How to design buildings with Life Cycle Assessment by accounting for the material flows in refurbishment

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Abstract. This paper will analyse and present a detailed overview of ways to design buildings in a circular economy by using Building Life Cycle Assessment and will be based on hundreds of case studies and years of practical experience in the building sector. The theoretical framework is defined by Life Cycle Assessment methodology and indicators and will focus on why performing an LCA is a necessary step to assess sustainable material choices and make design choices that ensure circularity and lower carbon emissions and other environmental impacts through the whole lifecycle of the building. Moreover, the focus will be on integrating Life Cycle Metrics with BIM and other design tools in order to enable making choices in the design stage and taking better decisions on the basis of alternative design suggestions. Finally, the paper will propose actionable, realistic strategies to perform carbon footprint and other LCA-related calculations in a fast, reliable, and cost-effective way. The paper will cover the whole lifecycle of a building, with a strong emphasis on disposal and reuse in a cradle to cradle perspective.

Keywords: life-cycle assessment, low-carbon design, decarbonization, circularity.

1. Introduction
The building industry is one of the largest contributors to greenhouse gases in the world with close to 40% of the total annual share of emissions [1]. And, with estimated population growth and its resulting urbanization [2], it is reasonable to foresee the growing demand of resources by the building industry. If this demand is met solely by further material extraction, it will lead to further environmental degradation. Thus, the transition to a circular economy, where materials are kept inside the production loop to reduce further material extraction is very important.

The Ellen MacArthur Foundation, promotes the transition to a circular economy from our current linear extract-user-dispose economic model, has developed an action framework: ReSOLVE. This framework includes six (6) action areas to promote this transition: Regenerate, Share, Optimise, Loop, Virtualise, and Exchange [3]. Among these actions, “optimise” system performance requires to develop and quantify parameters for the evaluation of building options. With a growing threat of climate change, embodied carbon is an important parameter to include in this discussion. For instance, a recent study
shows that the circular economy has the potential to reduce carbon emissions by 56% in the European Union by 2050 through material recirculation and efficiency, and new business models [4].

This paper focuses on how life cycle assessment (LCA) can be used to optimise decision-making by providing quantifiable environmental impact data on material use in a building’s life-cycle. The results show the impact to guide material selection and design decisions. This information will help understand what elements of a building provide opportunities for a circular economy approach based on their material flow, and help guide future design decisions and material selection.

2. Building elements in time and the circular economy

The circular economy (CE) is “…an alternative to a traditional linear economy (make, use, dispose) in which we keep resources in use for as long as possible, extract the maximum value from them whilst in use, then recover and regenerate products and materials at the end of each service life.” [5] (WRAP)

When we consider that the average age of the building stock is over 60 years [6], it is difficult to consider buildings more than repositories of materials. Yet, buildings are not static and respond to market demands for renovation or change. For example, demands to improve energy performance in buildings and reduce energy use are a major focus of policy across Europe and have major implication in material use for buildings [7].

Other market demands tied to function and aesthetic cannot be disregarded either. Frank Duffy argued that buildings are “…several layers of longevity of built components” [7]. This introduced the idea that building elements changed at different rates based on their function. Originally, Duffy included four layers: shell, services, scenery, and set. Later Brand [8] expanded these into “six shearing layers of change” including the original four (renamed) structure, services, space planning, and stuff, adding site and skin. Each layer has an average service life based on material durability, technological life, and owner’s preference (see Figure 1). Most recently, Arup expanded this into a seventh layer to include (urban) system [9].

Figure 1. Shearing (building) layers of change. Conceptual breakdown of different rates of change in building components [8].

To illustrate this concept, consider that building elements that will have a more frequent change, repair, or replacement are found in the building skin, its services, and its space plan. For instance, the skin can be replaced every 20 years to keep up with aesthetic trends and/or to repair the wear of the façade elements. Replacement of building services, mechanical, plumbing and electrical systems will depend
on use and internal spatial rearrangement. So, these can be tied in to space planning. Also, the space plan can have the most variable service life, as commercial interiors can change every three years and the most conservative residential spaces can take up to 30 years. Quantifying these elements and the impacts associated to these materials is important, as this will determine material flows with their corresponding embodied carbon and other environmental impacts.

3. Life cycle assessment as a tool to measure circularity

Life cycle assessment is a methodology that measures the environmental impacts of associated with products and systems, and it is widely used for whole buildings. For the construction industry and buildings, the application of the methodology follows standards EN-15840/15978 and ISO-14040/14044/21930.

The life cycles stages of the analysis are defined and organised according to the standard EN-15978 and are shown in Figure 2. The defines the use of 24 environmental impact categories. Yet, for purposes of this study, only Global Warming Potential (GWP) will be analysed. GWP is measured in Kg of CO2-eq and represents greenhouse gases (GHG) a measure associated with climate change.

In a whole building LCA, impacts occur along the production of building materials, the construction process, the use or operation of the building, and finally, at its end of life. So, when we apply the concept of the building “shearing layers of change”, we can measure the impact that certain building elements will produce based on how often they will be replaced. These impacts will be accounted for in modules B1-B5 based on the type of impact. For example, the “structural layer” has an expected life of more than 60 years and will only be accounted once in an analysis with a similar study period. Yet, the building’s “skin” or façade will most likely be replaced every 20 years. Thus, the embodied impact of the “skin” will be accounted at least three times: at its construction (year 0) and two replacements (years 20 and 40) before the expected end-of-life of the building at year 60. And, as mentioned earlier, the replacement of these materials quantities is irrespective of the materials technical service life, as the changes to these building elements are associated with owner’s decisions.

As a consequence, building materials associated with these building “layers” will determine material flows within a building’s life cycle, the environmental impacts of replacing these elements, and provide opportunities for the improvement of materials used in the building.

4. Design buildings in a circular economy

To guide the building design process, it is important to measure the impacts of the available options to the design team. This allows to choose the optimal solution based on the embodied impact of the building.
component. This requires to design with the rate of change of building components in mind. Also, it is important to have access to data for timely analysis during this process. And, it is important to develop benchmarks based on historical data to quantify the potential of improvement.

These three actions areas can be summarised into design strategies, leverage of technology for easy access to material data, and the development of benchmarks to set improvement goals.

4.1. Design strategies for the circular economy
Based on the different rates of change of building components, designers can focus on three main areas to minimize embodied impacts. These strategies are:

4.1.1. Design for change. Interior space plan, services, and the building skin, will change in time to respond to users’ functional needs. Some of these elements can be designed for easy disassembly and material recovery.

4.1.2. Design for resource use efficiency. Even materials with long service lives such as structural systems can be made very efficiently: thinner floor slabs, optimal structural frames, and pre-fabricated elements, so as to minimized the amount of material that will wasted in the production and to reduce the amount of material that will be part of the building.

4.1.3. Use materials with low-embodied carbon and/or recycled content. Irrespective of the rate of change of the building component, it is good practice to use low-embodied carbon materials. Structural systems can benefit of recycled content to reduce their footprint. For example, reinforced concrete can use cement substitutes and recycled steel to reduce their carbon footprint. Also, those materials that will replaced more frequently because of renovation/refurbishment could include recycled content or renewable materials to minimize their accumulated embodied impacts in time.

4.2. Leverage Building Information Modelling (BIM) for timely access of building material data
Building design is a complex process involving many disciplines. The documentation created and used during this process can later be used for building operations management. As virtual building representations, BIM can be used for material quantity take-off for estimating purposes. Thus, they are also a good source of material quantity data that can be extracted to perform an LCA at any point in time. So, during the design process, a team can use BIM to extract material quantities and create impact scenarios based on LCA calculations.

4.3. Develop embodied impact benchmarks for buildings
Understanding the impact on embodied carbon by the rate of change in building components can help refine the development of benchmark data for buildings. This information can be used to set improvement goals and/or focus design/procurement efforts. These efforts can then be evaluated both from an environmental, social and financial perspectives via cost-benefit analysis.

5. Case study
To illustrate the impact of the rate of change in building components, three material use scenarios for a conceptual building are analysed. The conceptual design data is generated with Carbon Designer, a building design tool developed in One Click LCA. This tool was developed from a sample of calculated buildings’ LCA. The scenarios explore the impact of the service life of building elements on the building’s embodied carbon.

This study was performed using One Click LCA, a software designed for whole building LCA. The case study building was generated using the Carbon Designer tool. This tool was designed using historical data from several building LCA calculated with One Click LCA. The input parameters are building area (4000 m2), number of floors (4), and defining the main material of the structural frame
The output of Carbon Designer is a conceptual building with material quantities. The embodied carbon of this building type is calculated and divided by building element; see Figure 3.

Figure 3. Embodied carbon breakdown by element of conceptual building (307 CO$_2$-eq kg/m$^2$) [11]

Carbon Designer uses material industry averages and/or EPD found in One Click LCA’s database. These materials include the option to use their technical service life in the LCA calculations or edit that parameter to reflect changes in the frequency of material replacement. The model includes only material data for structure, skin, and space planning layers. A summary of the impacts per building element/layer for the Baseline building is presented in Table A1 in the Appendix section.

This study includes three scenarios. The first scenario considers the use of the technical service life for the building materials used in this project and represents the “baseline” of this study. The second scenario (SKIN20) assumes that the owner changes the building skin or envelope every 20 years. The third scenario (SPACE10) represents interior refurbishment due to changes in space planning every 10 years. In the Appendix, Table A1 classifies the elements replaced in scenario SKIN20 in layer “Skin”, and the elements replaced in scenario SPACE10 are classified under layer ”Space”. In scenarios SKIN20 and SPACE10, the materials were replaced with their equivalent material, and their impacts added to modules B4-B5 in the analysis. The results are summarized in Tables 1 and 2 and shown in Figure 4.

6. Results.

The embodied carbon breakdown of the “Baseline” building includes approximately 58% of its impacts in the structure, 23% in its skin, and 18% in its space plan; a detailed breakdown of the material components for the “Baseline” is shown in Table A1.

The embodied impacts of the three scenarios is presented in Table 1. The modules and life cycle stages reported follow the EN-15804 standard as described in Figure 2. Changing the service life of the skin to 20 years from the technical life used in the baseline building shows an increase of 6%. The elements changed include roof tiles, the insulation of the external walls and brick cladding, and windows and external doors.

Similarly, renovating the space plan every 10 years increased by close to 67% the total embodied carbon. Renovation of the space plan included changes to the internal partitions, floor and ceiling finishes. Also, increases in material use in Kg by scenario are shown in Table 2.

In addition, the impacts of the construction materials (A1-A3) represent close to 86% of total embodied impacts in the Baseline scenario. Yet, this value goes down to 81% in SKIN20 and 51% in SPACE10 as the impacts from “maintenance and material replacement” (B4-B5) increases in the two scenarios. In particular, the impact of B4-B5 is closely equal to the initial material impacts (A1-A3) in the SPACE10 scenario.
Table 1. Changes in Global Warming Potential by component service life scenario.

| Module | Description                          | Baseline | SKIN20 | SPACE10 |
|--------|--------------------------------------|----------|--------|---------|
| A1-A3  | Construction materials               | 1.17E+06 | 1.17E+06 | 1.17E+06 |
| B4-B5  | Maintenance/material replacement     | 1.47E+05 | 2.31E+05 | 1.06E+06 |
| C1-C4  | Deconstruction                       | 4.47E+04 | 4.47E+04 | 4.47E+04 |
| Total  | (Kg of CO2e)                         | 1.36E+06 | 1.45E6  | 2.27E6  |
|        | (+6.1%)                              |          | (+66.6%)|         |

Table 2. Changes in Kg of material

| Module | Description                                      | Baseline | SKIN20 | SPACE10 |
|--------|--------------------------------------------------|----------|--------|---------|
| A1-A3  | Construction materials                           | 4.96E+06 | 4.96E+06 | 4.96E+06 |
| B4-B5  | Maintenance/material replacement                 | 6.38E+04 | 2.09E+05 | 1.96E+06 |
| Total  | (Kg of material)                                 | 5.02E+06 | 5.17E+06 | 6.92E+06 |
|        | (+2.9%)                                          |          | (+37.8%)|         |

Figure 4. Embodied carbon by building layer change scenario. [11]
7. Closing remarks
This case study shows the importance of considering the impact of material replacement during the life cycle of a building based on expected changes in building use. It supports the argument that analysing building’s embodied carbon need to consider changes in material components in time. The impact of space plan, a layer associated with finishes and service systems needs to be studied in greater detail. It also opens the possibility of developing products that could lower the impact of increase in material replacement by including recycle content, renewable materials, and/or could be reused in other structures.

The aim of this paper was to show that the refurbishment/renovation of the building skin and internal spaces adds considerable resources and impacts in the building’s life cycle. These material flows need to be included as an important part of a circular model for buildings. And, should be the subject of further research.

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### Appendix A

Table A1. Carbon breakdown by layer of the “Baseline” building

| Building elements | Amount | Tons CO$_2$e | Carbon Share | Layer |
|-------------------|--------|-------------|--------------|-------|
| Foundation        | 4000 m$^2$ | 32 tn       | 2.90%        | Structure |
| Ground slabs      | 1000 m$^2$ | 140 tn      | 12.00%       | Structure |
| Floor slabs       | 3000 m$^2$ | 271 tn      | 24.00%       | Structure |
| Columns           | 345 m    | 16 tn       | 1.40%        | Structure |
| Beams             | 576 m    | 102 tn      | 9.00%        | Structure |
| Balconies         | 40 m$^2$ | 2.9 tn      | 0.25%        | Structure |
| Staircases        | 14 m    | 11 tn       | 0.99%        | Structure |
| Roof slab         | 1000 m$^2$ | 79 tn       | 7.00%        | Structure |
| Roofs             | 1000 m$^2$ | 129 tn      | 11.00%       | Skin |
| External walls    | 1686 m$^2$ | 83 tn       | 7.40%        | Skin |
| Cladding          | 1686 m$^2$ | 40 tn       | 3.60%        | Skin |
| Windows           | 800 m$^2$ | 1.7 tn      | 0.15%        | Skin |
| External doors    | 20 m$^2$ | 11 tn       | 0.99%        | Skin |
| Internal walls    | 4260 m$^2$ | 148 tn      | 13.00%       | Space |
| Floor finishes    | 3778 m$^2$ | 40 tn       | 3.60%        | Space |
| Ceiling finishes  | 3778 m$^2$ | 18 tn       | 1.70%        | Space |