010s. However, current industry carbon targets for buildings, which chart a path to net-zero carbon buildings, are based on ALCA. Weidema et al. [11] argue that changes need to take place for targets to be met and, therefore, a consequential model should be used to appropriately capture these changes. Additionally, studies by Plevin et al. [10] and Weidema et al. [9] argue that the use of ALCA to support policy can perpetuate the selection of sub-optimal design decisions and ignore consequential impacts that result from decisions made to meet current ALCA targets. Therefore, the continued use of ALCA within the built environment may in fact hinder progress in reducing environmental impacts.
2. **Methods**

The presented work uses a case study building to analyze the differences between attributional and consequential LCAs. This work focuses on how ALCA and CLCA differ when applied to building-level assessments.

### 2.1. Case Study

A building constructed in 2018 in Swansea, UK, and displayed in Figure 1 below, was chosen for the assessment used within the presented work. The building is 376 square metres ($m^2$) net internal area (NIA) and is predominantly used as an office building. The building employs several design strategies to make it “low-impact”, including: an off-site construction modular building fabric; on-site energy generation; and, on-site energy storage. The life cycle inventory for the case study building was prepared using as-built construction drawings and material specifications provided by the building designer and operator. The building is comprised of 12 prefabricated volumetric units that were affixed on-site to form the two-storey building fabric. Prefabricated timber roof trusses were installed on-site to provide the structure for the curved roof. The building has a 22-kilowatt peak (kWp) copper indium gallium selenide (CIS) laminate building integrated photovoltaic (BIPV) array integrated into the roof covering. A 110-kilowatt hour (kWh) lithium iron phosphate (LFP) battery provides on-site energy storage capacity for the building. The on-site energy generation and energy storage capabilities, coupled with the ability to export to the grid, enable the building to serve as an “Active Building” [12].

![Figure 1. Overview of case study building.](image)

### 2.2. LCA Goal and Scope

In order to compare the ALCA and CLCA appropriately, the scope of the assessments have been aligned, as presented in Table 1 below. The assessments are limited to the life cycle stages that are associated with material production, transportation, and construction. These life cycle stages are often referred to as the upfront embodied impacts and defined as A1-A5 by EN 15978 [3, 13]. Since the building uses a modular construction, the A4 (transportation) and A5 (construction stage) impacts have been reported as one value to represent the total impacts of constructing the modules offsite, transporting to site, and finishing the building onsite. The impacts associated with A4 and A5 have been calculated based on the method presented by Quale et al. [14] that has been adjusted to reflect transportation distances for locally constructed building modules.

The goals for the ALCA and CLCA, as listed in Table 1, have been developed to allow for a meaningful comparison of results, while acknowledging that the assessments seek to answer fundamentally different questions. The LCA models have been developed using ecoinvent 3.6 [15] background datasets with the ReCiPe 2016 Midpoint Heirarchist [16] impact assessment method. The hierarchist assessment method was chosen for this assessment as it calculates climate change for a 100-
year timeframe and characterises 207 greenhouse gases, as outlined by the 5th Intergovernmental Panel on Climate Change (IPCC) Report, within the calculation \[16, 17\]. The presented analysis is restricted to Global Warming Potential (GWP) assessed over a 100-year time scale [GWP\(_{100}\)] to enable a detailed comparison of the background processes that contribute to the ALCA and CLCA results. The focus on GWP\(_{100}\) aligns this work with current industry policy and national carbon reduction targets.

\[\textbf{Table 1. Goal and Scope for ALCA and CLCA.}\]

| Elements of Study                        | ALCA                                      | CLCA                                      |
|-----------------------------------------|-------------------------------------------|-------------------------------------------|
| Background Dataset                      | Cutoff ecoinvent v3.6                     | Consequential ecoinvent v3.6              |
| Goal of Study                           | Quantify the environmental impact of the building’s design based on average unit processes | Quantify the environmental impacts from the changes to the global markets that result from the building being constructed |
| Impact Assessment Method                | ReCiPe 2016 Midpoint Heirarchist          |                                           |
| Life Cycle Stages Scope                 | A1-A5 (Upfront Embodied Impacts)         |                                           |
| Scope of Building Elements              | 1 – Substructure                          | 3 – Internal Finishes                     |
| Included                                | 2 – Superstructure                        | 5 – Building Services                     |

The same life cycle inventory, i.e. the quantities and material specifications for the case study building, has been used as the foreground data for both ALCA and CLCA models. For the presented study, “market for” processes with a global representativeness have been chosen to ensure the two models have the geographic and technological representativeness matched to the greatest extent for the chosen background processes. Therefore, the foreground systems are consistent across both models, while the different background systems enable a comparison between ALCA and CLCA to be made. The consequential ecoinvent dataset has been made to reflect the impacts of “small-scale, long-term decisions” \[4\]. As argued by Weidema et al. \[4\], the consequential ecoinvent dataset is also appropriate for determining the impacts from “small, short-term decisions” as these decisions contribute “to the trend in market volume”. Therefore, by assessing one building with the consequential ecoinvent, the CLCA quantifies how the individual design, material selection and construction decisions all contribute to the collective trend within the built environment.

3. **Results**

The embodied impacts for the case study building are reported in terms of kilograms of carbon dioxide equivalence per square metre of net internal area [kgCO\(_2\)/m\(^2\)] and are summarized in Table 2. The breakdown of GWP\(_{100}\) impacts by life cycle stage presents the same rank order for both CLCA and ALCA results. The breakdown of A1-A3 impacts is further investigated in Section 3.1.
### Table 2. A1-A5 GWP \(_{100}\) Results

| Life Cycle Stage | ALCA [kgCO\(_2\)/m\(^2\)] | CLCA [kgCO\(_2\)/m\(^2\)] | % difference (CLCA > ALCA) |
|------------------|--------------------------|---------------------------|-----------------------------|
| A1-A5 Total      | 503.7                    | 597.6                     | 19%                         |
| A1-A3            | 447.1                    | 552.7                     | 24%                         |
| A4-A5            | 56.6                     | 45.0                      | -21%                        |
| Energy Use       | 44.6                     | 32.7                      | -27%                        |
| Materials        | 8.9                      | 9.1                       | 2%                          |
| Material Transport | 1.6                    | 1.8                       | 12%                         |
| Waste Management | 1.5                      | 1.4                       | -6%                         |

#### 3.1. Building Element Contribution Analysis

The largest proportion of the A1-A3 impacts is associated with the building’s superstructure, with external walls and frame being the largest contributors, followed by building services, substructure and internal finishes. Figure 2 presents the contribution analysis for the A1-A3 GWP\(_{100}\) results. The contribution analysis is based on the building element classifications from the Royal Institute of Chartered Surveyors (RICS) new rules of measurement (NRM) [18]. The CLCA results range from 84% to 210% of the ALCA results for the individual building elements reported.

![Figure 2. Comparison between ALCA and CLCA GWP\(_{100}\) results](image-url)
‘2.1 Frame’ presents the largest difference in magnitude between the ALCA and CLCA models. The structural frame of the building is made of hot and cold rolled structural steel sections. Table 3 compares the rank order of the ALCA and CLCA GWP₁₀₀ based on building element classification. The percentage (%) difference represents how much the CLCA results differ when compared to the ACLA results. As seen in Table 3, the frame is the largest contributing building element to the total GWP₁₀₀ within the CLCA model, whereas the external walls presented the largest contribution to the GWP₁₀₀ within the ALCA model. Additionally, the CLCA results place the substructure above the electrical installations and the water installations above the wall finishes in terms of rank order.

There are also three differences within the rank order for GWP₁₀₀ impact when compared by building sub-element classification. Within the consequential model, ‘2.5.1 External Walls above Grade’ has a higher GWP₁₀₀ than ‘5.8.5 Local Energy Generation’. Additionally, ‘2.5.3 Solar/Rain Screening’ has a higher GWP₁₀₀ than ‘1.1.1 Standard Foundations’ and ‘5.7.1 Central Ventilation’ has a higher GWP₁₀₀ than ‘2.6.1 External Windows’ within the consequential model.

| Building Element Classification | Rank Order | % Difference |
|---------------------------------|------------|--------------|
| 1.1-Substructure                 | 4          | 3            | 17%          |
| 2.1-Frame                        | 2          | 1            | 82%          |
| 2.2-Upper Floors                 | 9          | 9            | 110%         |
| 2.3-Roof                         | 5          | 5            | 6%           |
| 2.5-External Walls               | 1          | 2            | 7%           |
| 2.6-Windows and External Doors   | 6          | 6            | 18%          |
| 2.7-Internal Walls and Partitions| 8          | 8            | 32%          |
| 3.1-Wall Finishes                | 11         | 12           | -5%          |
| 3.3-Ceiling Finishes             | 10         | 10           | 18%          |
| 5.4-Water Installations          | 12         | 11           | 65%          |
| 5.7-Ventilation Systems          | 7          | 7            | 36%          |
| 5.8-Electrical Installations     | 3          | 4            | -16%         |

3.2 Analysis of Background Processes

The processes that present large differences between the GWP₁₀₀ impacts for the CLCA and ALCA results are summarized in Table 4. For the purposes of this analysis, results that display a difference of 25% or more in the negative, or 75% or greater in the positive are chosen to represent those processes with “large differences” between the ALCA and CLCA results.
The electricity, medium voltage – GB process presents the largest negative difference between the ALCA and CLCA results. The lower GWP$_{100}$ impacts associated with the electricity production in the CLCA model was the cause for the lower GWP$_{100}$ impacts for the A4-A5 life cycle stages reported in Table 2. The differences between the background systems for the electricity, medium voltage - GB process are further discussed in Section 4.1. The differences between the ALCA and CLCA for the sawnwood, beam; sawnwood, board; steel, low-allowed hot rolled; steel, low-alloyed; particle board, outdoor use; particle board, indoor use are all discussed in Section 4.2.

Gypsum fibreboard and Light clay brick resulted in small increases for ‘2.7.1 Walls and Partitions’ and ‘2.5.1 External Enclosing Walls above Grade’, respectively, and are not discussed further in this paper due to their minimal use in the building. There were two differences in how the background processes were selected within the ALCA and CLCA models: particle board is classified for indoor and outdoor use within the ALCA dataset whereas it is represented by one process within the consequential dataset; copper was modelled as copper-rich materials within the consequential model. These two differences were not seen to lead to significant influences within the results other than those pertaining to the modelling differences for particle board as discussed in Section 4.2.

### Table 4. Processes that present large differences between ALCA and CLCA GWP$_{100}$ results

| Unit Process                        | % of total ALCA | GWP$_{100}$ ALCA | GWP$_{100}$ CLCA | Reference Flow | % difference |
|-------------------------------------|----------------|------------------|------------------|----------------|--------------|
| Polyurethane, rigid foam            | 4%             | 5.97             | 4.48             | kgCO$_2$e/kg   | -25%         |
| Photovoltaic laminate, CIS          | 10%            | 114.7            | 80.9             | kgCO$_2$e/m$^2$| -29%         |
| Sawnwood, beam, softwood, dried (u=10%), planed | 1%             | 100.5            | 53.3             | kgCO$_2$e/m$^3$| -47%         |
| Sawnwood, board, softwood, dried (u=10%), planed | 1%             | 124              | 65.5             | kgCO$_2$e/m$^3$| -47%         |
| Electricity, medium voltage - GB    | 3%             | 0.38             | 0.03             | kgCO$_2$e/kWh  | -92%         |
| Steel, low-alloyed, hot rolled      | 9%             | 1.88             | 3.44             | kgCO$_2$e/kg   | 83%          |
| Steel, low-alloyed                  | 8%             | 1.61             | 3.08             | kgCO$_2$e/kg   | 91%          |
| Particle board, outdoor use         | 2%             | 383.7            | 783.4            | kgCO$_2$e/m$^3$| 104%         |
| Particle board, indoor use          | 1%             | 372.3            | 783.4            | kgCO$_2$e/m$^3$| 110%         |
| Gypsum fibreboard                   | <0.1%          | 0.30             | 0.75             | kgCO$_2$e/kg   | 150%         |
| Light clay brick                    | <0.1%          | 0.16             | 0.47             | kgCO$_2$e/kg   | 194%         |

4. Discussion

As shown in Figure 2 and Table 3, the A1-A3 CLCA results ranged from -16% to 110% when compared against the ALCA results for individual building element classifications. However, understanding what is driving the differences in results is arguably more important than simply acknowledging that there is a difference. The following discussion has been divided into two sub-sections to further investigate the background processes within the LCA models. Section 4.1 discusses how the different background modelling approaches influence the environmental impacts associated with electricity production. Section 4.2 investigates the role of substitution and cut-off within the investigated processes.

#### 4.1. Electricity Production

The background model structure for the Electricity, medium voltage – GB differs between the consequential and attributional datasets. ALCA uses an annual average generation mix to represent a unit of electricity, which is dominated by natural gas, wind and nuclear. The GWP$_{100}$ for electricity, medium voltage – GB in the ALCA model is 377.2 gCO$_2$e/kWh.
CLCA quantifies the environmental impact that results from how the marginal generation mix responds to a change in electricity demand, as explained by Vandepaer et al. [19]. The make-up of the marginal mix is significantly affected by timeframe, and is typically split into ‘long-run’ and ‘short-run’. The long-run marginal mixes are estimates of the new generators that will be built over many years [20], [21]. This is the approach taken by most CLCAs. Thus, the GWP100 for electricity, medium voltage – GB in the CLCA ecoinvent model is 29.1 gCO2e/kWh, and is dominated by wood (biomass incineration), wind and nuclear in descending order [19].

The actual (long-run) marginal emissions factor for UK electricity in the year the case study building was constructed is 313 gCO2e/kWh as published by the Department for Business, Energy & Industrial Strategy [22], which is over ten times higher than that from the consequential ecoinvent dataset. The disparity in marginal emissions factors highlights the scale at which the UK’s national grid is projected to decarbonize into the future, while also highlighting the importance of understanding how electricity is modelled within the background dataset for LCAs. The choice of marginal emissions factors greatly influences the magnitude of environmental impacts from energy related processes within geographies with decarbonizing electricity networks. Understanding how electricity production is modelled within both ALCA and CLCA background datasets is crucial for interpreting the results from both methods. The appropriate approach depends on the goal and scope of the study and will need to clearly communicated to ensure results can be accurately interpreted and, if appropriate, compared.

The modelling differences for the electricity production background datasets caused the lower CLCA impacts observed for the CIGS photovoltaic laminate and the sawnwood production processes. The electricity production impacts in Germany, China, and North America, among others, were observed to lead to the lower GWP100 impacts within the CLCA results when compared to their ALCA counterparts. Similar to the electricity, medium voltage – GB process discussed above, the differences in the background modelling are associated with the use of long-run marginal plant emissions factors to calculate electricity production impacts within LCAs. Thus, the use of long-run marginal mixes for electricity has a significant effect on results, and should be investigated further to ensure the impacts of upfront material selection in buildings and energy use during construction are quantified appropriately.

4.2. Substitution versus Cut-Off

One of the main differences between how systems are modelled within consequential and attributional LCAs is how co-products are dealt with. Co-products come from processes that create multiple products. Within an attributional modelling approach, co-products are either cut-off from the system boundary of the assessment when they are considered to be a waste by-product of the product being assessed, or the total environmental impacts are allocated between the different co-products when the co-products are seen to have an economic value [23, 24]. By contrast, consequential LCA uses system expansion to capture all the environmental impacts that arise throughout the supply chain and assigns a negative impact (a ‘benefit’), to the co-products that are not the aspect of the supply chain that drives the production capacity [4, 8, 23]. The negative impacts assigned to co-products represent the avoided impacts that would have otherwise taken place to produce these products independently. Ekvall and Weidema [25] state that the use of system expansion is a more complete means of representing the environmental impacts of a system that produces multiple products.

Within the model, system expansion is seen within the background datasets for the sawnwood products (ie sawnwood, board and sawnwood, beam), particleboard, and the steel processes. Sawdust, bark chips and offcuts are co-products of the process used to create sawnwood. These co-products are excluded from the attributional model as they are treated as waste from the sawnwood production. Since the consequential LCA quantifies the total environmental impacts that result from this process, negative impacts are assigned to the co-products that do not influence production capacity in order to balance the fluxes experienced by the environment. Therefore, the incidental production of sawdust, bark chips and offcuts ultimately lowers the environmental impacts associated with the production of sawnwood.

Whereas the production of sawnwood experiences a benefit from producing additional co-products, the production of particleboards is assigned additional environmental impacts within a CLCA. This is
due to the use of wood chips, which exist within a constrained market, to make the boards. The concept of constrained markets is discussed by Ekvall & Weidema [25], in short a constrained market exists when the production of one product is controlled, or constrained, by external factors. Wood chips are produced as a co-product from a multi-product system that ultimately produces sawnwood. Therefore, sawnwood is the determining product and the market for wood chips is constrained by the production demand for sawnwood. As such, an increase in demand for wood chips to produce particleboard will not result in an increase in wood chip production but a decrease in availability of wood chips for other processes [25]. In this case, the increased in demand for wood chips to create particleboard decreases the availability of wood chips that can be used to create energy through incineration and energy recovery. Therefore, the consequential model burdens the production of particleboard with the production of energy from an alternative process. The use of system expansion within CLCA models provides an understanding of how an increase in demand for one product can result in changes within other systems and processes.

The steel processes exhibit a similar difference as that seen in the particleboard comparison. Within the steel processes, the impacts for the use of iron scrap differ between the attributional and consequential datasets. This is a result of the iron scrap being burden-free, i.e. having no environmental impacts attributed to its use, within the cut-off approach used for the attributional model. By contrast, within the consequential dataset, an environmental impact is assigned to the use of iron scrap. Iron scrap is a by-product of steel production. Therefore, an increase in demand for iron scrap is assumed to lead to an increase in steel production as the iron scrap market is constrained by steel production. As such, the consequential dataset models the impacts of steel production that will result from increasing scrap demand. This is another example of how system expansion and cut-off criteria within consequential and attributional models, respectively, can lead to varying results.

4.3. Application of CLCA to Buildings
The application of CLCA has yet to be seen beyond isolated academic studies for the built environment. Since CLCA has yet to see wide-scale use within the built environment, it is appropriate to discuss whether CLCA should be used, and how it should be used, to assess the built environment. As discussed by Weidema et al. [4], the consequential ecoinvent dataset has been developed to assess “small-scale, long-term decisions”, which correspond to Situation B “meso/macro-level decision support” as outlined in the ILCD Handbook [26, 27]. Impact reduction strategies are an example of “meso/macro-level” studies, as these strategies aim to cause changes within the supply chains associated with buildings to ultimately lower the environmental impacts of the built environment. Based on this principle, impact reduction strategies should be developed using a consequential approach. However, from the perspective of the building designer, design decisions for an individual building fall under the “micro-level” (Situation A) [27]. The construction of one building is unlikely to lead to systematic changes within the national grid structure nor the material supply chains that the building interacts with. Weidema et al. [4] argue that the consequential dataset is also applicable to these “small, short-term” decisions as it is the collective impact of these decisions that influence trends within the global markets.

Aligned with the ILCD Handbook, designers can use ALCA to assess the environmental impacts of an individual design [26, 28]. ALCA can accurately quantify the environmental impacts that have occurred if the building is assessed after its completion. This form of assessment would be valuable for reporting purposes but is limited in terms of guiding design decisions. ALCA does not account for material availability and would therefore assume that low-impact material substitutions have an infinite supply. The continued use of ALCA to guide design decisions would allow endless material substitution strategies to be used, rather than focusing on more important strategies such as using less material in the first place. CLCA would promote material efficiency over reliance on constrained resources such as GGBS, fly-ash and scrap steel. As discussed in Section 4.2 the use of materials from constrained markets may not lead to impact reductions and can in fact lead to more environmentally impactful processes taking place.
The use of CLCA within the building design process can provide a better understanding of how design decisions influence other markets. The use of a consequential approach within the building design process would help identify which processes, or design decisions, would lead to net-reductions in environmental impacts and which would result in processes with greater environmental impact supplying the market demand. However, a better understanding of CLCA needs to be distilled to ensure the results from CLCA studies are not directly compared against those from ALCA studies without acknowledging how the studies, and their background considerations, differ.

5. Conclusion
The attributional and consequential assessments produced three differences in rank order of building element classification when compared by their respective magnitudes. Most notably, ‘2.1-Frame’ was the largest contributing building element within the consequential LCA (CLCA) model whereas ‘2.5-External Walls’ was the largest in the attributional LCA (ALCA) model. Based on the comparative LCA, it was seen that life cycle stages dominated by energy reported lower GWP100 whereas life cycle stages dominated by material usage reported higher impacts when assessed using a consequential methodology. The main differences in results depended on whether: (1) the electricity generation is modelled with an annual average generation mix or by a long-run marginal mix, and; (2) whether the model uses a system expansion or cut-off approach. From the comparative study, it was seen that CLCA provides more favourable results for materials that are a part of systems where negative impacts are assigned to co-products produced from multi-product processes. Products that use materials from constrained markets or recycled content exhibit higher impacts in CLCA due to the use of system expansion to identify the substitutions that take place with changes in demand. It is important to note that what may be considered a constrained market in a global context may not represent a local context.

As the study has been limited to the use of global market processes within the consequential ecoinvent, future work should investigate whether the assumptions regarding the marginal suppliers at a global level are appropriate at more disaggregated regional levels, i.e. country- or continent-specific.

The application of consequential LCA to individual buildings should be further developed to ensure the environmental impacts that arise as consequences from design decisions and construction techniques are accurately represented within the CLCA results. The short-term effects of impact reduction strategies and design decisions should be compared against their long-term effects to ensure that the assumption that these short-term effects are negligible is appropriate for the built environment. Additionally, the underlying assumptions regarding marginal processes should be investigated to determine if they are appropriate for use within consequential assessments for the built environment. Consequential LCA should be used to evaluate the environmental impacts of impact reduction strategies to better guide the built environment towards a net-zero future. ALCA provides a useful means for accounting the carbon impacts of a building. It is important to note that the impacts reported from the CLCA, using the current consequential ecoinvent dataset, do not represent the environmental impacts of the building. Instead, the CLCA reports the environmental impacts that result from how markets respond to the changes in demand that are associated with the materials and energy needed to produce the case study building. For the building designer, CLCA provides valuable insight into how their design decisions influence the availability of materials and energy for other processes. However, the results from attributional and consequential studies should not be directly compared without considering how the background datasets are formulated, as these two LCA methodologies seek to answer fundamentally different questions.

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