Assessment of the circularity and carbon neutrality of an office building: The case of't Centrum in Westerlo, Belgium

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Assessment of the circularity and carbon neutrality of an office building: The case of ’t Centrum in Westerlo, Belgium

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Abstract. Circular building design is a concept that is gaining great interest from architects, construction professionals, and their clients but is still rarely adopted in practice. One of the earliest design decisions architects and developers should make to design a circular building is to determine the building’s construction system. The choice of constructive and structural systems, such as columns, beams, and slabs, is crucial to upgrade the reuse cycles in the future. Flexible construction systems can make it easier to dismantle the structures and recover, upgrade, modify, or transform building materials. Therefore, this paper assesses the carbon emission impacts of two construction systems for an office building in Belgium using life cycle assessment (LCA) and circularity criteria. One-Click LCA software was used for the calculations. Parametric analysis took place for two construction systems scenarios involving a steel structure and a timber structure. Life Cycle Assessment and comparisons of the various construction systems are made based on ISO 14040, 14044, and CEN/TC 350 standards with a focus on carbon neutrality. The results show that using local plant-based materials such as wood can drastically reduce office buildings’ carbon footprint. Based on the sensitivity analysis results, the overall global warming potential impact is mostly sensitive to the construction material’s weight and reuse and dismantling ability. This paper provides a better understanding of building structural systems; to inform architects about the circularity potential of different construction systems.

1. Introduction

The circularity paradigm implicates a new era of building design that has been of great interest to architects, construction professionals, and their clients [1]. However, the paradigm is still not common, although it is present in practice and research [2,3]. Therefore, the paper aims to learn from a real case study of a circular office building under development. The case of ’*t Centrum* in Westerlo, Belgium, is considered a pioneer project in circularity. The building is designed to last for 20 years and is designed, constructed, and operated within an experimental setting that allows the building’s dismantling and reconstruction every five years. In this context, this study will answer three main questions:

- How can we evaluate the circularity of the building?
- What is the most sustainable structural system regarding carbon neutrality and circularity?
- To what extent is *’t Centrum* project circular and carbon neutral?

The study’s scope is limited to the structural system and materials choice of *’t Centrum* building as a case study. Then, a parametric analysis will be performed for alternative construction materials (steel vs. timber). The research findings are used to inform architects about the circularity potential of different construction systems and their environmental impact.

2. Literature Review

The emergence of the building circularity concept is strongly related to environmental assessment methods applied in the construction industry. The proliferation of environmental product declarations (EPDs) and the introduction of the so-called "Material Passports" change the way designers materialize their buildings. The emergence of life cycle assessment tools and software allows for full building inventories and total building environmental evaluations. For instance, Heisel et al. [2] described the Madaster platform, storing the materials' details and assessing the building's circularity [4].

The climate emergency and energy transition goals are forcing the construction sector to embrace low-impact buildings. Several studies tried to associate energy neutrality targets with building materials emissions in embodied energy and embodied carbon. However, very few countries addressed embodied carbon emissions in their Energy Performance of Buildings Directive (EPBD) regulations [5]. The introduction of the EPDs in 2018 for building materials in most EU member states was one of the first large-scale steps to quantify buildings' carbon emissions [6]. But, the use of EPDs is still voluntary in most countries without any emission thresholds.

In parallel, the building circularity concept is gaining more and more attention, despite the few studies that address the concept and definition [7]. Several authors like Durmisevic and [8] Antonini et al. [9] tried to develop reliable indicators for circular buildings' reversibility and durability features. Cottafav et al. and Attia addressed the gap between embodied impacts and architectural and structural design aspects [1,3]. The difficulty of defining or building a circular building based on circularity indicators and technologies to enhance buildings' service life while closing material loops is still challenging [10].

The short review above confirms a need to investigate both concepts (carbon neutrality and circularity) and the need to couple them. Our case study approach aims to achieve that.

3. Methodology

The case study was chosen because it represents a circular office building that will be dismantled every five years over twenty years. The project's nature and brief make it one of the unique endeavors to learn about regenerative building's circularity. The case study's evaluation is focused mainly on the building structure during the construction, operation, and demolition phase. A parametric analysis took place for two different construction systems, namely steel and timber constructions. The analysis process was performed in two steps:

- First, perform a detailed LCA for the environmental impact of the two structural materials focusing on their carbon emissions.
- Second, perform parametric analysis for the project construction system and also for other different construction systems.

A site visit was conducted to learn about the project details from the design team and get acquainted with the project delivery process and design brief.

3.1. Life cycle standards and system boundary

The building industry accounts for almost 40% of the total carbon emissions directly responsible for climate change and global warming [11]. This study included a life cycle assessment analysis for the materials and resources. A study pointed out that embodied energy can be up to 60% of the building life cycle [12]. A life cycle assessment to compare the environmental impact and CO_2 emissions of the structure has been done according to ISO 14040 and 14044 standards [13,14,15]. According to EN 15978 life cycle stages of the building divided into five stages: product stage (raw materials supply, transport, and manufacturing), construction stage (transport and construction installation on-site process), use stage (maintenance, repair, and replacement, refurbishment, operational energy use: heating cooling, ventilation, hot water and lighting and operational water use), end-life stage (deconstruction, transport, and disposal), and reuse stage (recovery and recycling potential) [16] (see Figure 1).

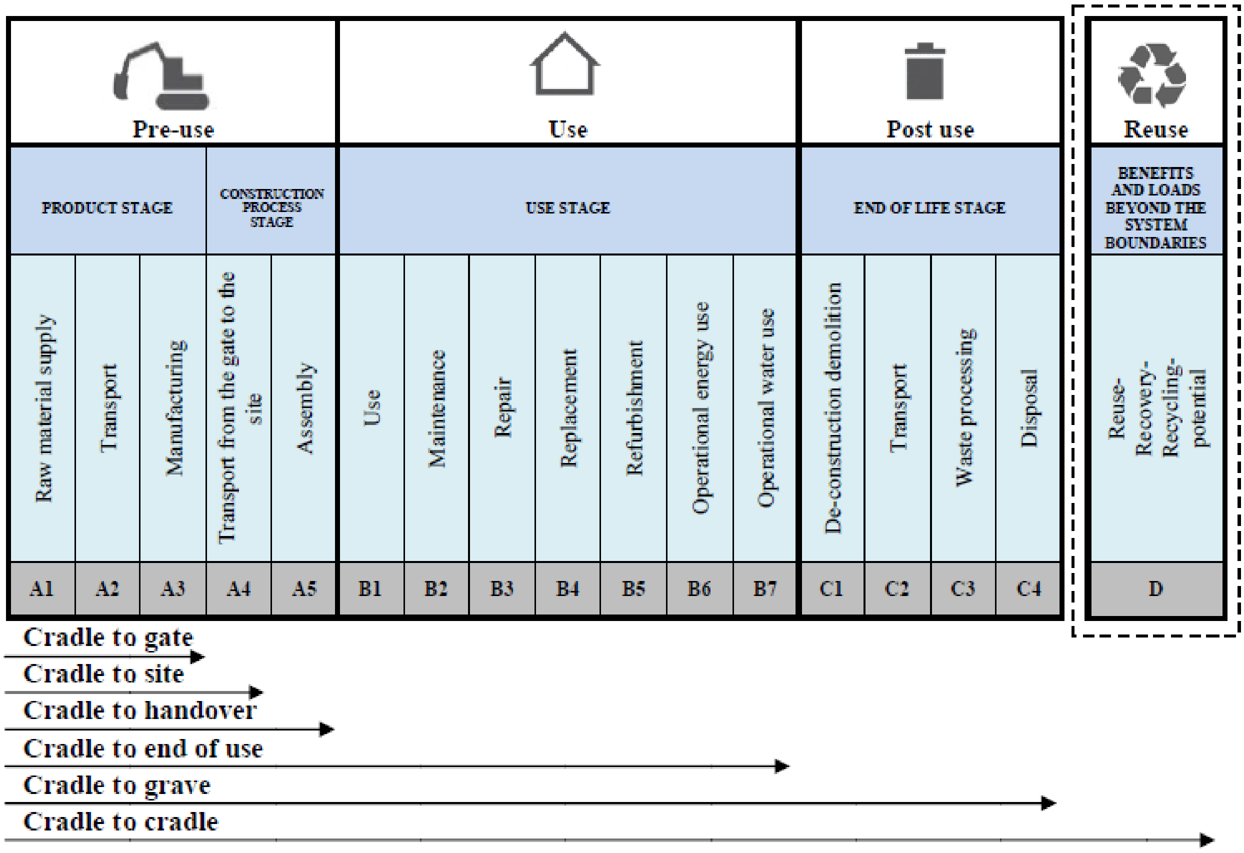

Figure 1. Description of the stages during the buildings' life, according to EN 15978.

3.2. One-Click LCA software

One-Click LCA [17] is a life cycle assessment software that allows calculating life cycle assessment, life cycle costing, carbon footprint, and other environmental impacts. It is compliant with more than 40 Green Building certification schemes around the world. LCA considers several environmental impacts, including carbon footprint over the whole life cycle, which makes achieving real sustainability possible. One-Click LCA allows easy-to-use, entirely browser-based sustainability assessment for building projects and does not require LCA expertise from its users [18].

In terms of its built-in database, One Click LCA integrates data from nearly all of the available environmental product declaration EPD worldwide, including Belgium, of course. Customizations of the energy mix of the building are possible based on the project's geographical location.

3.3. Functional unit, year, tools, and indicators

The functional unit to compare both buildings was 1kg/year. For the calculation model, the occupancy for 5 years to each phase of the project. The cradle to grave LCA was made based on collected data from the available information on the official websites of Kamp C and other consortium members of *'t Centrum* project. To calculate the environmental impact resulting from the biogenic CO_2 circulation, an approach of CO_2 storage in the buildings for five years and 20 years. According to Global Warming Potential (GWP), the LCA indicators were summarized as an indicator of greenhouse emissions, including biogenic carbon dioxide. Biogenic CO_2 is captured in biomass during a plant or tree's growth and, consequently, in a biologically-based product [1].

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3.4. Life cycle inventory

An inventory has been created, which referred to building materials of the five life cycle stages mentioned earlier, and according to EN 15978 [16]. The drawings were used to show the main difference between the structural system for the case study and the other structural system prepared, especially concerning materials, composition, and the various carbon emissions resulting from them.

By inspecting the project's structural system materials as shown in lists data concerning the weight of significant building materials (see Table 1 & Figure 2), we can see that timber is dominating the total building weight reaching almost 73% of the weight share. All the columns, beams, and the slabs of the ground, floors, and roof were made in timber. Cellulose insulation is the second most common material reaching almost 14%. It was used between the floor layers. In contrast, the concrete used in the building's foundation block reaching nearly 8% of the weight share.

We contacted some companies specialized in the manufacture of materials. We were provided with the weights of the different elements according to the design concept used in constructing the project and the steel structure proposal [19,20,21,22,23].

Table 1. Weight share of material groups in the analyzed two types of structure.

Building Material Category	Timber structure		Steel structure	
	Amount [kg]	Share [%]	Amount [kg]	Share [%]
Pine timber (structure)	185005	73.5	×	×
Steel (structure / foundation bars)	1750	0.7	271576	27.5
Concrete (foundation / floors)	22000	8.74	682300	69
Cellulose / Rockwool (insulation)	36600	14.5	27450	2.77
Polyurethane & rubber (waterproof)	525	0.21	525	0.053
Recycled polyester(protective layer)	74	0.03	74	0.007
High-density polyethylene (drainage HDPE)	147	0.06	147	0.015
Polyester fibers (geotextile)	73	0.03	73	0.007
Polyethylene(filter layer)	25	0.01	25	0.002
Soil	5490	2.18	5490	0.56

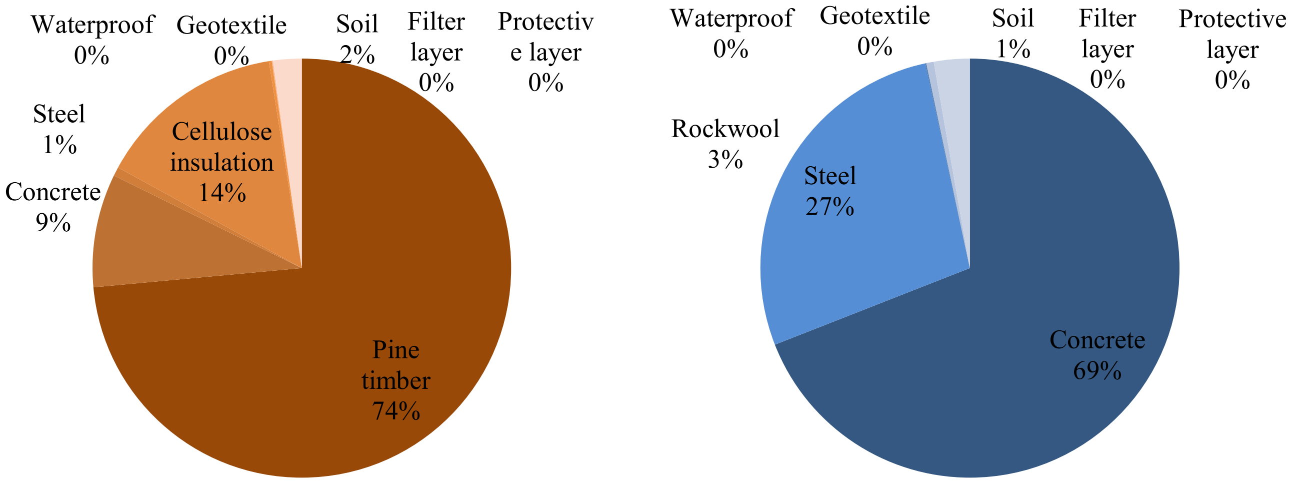

Figure 2. Weight share of the two types of structural materials percentage (timber & steel)

3.5. Operation carbon emissions

According to Flanders requirements in 2020, the maximum energy-efficient (E-peil) for office buildings must be 55, and in 2021 the maximum E-peil will be 50 [24]. So this project should comply with these zero energy use requirements [25].

Use stage B1- B7: This stage should capture the carbon emissions associated with the activities and operation of the project from the end of construction stage to the end-of-life stage (see Figure 1) includes the following:

1. In-use emissions B1: This covers the carbon emissions from products and materials (e.g., refrigerants, paints, carpets) in the building's regular operation during the use stage.
2. Maintenance emissions B2: The carbon emissions of all maintenance activities, including cleaning and the carbon impacts from energy and water use associated to these activities.
3. Repair and replacement emissions B3–B4: This stage involves any emissions arising from the repair and replacement of relevant building components in line with realistic scenarios developed from the LCA. These should capture all emissions associated with the supply of new products.
4. Refurbishment emissions B5: The detailed LCA should incorporate any known refurbishment scenarios going forward in the building. This module would cover a planned future extension or change the spatial function of the building.
5. Operational energy use B6: All operational emissions from building-related systems should be included as assessed at the design stage. This should cover regulated energy consumption, including heating, cooling, ventilation, domestic hot water, lighting and auxiliary systems as projected over the project's life cycle, and all energy generating units such as solar thermal panels, etc. Data for this section is usually provided by the services consultants and should include an estimate of unregulated energy use.
6. Operational water use B7: All carbon emissions relating to operational water consumption, both supply and waste, throughout the building's life cycle should be included [26].

This study considers future uncertainty and realistic scenarios developed for the maintenance, repair, replacement, refurbishment, and building operation. This study based on the available information on the Kamp C website [27], and there is no technical information related to this stage.

3.6. Limitations

This study excluded water installations and sewage installation, including roof gutter systems excluded from the study. Also, the damage categories were excluded - human health, ecosystem quality, climate change, resources, and impact categories(carcinogens, on-carcinogens, respiratory inorganics, ionizing radiation, ozone layer depletion, respiratory organics, aqua terrestrial ecotoxicity, terrestrial acidification/nitrification, land occupation, aquatic acidification, aquatic eutrophication, global warming, attic ecotoxicity.

4. Case study

The case study was chosen based on an extensive case study review conducted by Attia et al. (2021) [10]. Out of six case studies located in the Netherlands and Belgium, we identified the most promising building that embraces the circularity principles. The knowledge center of sustainable building Kamp C is currently erecting a fully circular building. The building ambitions aim to limit material impact, the reuse of building components, and the design's maximum adaptability to new and future needs. More importantly, the building will be dismantled and re-assembeled three times over 20 years. The project is designed and constructed by a consortium of Kamp C [27] (see Table 2). Construction works already started at the end of 2020 in Westerlo, Belgium (see Figure 3). The project is located at latitude N 51.13 and longitude E 4.86 and is 14 m above sea level.

Table 2. Kamp C consortium companies of *'t Centrum* project.

Architect	Design & engineering	Structural engineering	Constructor	Constructing with green & natural elements	Geothermal energy	Research
West Architecture	TEN-agency	Streng-th	Beneens	Muurtuin	Tenerga	VITO

Figure 3. *'t Centrum* project drawings [28]

't Centrum building has many advantages, not only for the environment but also for future users. The building will be sustainable and energy neutral, with lots of light and surrounded by greenery. It contains a modular office layout and transformable workplaces. Adjustments can be made quickly, without needing to add a lot of extra energy and new materials. The used materials are reusable, so when the building is outdated, it can be completely disassembled. The design is based on a fixed grid structure, in which two cores are used. The stairs, lifts, and sanitary blocks are located in these cores. Everything around the core is flexible and adaptable. What is an office one moment can become an open meeting space at another. The building can also be completely dismantled. Suppose modifications to the building are needed in the next 20 years. In that case, all elements can easily be disassembled and assembled in other places but in the same location every five years according to Kamp C scenario (see Figure 4).

Furthermore, sustainable and reusable materials have been used, and the building is a living lab for circular construction. A timber structure was chosen in *'t Centrum* building. This gave many more possibilities for dry fastening methods, associated dismount ability, and fire safety solutions.
The project will be built with a timber structure. Ceiling, floors, and interior partitions will be in timber as well.

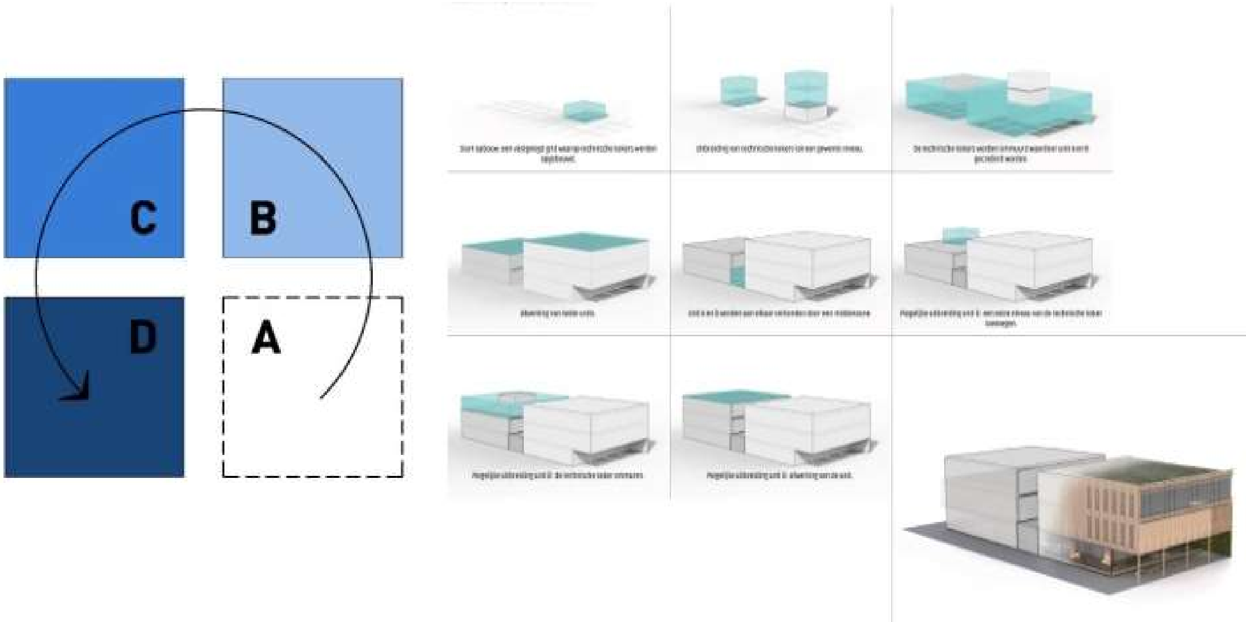

Figure 4. Circularity concept of *'t Centrum* project [28]

As a circular project, *'t Centrum* will be built in four buildings A, B, C, and D. They will be dismantled, rebuilt, and used in four phases, one by one:

Phase 1: Units A and B are being built. These units are connected using a green central zone and thus form one building. This building meets all aspects of circular construction. Materials are recruited as much as possible and recycled with as much value retention as possible.

Phase 2: Because the building is placed on a fixed surface, any extension is easy. For example, in a second phase, unit B can be bred with an extra taper. The same aspects of circular construction are used in building this level.

Phase 3: Based on a resource depot 2.0, materials technologies are continuously evaluated and, in this way, can also undergo improvements and transformations. Unit C can thus be built with the most sustainable, innovative raw materials, materials, and technology possible at that time. Heir, we speak of circular innovation. Unit C is connected to unit B with the same central zone.

Phase 4: Unit A is broken down so that the raw material depot 2.0 is physically replenished with reusable materials. Unit D can be built up in combination with the new, sustainable materials and techniques from the existing depot. Materials that cannot be used anymore in their current state are transformed into an application in which they can be used, recycled, or sold so that they can lead a new life elsewhere. In this way, we go one step further in circular innovation. Unit D is reconnected to unit C in the same way. The research has been based on the available information about the project on Kamp C website. The structure elements, dimensions, and details have been designed to start the simulation for timber and steel structural systems (see Figure 5 & Figure 6). Where the timber columns and beams were adopted dimensions 30cm, foundation precast bases with 70x70x20cm with a height of 50 cm, timber floors, Cellulose insulations, and roof garden has been used in this project as well. H beams have been used for the steel structural system with the same dimensions and precast foundation bases with

70x70x35cm but the same weight of the timber structure's foundation bases. Rockwool insulation has been used in the steel structure option.

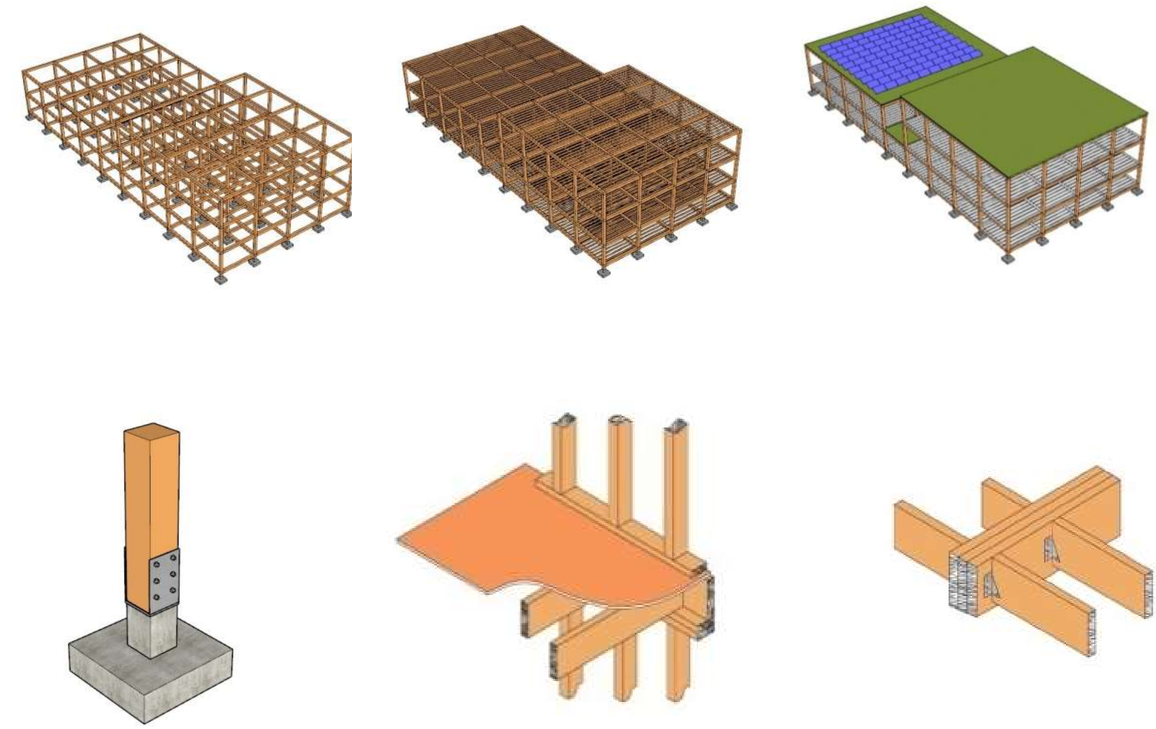

Figure 5. Visualization of timber structural system and timber details

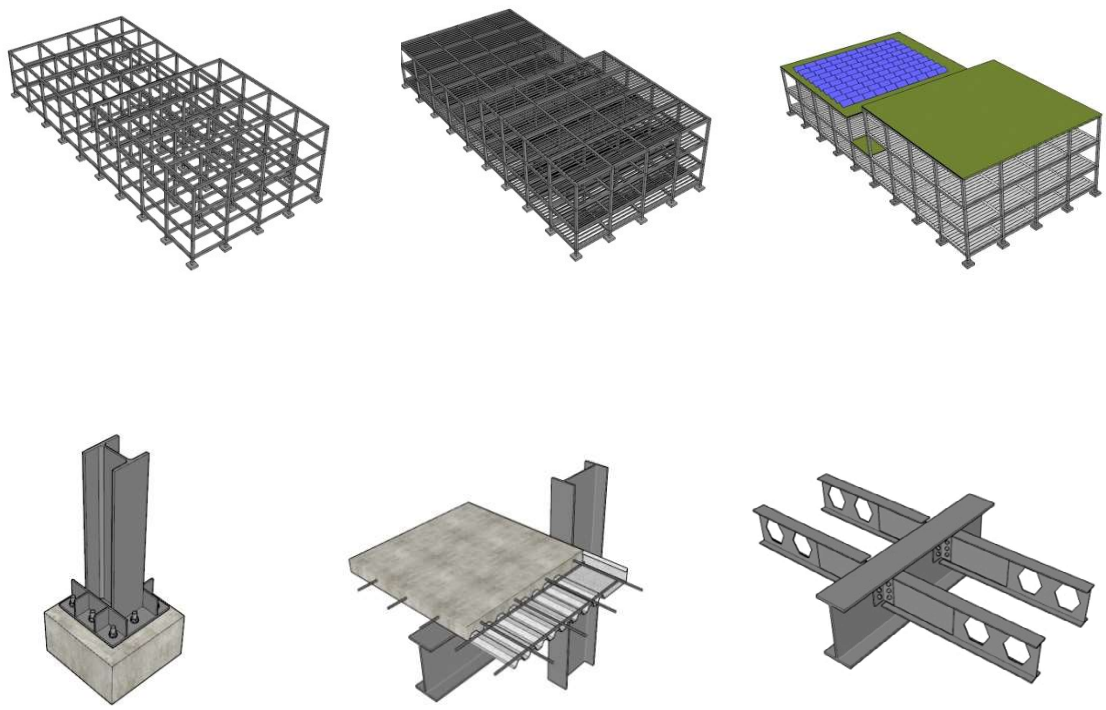

Figure 6. Visualization of proposed steel structural system and steel details

5. Results

5.1. Carbon neutrality

From a life cycle thinking approach [29] and based on EN 15978 [16], there are two definitions associated with building carbon neutrality: the embodied carbon emissions stage (A1-A5) and the carbon emissions in the use stage (B1-B7) (see Figure 1). Table 6 shows the carbon emissions of building elements during the entire building life cycle and their reuse according to the proposed scenarios and focuses on the pre-use stage of structural system materials (see Figure 7 & Figure 8).

Table 6. kg CO_2 emissions during life cycle stages for different structure materials and other scenarios.

Life cycle stages	Timber structure		Steel structure	
EN 15978	5 years Kamp C scenario	20 years Proposed scenario	5 years Kamp C scenario	20 years Proposed scenario
Biogenic carbon storage	-382101	-382101	-18	-18
Product stage A1 - A3	211 030	211 030	1 210 963	1 210 963
Construction StageA 4 - A5	39211	39211	42589	42589
Use Stage B1 –B7	154817	125521	323845	125521
End-of-life Stage C1 –C4	11104	11104	12 180	12 180
Re-use D	-134995	-131303	-488894	-465515
Total life cycle	-100933	-126537	1100667	925722

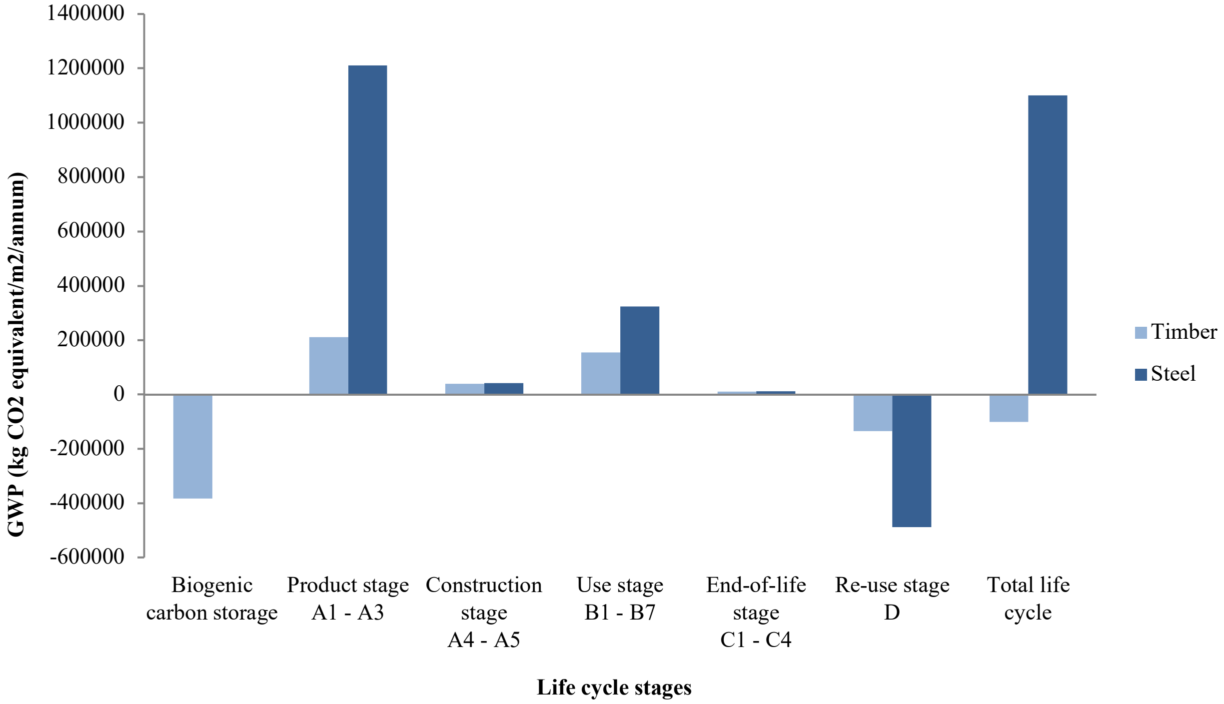

Figure 7. Comparison of the global warming potential for the different structure materials reuse every five years for 20 years.

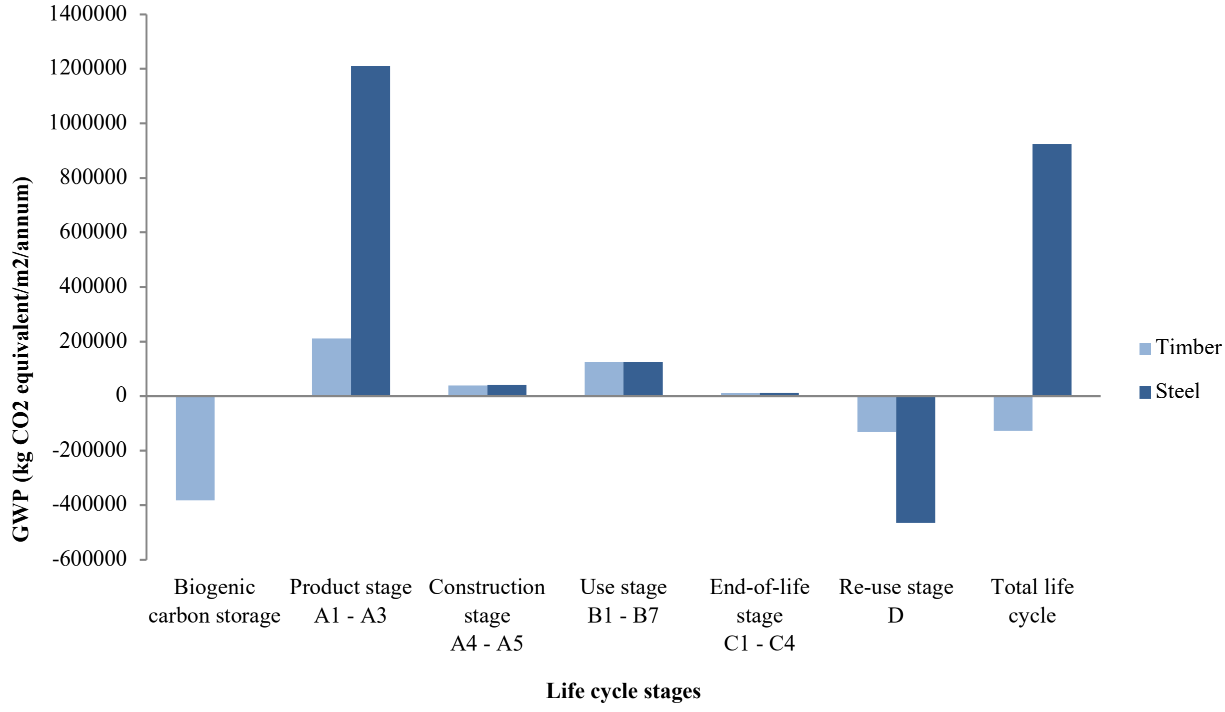

Figure 8. Comparison of the global warming potential for the different structure materials reuse every 20 years.

5.2. Building materials inventory

The results highlight the environmental impact of the building's structure during the building's life cycle and the reuse of materials several times according to the scenario targeted by Kamp C, and compare this to a hypothetical scenario for 20 years for timber and steel structure. Through an inventory of the main building materials for the structural system in the building (see Table 1 & Figure 2), we can see the following difference:

5.2.1 Timber structural system

Timber reaching almost 73% of the structural structure in the timber building. The study proved that the most carbon emissions during the life cycle of the building occur during the product stage (A1-A3) in general, as the study showed that carbon emissions in the timber structure are five times less of it in the steel structure during this stage (see Table 6).

5.2.2 Steel structural system

Steel reached almost 27% and concrete 69% of the steel building's structural system due to using concrete in the building floors, unlike the timber building. The study showed that carbon emissions in the product stage (A1-A3) are huge compared to the timber structure (see Table 6).

The carbon emissions were close during their calculation for the construction stage (A4-A5), use stage (B1-B7), and the end-of-life stage (C1-C4). The sum of carbon emissions during the life cycle of the whole building resulted in a remarkable difference between the use of timber structure and steel structure for 5 and 20 years scenario. On the other hand, the difference in carbon emissions is not significant between the 5 and 20 years scenarios for the same structural system material (see Figure 7 & Figure 8). Biogenic carbon storage had a substantial impact on carbon emissions. The difference between the timber structure and the steel structure leads to the conclusion that the building designed with a timber structure is considered.

5.3. Circular design criteria

5.3.1. Design criteria for circular building

According to Attia et al. (2021), four primary critical design criteria should be used to assess the building's circularity, namely: (1) carbon footprint, (2) reused content, (3) disassembly potential, and (4) flexibility and adaptability design. They are the most effective design criteria that can help designers make strategic design decisions for a circular building design; construction system, spatial function, and building materials [10] (see Figure 9).

These design criteria are what Kamp C should adopt in designing and building *'t Centrum* project during the reuse phases. But in this study, we focused on the structural system, which will help develop future research addressing the other aspects of the circular building design.

Circularity criteria for buildings should not be treated in isolation from carbon neutrality. The circularity criteria must be coupled to carbon footprint reduction measures of the building materials [30].

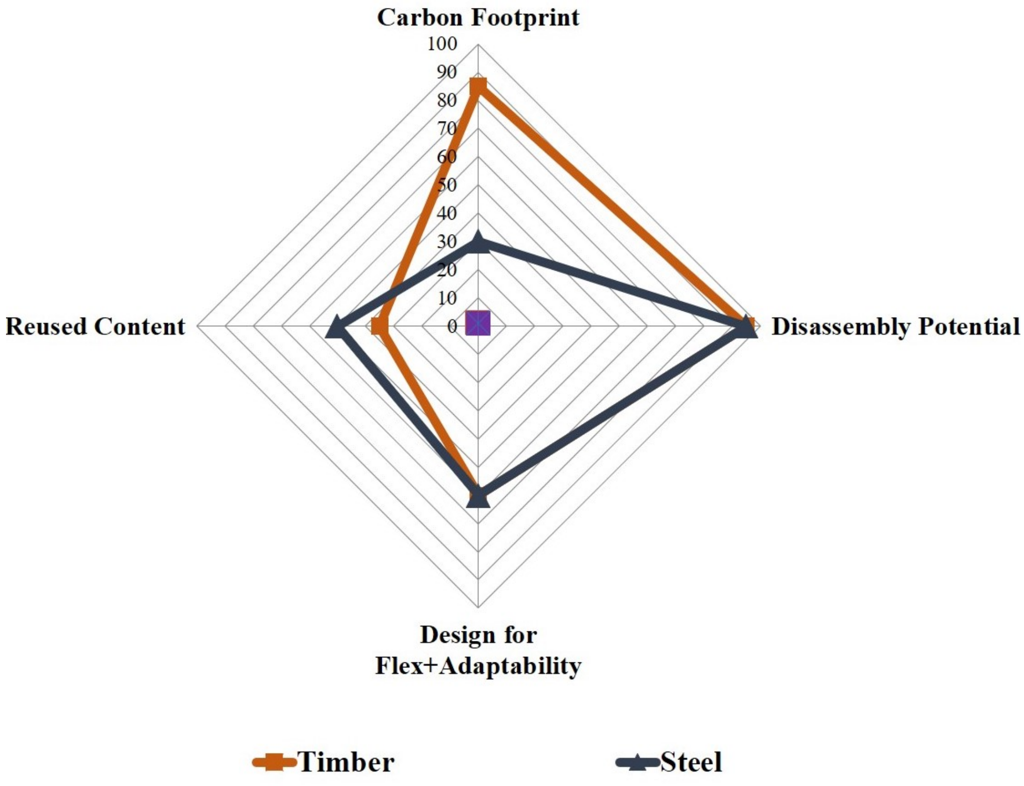

Figure 9. The circularity criteria of *'t Centrum* project for timber and steel structures

5.3.2. Construction system

The study's scope is limited to the construction system of *'t Centrum* Building as a case study. This paper will provide an assessment of the environmental impact of the timber and steel structural systems, and the extent to what it achieved circularity and carbon neutrality by focusing on the following:

1. Embodied carbon: By analyzing the project's timber structural system based on the available information, we find that the value of embodied carbon reaches -131860 kg CO2, making the project achieve the necessary carbon neutrality criterion.
2. Disassembly: The concept of this project depends on the disassembly of its components to be reused again.
3. Reuse cycle: After disassembling each time, the structural components will be reused about three times.

4. Recycled content: According to available information, this project's construction in the beginning will not be with recycled contents or maybe, but in a small proportion.
5. Usage adaptation: The building is an office building, and it will remain so throughout its use and reuse at every stage, and if a change in design occurs, it will not go outside the offices' framework.

Table 7 showed the durability of elements subject to reuse every five years for 20 years (Kamp C scenario). The table shows the building elements and how they are reused after the building was demolished and rebuilt. In contrast, some materials are not reused due to their damage after demolition. These materials that cannot be used anymore in their current state will be used, recycled, or sold so that they can lead a new life elsewhere. In this way, we go one step further in circular innovation, which will undoubtedly significantly impact evaluating these carbon emissions elements and achieving circularity. For the proposed scenario for 20 years, it was assumed that the building elements would not be replaced during the building's life.

Table 7. Durability of elements subject to reuse every five years for 20 years (Kamp C scenario).

Building inventory elements	Timber structure		Steel structure	
	Durability [years]	Number of reuse	Durability [years]	Number of reuse
Structure elements	20	3	20	3
Foundation	20	3	20	3
Insulation	20	2	20	3
Waterproof	20	0	20	0
Protective layer	20	0	20	0
Drainage	20	0	20	0
Geotextile	20	0	20	0
Filter layer	20	0	20	0
Soil	20	0	20	0

6. Discussion

In this section, we discuss the answers to the three main research questions:

- How can we evaluate the circularity of the building?

This study adopted a multi-criteria evaluation approach developed by Attia et al. 2021 [10]. The evaluation approach combined four main criteria, namely: (1) carbon footprint, (2) reused content, (3) disassembly potential, and (4) flexibility and adaptability design. The four key indicators allowed to address circularity more consistently and involved spatial and qualitative evaluation methods. The strength of the suggested approach is mainly due to its comprehensiveness beyond the narrow scope of LCA. By applying the multi-criteria evaluation approach, the study informed the design team about *'t Centrum* buildings circularity. Despite the simplicity of the used radar graph, the design team of *'t Centrum* appreciated the evaluation results and changed the design to ultimaly increase the overall circularity score.

- What is the most sustainable structural system regarding carbon neutrality and circularity?

This article focused on the embodied carbon in structural steel and timber once its design has been optimized. Results indicate that timber structure is superior to the steel structure in achieving circularity and reducing carbon emissions. Carbon emissions in the timber structure are five times less than the steel structure during the product stage (A1-A3). There is a remarkable difference in carbon emissions between timber structure and steel structure during the whole building's life cycle (A1-D or Cradle to grave). The difference is up to ten times less in the timber structure in the five-year scenario and up to eight times less in the 20 years scenario. The biogenic carbon storage effect made the timber alternative negative in carbon emissions, unlike the steel structure.

- To what extent is *'t Centrum* project circular and carbon neutral?

As shown in Figure 9, the building scores high in carbon footprint and disassembly potential. The most influential factor in the environmental impact of the structural systems was the roof insulation. However, designers must increase reused content of materials as much as possible and prepare for occupancy alternative functional scenarios. As architects, we significantly influence the circularity and the amount of embodied carbon in buildings. Therefore our specifications must not be written in isolation of the circularity criteria applied in this study. Also, we advise the European Union legislators to combine the environmental impact assessment of materials with circularity indicators. LCA is a powerful method for building sustainability evaluations, but it is not enough to achieve long-lasting sustainability. Moreover, architects must engage with contractors, subcontractors, suppliers, and clients to make sure that, collectively, they realize the circularity compliance we all need to make. This may require us to change how we design and build but will ultimately leave us with circular and low-carbon buildings.

Finally, this study is initial and should be further developed. The boundary conditions should extend the study scope to include the building envelope and building services (HVAC systems). With other drivers such as durability and steel connections influencing timber members, we are often given far more strength in our timber structures than we assume in our designs. Could we engage with the contractor to agree on timber strengths aligned with the construction needs, leading to the dismantling of building construction elements?

7. Conclusions
The use of the building's steel structure is associated with high carbon emissions despite its circularity achievement. In contrast, the use of timber structural systems in the building is considered one of the best materials in the short and long term. It achieves a more significant benefit by combining circularity and achieving the desired goal of reducing carbon emissions. Timber can make the building have a negative environmental impact. The research recommends designers address the four circularity principles presented in this study to assess future buildings, namely: (1) carbon footprint, (2) reused content, (3) disassembly potential, and (4) flexibility and adaptability design. LCA's use in early design stages is not enough to inform the design decision-making to achieve circularity.

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