

Article

A Parametric Approach to Optimizing Building Construction Systems and Carbon Footprint: A Case Study Inspired by Circularity Principles

Muheeb Al-Obaidy ^{1,*} , Luc Courard ²  and Shady Attia ¹ 

¹ Sustainable Building Design Laboratory, Department Urban and Environmental Engineering, Faculty of Applied Science, Université de Liège, 4000 Liège, Belgium; shady.attia@uliege.be

² GeMMe Building Materials, Department Urban and Environmental Engineering, Faculty of Applied Science, Université de Liège, 4000 Liège, Belgium; luc.courard@uliege.be

* Correspondence: muheeb.al-obaity@uliege.be; Tel.: +32-4-366-95-69

Abstract: There is a global call for a paradigm shift in the construction industry towards carbon neutrality, but a scant effort has been made in practice, especially concerning circularity. This paper helps bridge the gap by introducing a parametric approach to optimize sustainable construction design. The methodology was tested on a newly constructed office building, inspired by circularity principles, in Westerlo, Belgium. The methodology consists of parametric construction-typological analysis, automated through One Click LCA software (Life Cycle Assessment) and Microsoft Excel with 21 alternate designs and 630 iterations. The parametric variations involved three key performance indicators: construction system, materials' environmental impact, and materials; reuse of content. The environmental effects of both construction systems (i.e., structural system, foundation type, materials, and envelope details) and reused building materials content (i.e.,) were evaluated by the parametric analysis for four construction systems scenarios. Environmental impact analysis for timber, steel, concrete, and hybrid construction systems was conducted, following ISO 14040 and CEN/TC 350 standards. The focus of the whole life cycle assessment was mainly on carbon neutrality. Results indicate that using local biosourced materials, including timber, can remarkably reduce buildings' environmental impact. The sensitivity analysis results provide hard evidence that the construction material's weight, materials reuse potential, and construction dismantling ability are the most influential factors in carbon-neutral buildings. This paper should improve professionals' understanding of the impact of different structural systems choices and inform building designers about the circularity potential, and carbon footprint of construction technologies.

Keywords: circular building; environmental impact assessment; life cycle analysis; multicriteria approach; timber construction; carbon emissions



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1. Introduction

The building sector is a significant contributor to resources exploitation and carbon footprints. According to the Ellen MacArthur Foundation [1], the global consumption of material resources will reach 90 billion tons by 2050 (up 125% since 2010), exceeding all levels that the planet can sustainably provide. Thus, by 2050, 50% of the carbon emissions in the construction sector will come from new buildings [2]. The principles of circularity for the sustainable design of buildings aim to facilitate the durability of construction materials and building elements to reduce the environmental impact [3]. However, implementing resource efficiency concepts and the circular economy to buildings is not widespread [4,5]. The architectural, engineering, and construction (AEC) industry faces several dilemmas concerning structural resistance, elements longevity, ease of disassembly, flexibility, simplicity of products composition, etc. Within the context of the Circular Building: 't Centrum

project, this article presents the results of a case study for an office building located in Westerlo, Belgium.

The provincial *Center for Sustainable Building & Living Kamp C* of the city of Antwerp developed the first circular building in Belgium. The building is carbon neutral and integrates the circularity principles serving as an accelerator for modular and circular construction. The building's inauguration will occur in March 2022, and the building is planned to be dismantled and re-assembled three times by 2037, every time on a new site next to the original location. The idea of the re-deconstruction is to evaluate the adaptability, durability, ability to reuse the structural elements to reduce waste and facilitate high-quality building elements tracing and management.

Therefore, this paper aims to inform and support actors along with the AEC industry and the construction materials value chain. The article aims to answer three main research questions:

1. How to evaluate resource efficiency and the circular economy concepts applied in this building?
2. What makes a construction system carbon neutral and resource-efficient?
3. To what extent can the design of an office building apply principles of circularity in construction?

1.1. State-of-the-Art Research on Circularity and Environmental Impact

For the last 20 years, an increasing number of scientists have been using the terms 'circularity' or 'regenerative' in the domain of sustainable construction [3]. According to the Ellen MacArthur Foundation, the circular economy principles promote the regeneration of natural systems, keeping products and materials in use as long as possible, removal of pollution and waste [6]. The overarching aim of circular economy is to encourage the transformation towards a sustainable environment and positive impact buildings.

Since 2000, several European initiatives and projects have been conducted to define and promote circularity in the built environment and develop key performance indicators [7]. As part of the Buildings As Material Banks (BAMB) project, 15 partners from seven European countries developed a materials passport for buildings [8] and a framework for reversible building design [9]. However, the question remained on how to use quantifiable key performance indicators that can assist the design decision process [10]. The mandatory entry of Environmental Product Declarations (EPD) in 2018 across Europe helped to provide an objective and consistent method to evaluate building material impact [11] based on Life Cycle Assessment (LCA) [12]. The introduction of EPD played an important role in closing the knowledge gap to evaluate construction materials, products, and building elements [13]. For example, Cambier et al. [14] developed a design decision support tool for circular building design. The tool is based on the Design for Disassembly (DfD) principles (ISO20887) [9] to ease the deconstruction processes and procedures through planning and design [15]. In addition, the latest publications on the European voluntary reporting framework to improve the sustainability of buildings (Level(s)) [16] is a new tool to guide design teams, contractors, and builders. However, it remains challenging to evaluate the circularity of buildings, despite the proliferation of circularity evaluation indicators and technologies and methods that aim to extend buildings' service life to closing material loops in the construction sector [17]. There are recommendations that the EU Member States should develop national strategies or roadmaps to implement circular economy CE [18]. Considering the adoption of CE transformation action plans due to the different socio-economic conditions in the individual countries [19].

In summary, the knowledge gap remains wide on implementing and evaluating the concepts of resource efficiency and the circular economy for buildings. Several steps have been taken to evaluate circularity and carbon neutrality in the building sector.

1.2. Application of Different Construction Systems and Materials

Many building materials are used in construction, such as timber, steel, concrete, and masonry. Each material has different costs, weight, strength, durability, and circularity, suitable for specific applications. The choice of construction materials is based on cost and effectiveness in resisting the loads acting on the structure.

Around 40% of global carbon dioxide emissions, which reached 31 billion tons in 2021, are associated with the construction sector [20]. Embodied energy is another concern that can reach 60% during a building's life cycle [21]. To promote CE principles in the construction sector, The European Commission EC and the EU member states are looking forward to having a CE by 2050 and being halfway to achieving this critical goal by 2030 [17]. The building industry has a central role in responding to climate emergencies, and addressing upfront carbon is an urgent and essential focus [22]. Therefore, calls began to design low-carbon buildings and reduce construction with materials that do not meet the needs of circular design. For example, among others, the French government has announced a plan requiring that newly constructed public buildings need to be built from at least 50% timber or other natural materials by 2022, according to France Press Agency [23]. The new RE2020, the French building energy performance regulation, proposes a threshold of 100 kg of CO₂ per m² for embodied carbon emission, favoring biobased materials and timber [24].

The embodied energy of common construction materials such as timber, steel, or reinforced concrete is one of the critical topics currently researched worldwide thanks to the ever-growing concern on Sustainability and CO₂ emissions reduction in the construction domain [25]. There is a gradual shift towards replacing construction systems materials with materials that are more sustainable, circular, and less carbon-emitting, and from here, the idea of this study came to compare different construction system materials (timber, steel, concrete, and hybrid) to prove that.

1.3. Objective

According to the Ellen MacArthur Foundation [26], there are three principles of the CE, all driven by design:

1. Eliminate waste and pollution; it is crucial to consider waste and pollution as flaws in the design, not as inescapable by-products of the things that we make.
2. Circulate products and materials; making and designing things to last forever is not the only solution; the products can be designed to be reusable at their highest value.
3. Regenerate nature; we can boost the natural resources by returning nutrients to the soil, where everything will feed something else.

In this context, the study aims to support the early design decision-making of design teams, including architects and structural engineers, to select a building's construction system inspired by circularity principles. The choice of constructive and structural systems, such as columns, beams, and slabs, is crucial to upgrade the reuse cycles in the future, considering the rest of the building elements, such as the building envelope and others. Demountable construction systems can make it easier to dismantle the constructions and recover, upgrade, modify, or transform building materials. The paper proposes a new workflow to integrate environmental performative considerations for choosing materials in a design process, which can be easily expanded to more detailed and specific studies and applied to existing parametric tools and design software. In this context, the study aims to:

- Support the early design decision-making.
- Evaluate the circularity principles in timber construction.
- Adopt a parametric analytical approach to evaluate and compare different structural materials.
- Providing recommendations for circular building design for mid-size (above 1000 m²) office buildings.

In terms of context, this study focuses on the office buildings, which is considered a first step to realize and evaluate the circularity principles in Belgium in a practical way. This study shares the results of a parametric analytical approach to evaluate and compare different structural materials and systems during early design stages and specifically during the design decision-making process and design iterations regarding the selection and choice of construction systems and building material to bring circularity principles forward in design. This workflow is exemplified by examining the relationship between various building design parameters, environmental impact, and global warming potential. Following a parametric approach, this study investigates whether a circularity-inspired and environmental performance design approach can achieve a low carbon-emitting building. Moreover, it provides an overview of and recommendations for circular building design in Belgium.

The central hypothesis in this work is that the performative aspects of the building can be improved by applying a parametric approach to the building design parameters and choosing materials. The description of this workflow will be addressed in the following sections with the test of this hypothesis, defining its main findings and discussing them.

2. Methodology

2.1. Analytical Approach

Hypothetical models for performative evaluation have been applied with different construction systems (see Section 1.2). These models will increase the analytical exploration variability through the parametric evaluation approach. This study is based on performance predictions of the different construction systems conducted using validated simulation engines. For this study, besides the original design of the *'t Centrum* project mainly constructed in timber, three more models were designed representing the different construction systems of the same project to do the life cycle assessment: concrete construction, steel, and hybrid. For each construction system, a detailed evaluation has been done of the material's life cycle, total energy demand, and daylight performance. As shown in Figure 1, the analytical sequence is started by following the input of the fixed parameters (i.e., energy simulation parameters, materials data). Comparisons of the various construction systems environmental impact are made based on life cycle analysis requirements of ISO 14040, 14044, and CEN 15978 standards [27–29] with a focus on carbon neutrality by using One Click LCA software [30] according to TOTEM tool [31] indicators and MMG method [32]. The energy performance simulation has been started via EnergyPlus [33] and EPB [34] software for the different construction systems. 3D modeling has been made by Building Information Modeling (BIM) software Autodesk Revit® 2021. One-Click LCA plug-in was used for the materials inventory, SketchUp software has been used to visualize the building details. All results have been exported to Excel for post-processing and visualization. Then, all selected input parameters have been automated. Performance outputs are recorded for 21 alternate designs and simulation scenarios with 630 iterations in total. Regarding the calculation period, the four different construction systems simulate a scenario of 20 years, and other scenarios for 40 and 60 years as well to calculate the sensitivity analysis.

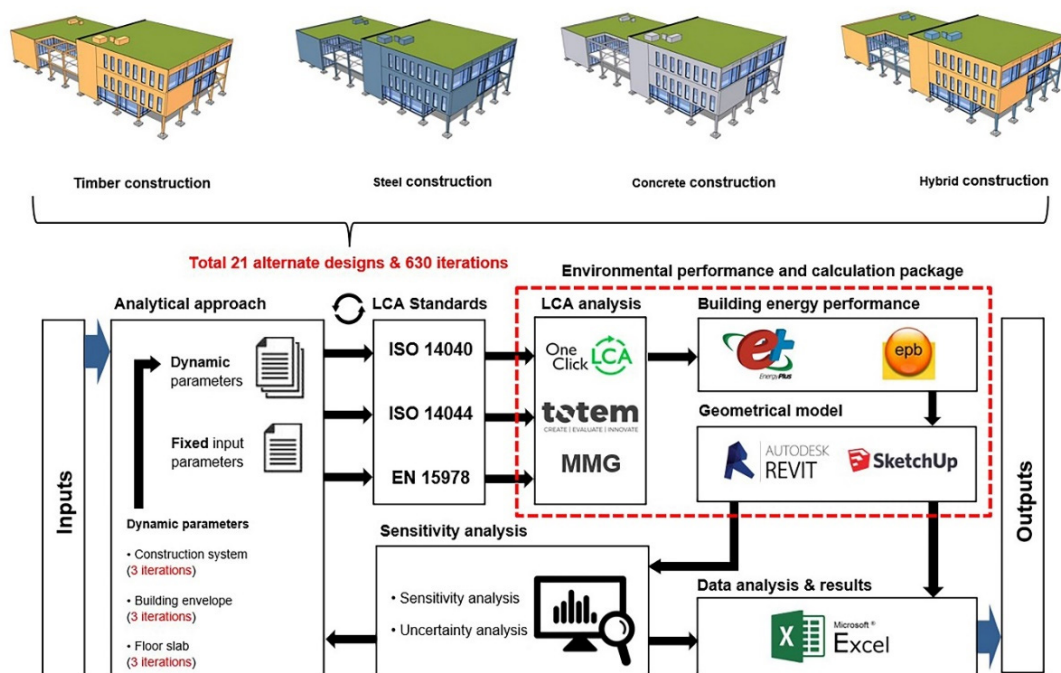


Figure 1. Analytic workflow showing the evaluation process of the different construction systems of 't Centrum project.

2.2. Life Cycle Standards and System Boundary

A life cycle assessment of the building construction systems took place to compare the environmental impact and CO₂ emissions according to ISO 14040 and 14044 standards [27,28]. Additionally, the CEN/TC 350 "Sustainability of Construction works" standard was used as a basis for the calculations. The indicated ISO standards provide valuable guidelines for LCA, which many researchers consider, but there is no total clarity on the data quality or the adopted system boundary [35]. LCA calculation has been done using the One-Click LCA software according to EN 15978 [29]. Figure 2 illustrates the five-building life cycle stages.

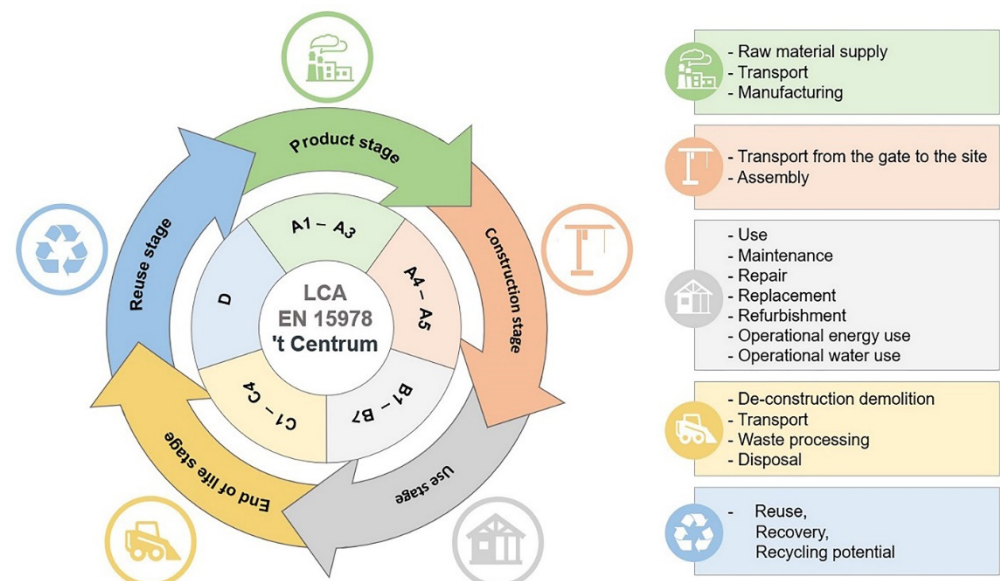


Figure 2. EN 15978 on the Sustainability of construction works.

2.3. Functional Unit Study Tools and Indicators

The LCA functional unit was 1 kg/year, and the occupancy period was estimated for 20 years. The specific nature of the project to be dismantled three times before 2037 made

it essential to limit the study to 20 years to assess its durability. Life cycle assessment (LCA) was based on the EPDs of the materials and project documents provided by Kamp C consortium members. The project documents, drawings, and materials quantities allowed the environmental impact assessment to be conducted. The Global Warming Potential (GWP), including biogenic CO₂ captured during the tree's growth, was calculated [3].

Building materials' environmental impact has been evaluated using the One-Click LCA software database [36] and the collected information after contacting the manufacturers. This evaluation was verified using TOTEM tool indicators (see Section 2.6.3).

Regarding the reuse content indicator, according to Rakhshan et al. (2020), the principal identified drivers of reuse content or the building components are economical, organizational, environmental, and social. Cost is the most reported sub-category, energy and global warming, organizational sustainability, and willingness [37]. During the design stage of the new building, it is essential to consider how the building content will be reused as elements or components in multiple cycles instead of the current linear approach [38]. There are new methods for reusing content, such as design for deconstruction (DfD) [39,40], and design for manufacture and assembly (DfMA) [41]. These methods have been introduced to prevent or decrease the waste of materials during the life-cycle of buildings. On the other hand, most of the existing buildings are not designed based on these methods or techniques, which leads to a large amount of waste during the renovation or the demolition phase. Although reuse is preferred to recycling, most of the recovery of construction and demolition wastes (CDW) in the buildings happens in recycling and not reuse [37].

Next, One-Click LCA treats reused content as recycled materials, not as building elements or components such as columns, beams, floors, etc. During the life cycle assessment of the building, One Click LCA leaves the reuse content indicator for the user to be included in the total results of carbon emissions. It is often a negative value. At the same time, EN 15978 neglects the effect of replacements on the surrounding interdependent building parts [42]. Module (D) covers the net benefits and loads arising from the reused content or the recycling or recovery of energy from end-of-waste state materials. Therefore, in this study, module D was calculated with biogenic carbon storage. The project was initially designed to be dismantled and rebuilt every five years.

According to EN 15804+A2 [43], the One-Click LCA calculation method [44] uses the following equation to calculate the net benefits and loads (Equation (1)):

$$e_{module\ D1} = (M_{MR\ out} - M_{MR\ in}) \left(E_{MR\ after\ EoW\ out} - E_{VMSub\ out} \cdot \frac{Q_{R\ out}}{Q_{Sub}} \right) \quad (1)$$

where ($M_{MR\ out}$) presents the amount of scrap content exiting the system, ($M_{MR\ in}$) presents the amount of scrap content fed into the system, ($M_{MR\ out} - M_{MR\ in}$) presents the net amount of scrap content produced by the system, ($E_{MR\ after\ EoW\ out}$) presents the amount of emissions, resources, and waste from material made from recycled scrap material, ($E_{VMSub\ out}$) presents the amount of emissions, resources, and waste from material made from primary materials, ($Q_{R\ out}/Q_{Sub}$) presents coefficient of quality difference, where ($Q_{R\ out}$) out corresponds to material made of recycled material and (Q_{Sub}) to material made of primary material. A value of 1 can be used.

Regarding the land-use footprint indicator, buildings cause soil sealing as land remains below constructions. Soil sealing occurs when agricultural or other non-developed land is built on top of it. The removal of topsoil layers to build on top of it leads to the loss of essential soil functions, such as food production or water storage [45]. It is insufficient to limit the land-use impact assessment only to the building's location. A life-cycle of a building includes the extraction of primary raw materials, manufacturing of construction materials, construction process, use stage of building with the maintenance, production of energy over the life-cycle of a building, demolition of the building, and end of life stage [17]. The land-use footprint evaluation was based on the LCA results. One-Click LCA program helps to obtain land-use footprint as a part of its results for all different construction systems in this study.

On the other hand, the number of building occupants has been calculated according to the design brief provided by the architect, which reports that occupants are 115 persons. For every Full-Time Equivalent (FTE), a net area of 12.5 m² is made available following the European standard (EN 15221-6) [46].

2.4. Case Study and Input Parameters

The case study was selected based on an extensive case study review in the Netherlands and Belgium [17]. A selection list was developed, including inclusion and exclusion criteria to make sure the case study was designed following circular economy principles. Figure 3 illustrates the chosen building *'t Centrum*, located at latitude N 51.13 and longitude E 4.86 and is 14 m above sea level. Table 1 list the project consortium members inclosing the architects and builders. The building is carbon neutral and integrates the circularity principles serving as an accelerator for modular and circular construction. The building's inauguration will occur in March 2022, and the building is planned to be dismantled and re-assembled three times by 2037, every time on a new site next to the original location.

Table 1. The project consortium companies.

Architect	Design & Engineering	Structural Engineering	Constructor	Constructing with Green & Natural Elements	Geothermal Energy	EPB Reporting	Concrete Technology	Research
West Architecture	TEN-agency	Streng-th	Beneens	Muurtuin	Tenerga	VESTAD	ResourceFull	VITO

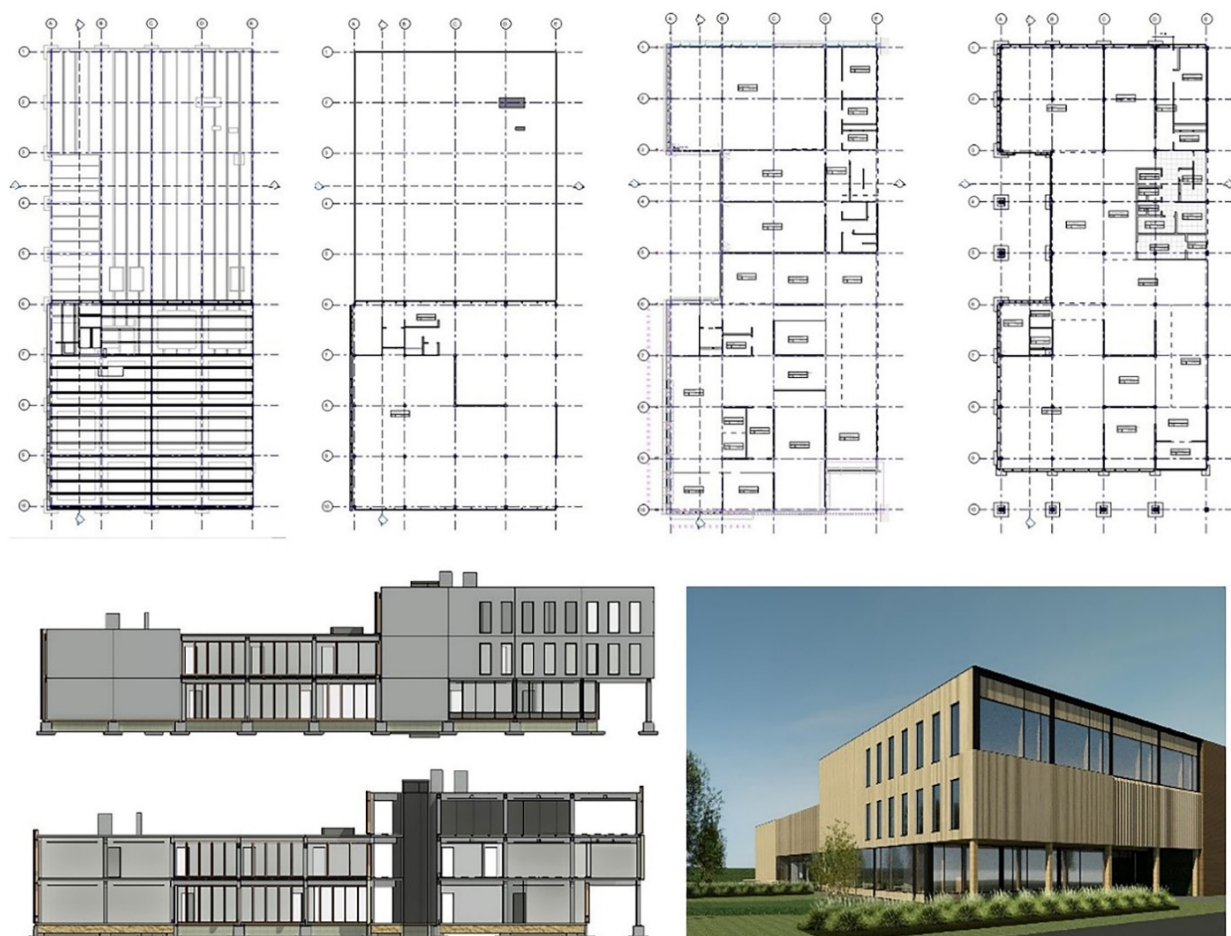


Figure 3. *'t Centrum* project drawings [47].

The building has a modular office layout and transformable workplaces. Therefore, it can be disassembled entirely when outdated. According to the Kamp C scenario, the building will be dismantled entirely during the next 20 years. The building is made from timber. A timber structure of CLT elements, manufactured by Binderholz [48], was used. The connection relies on dry fastening methods for dismantability. Ceiling, floors, and interior partitions are timber elements, using the dry adhesive method for the partitions and floor tiles fastening. The URBCON foundation technology was used to manufacture the concrete foundations of the project, a technology that guarantees the manufacture of foundations from the concrete slag provided by ResourceFull [49]. ResourceFull is a company that offers cement alternatives based on the use of secondary resources for more ecological alternatives to the construction industry. In total, 22,500 kg of secondary raw materials have been used, and 13,000 kg of CO₂ emissions have been saved compared to using other traditional foundations, according to ResourceFull [50].

For the other design options explored in this study, Figure 4 illustrates the use of three construction system materials for all building elements; steel, concrete, and hybrid. For the hybrid option, a steel structure has been used with precast concrete floors and timber envelopes. The same concrete foundations have been used for all other proposed construction systems to calculate LCA.

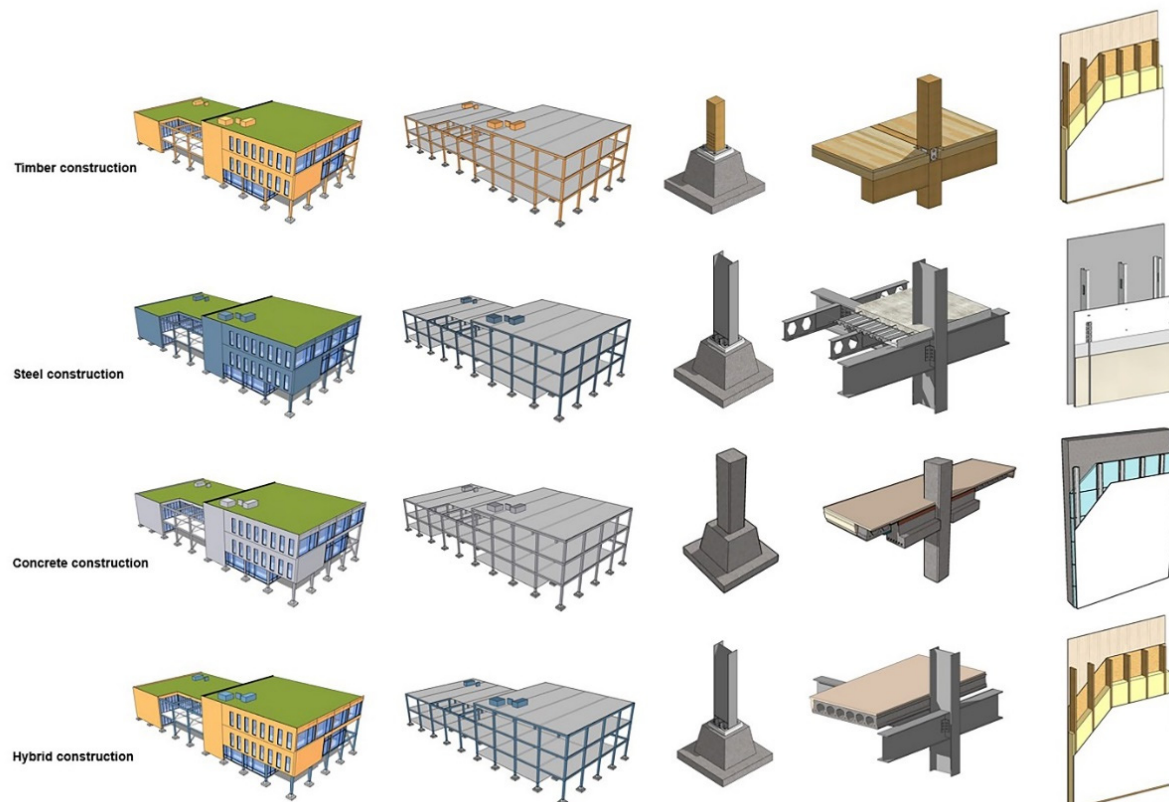


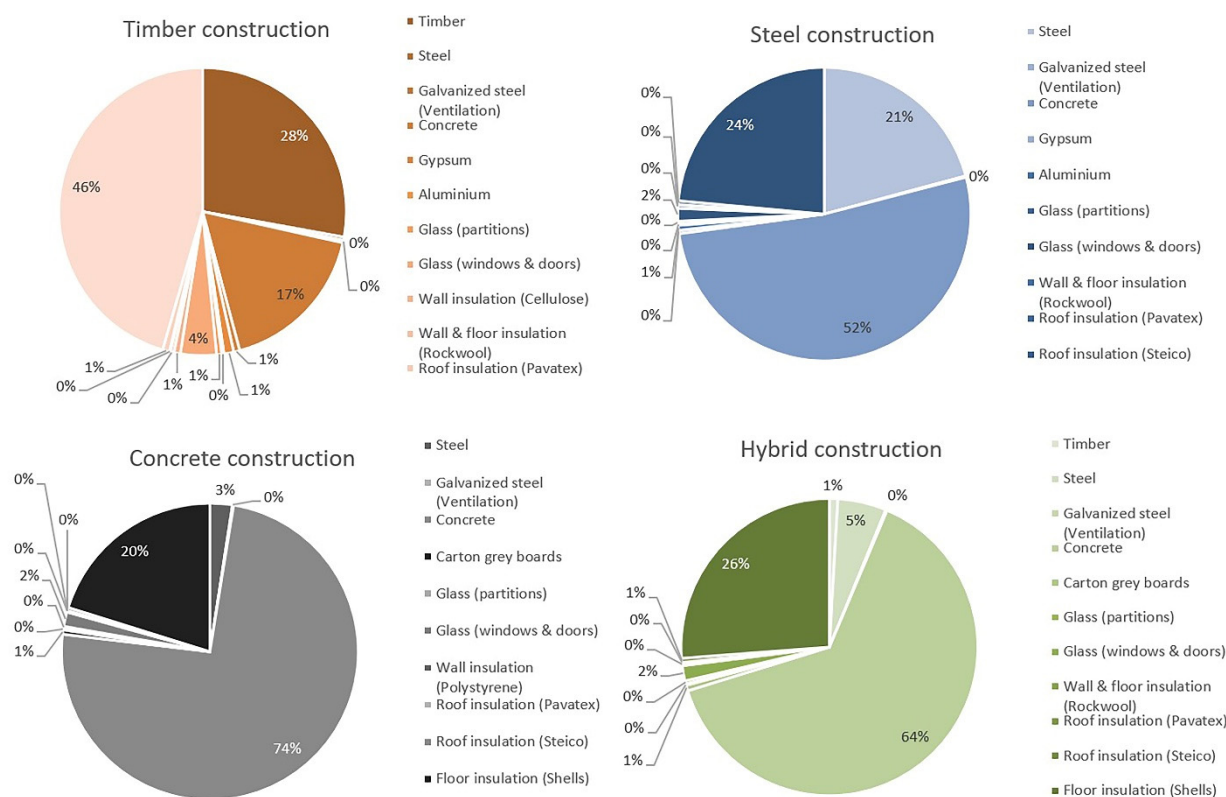
Figure 4. Visualization of the four construction systems and their building technical details.

2.5. Life Cycle Inventory

A life cycle inventory LCI was created based on EN 15978 [29] recommendations. Table 2 and Figure 5 provide a breakdown of materials elements used in the project and their environmental impact share.

Table 2. Breakdown of primary material groups based on their weight four construction scenarios.

Building Material Category	Timber Construction		Steel Construction		Concrete Construction		Hybrid Construction	
	Amount (kg)	Share (%)	Amount (kg)	Share (%)	Amount (kg)	Share (%)	Amount (kg)	Share (%)
Timber	216,585	27	×	×	×	×	12,324	0.91
Steel	2800	0.35	312,881	20.65	42,852	2.44	71,479	5.28
Galvanized steel	2210	0.28	2210	0.14	2210	0.12	2210	0.16
Concrete	135,000	17	780,464	51.51	1,303,213	74.31	863,325	63.87
Gypsum	5352	0.68	5352	0.35	×	×	×	×
Carton grey boards	8500	1.10	8500	0.56	8500	0.48	8500	0.62
Aluminium	2000	0.25	2000	0.06	2000	0.05	2000	0.07
Glass (partitions)	4500	0.57	4500	0.29	4500	0.25	4500	0.33
Glass (windows & doors)	31,352	4.02	31,352	2.06	27,452	1.56	22,400	1.65
Wall insulation (Cellulose)	5700	0.73	×	×	×	×	×	×
Wall & floor insulation (Rockwool)	3000	0.38	5300	0.35	×	×	3800	0.28
Wall insulation (Polystyrene)	×	×	×	×	2000	0.11	×	×
Roof insulation (Pavatex)	820	0.10	820	0.05	820	0.04	820	0.06
Roof insulation (Steico)	6200	0.79	6200	0.41	6200	0.35	6200	0.45
Services and cables (copper, plastic, etc.)	2000	0.25	2000	0.06	2000	0.05	2000	0.07
Floor insulation (Shells)	353,983	45.40	353,983	23.64	353,983	20.18	353,983	26.19

**Figure 5.** Weight share of the four types of structural materials percentage.

2.6. Environmental Performance and Calculation

In this section, we describe the environmental performance calculation and modeling software. All information about life cycle inventory can be found in Section 2.6.

2.6.1. Geometrical Model

In this study, 3D modeling has been made by Building Information Modeling (BIM) software Autodesk Revit. The Revit model was used and provided by the architect and Kamp C consortium members. One-Click LCA has been used to do life cycle assessments. SketchUp software has been used to show more clear details for the structure and envelope visualization.

2.6.2. Building Energy Performance Modeling

For energy simulation, EnergyPlus [33] has been used. Researchers, architects, and engineers use a whole building energy simulation program to model energy consumption such as heating, cooling, ventilation, lighting, and process loads in buildings. Antwerp weather file was selected as the closest and data-rich airport weather file to Westerlo. Antwerp falls under the Köppen-Geiger classification of temperate oceanic climate with no dry season and warm summer. Overall, Belgium's climate is mild-cold and humid, with significant rainfall during the year. Offices are typically heating- and cooling-dominated with an average of 2300 Heating Degree Days (HDD) and 45 Cooling Degree Days (2016–2020, base temperature 15 °C HDD and 24 °C CDD) [51]. Antwerp meteorological weather data for 2016–2019 were requested from the Belgian Royal Meteorological Institute [52]. The characterization of the building properties and occupant profiles was based on the input used for the Belgian EPB dynamic simulation model [34] that has been used for energy simulation in this project. The energy performance assumptions comply with the Flemish energy performance regulations for 2019, including insulation, installation, ventilation, and overheating requirements. The building is an all-electric zero energy building with three glazed facades. The ground floor is glazed with vacuum glass, and the upper floors are triple glazed. The building relies on a mechanical ventilation system with heat recovery. Six boreholes are coupled to the heat pump to meet the heating and cooling demand. Additionally, a parametric study was performed to estimate the impact of roof greening based on the work of Taleghani et al. [53]. The parametric study investigated the influence of using vacuum glass instead of triple glass and helped size the geothermal water to the air heat pump. VESTAD, the building services firm and member of the project consortium, provided their EPB report for the building envelope and installations, including the photovoltaic system. A complete study on the building energy model can be found in the master thesis of Caley's [54].

2.6.3. Building Life Cycle Analysis

Life cycle analysis was conducted with the help of One-Click LCA software. One-Click LCA allows the calculation of buildings' environmental impacts based on materials quantities [30,36]. The software allows being installed as a plug-in in Revit software. The software allows customizing the calculation according to the specificity of any geographical location, taking into account the available EPD and energy mix.

TOTEM is the second tool used to calculate the environmental impact of materials in this study. TOTEM stands for "Tool to Optimize the Total Environmental Impact of Materials" [31]. The TOTEM tool (version 1.0) was launched in Brussels on the 22nd of February 2018. Flanders started to develop this project under the Public Waste Agency of Flanders OVAM [55]. There are three main ambitions of the tool, according to Roos Servaes, 2018 [56]:

1. to analyze the environmental impact of building materials according to an objective and scientific-based evaluation method.
2. to optimize a design to reduce the environmental impact of the materials;
3. to support the architects, clients, etc., to decide in the design stage.

It is worth noting that the TOTEM tool does not refer to a database specific to reused and reclaimed materials. It uses the databases available for new materials (ECOINVENT and EPD's). TOTEM does not consider the impact of the production stage for the reclaimed materials or components [57].

2.6.4. Operational Carbon Emissions

The operational carbon emission calculation was based on the Flemish minimum building requirements for the primary energy use of 2020 [58]. The *E-peil* is a score that indicates how energy-efficient a building is. The lower the *E-peil*, the more energy-efficient the building is. Therefore the project is a zero energy building [59] (Equation (2)):

$$\frac{\text{Annual primary energy use}}{\text{The reference value of the annual primary energy use}} \times 100 \leq E - \text{peil} \quad (2)$$

The use stage or operational energy is responsible for a considerable share of buildings' life cycle environmental impact. Most environmental impact assessments, operational energy use, and other impacts are kept unchanged during the lifespan of the building, which is 60 years according to the accredited national LCA method for buildings in Belgium TOTEM [31] and EN 15978 [29]. The energy mix in Belgium will change over the building life cycle, impacting operational energy use. Several parameters impact the operational energy use and the carbon emissions of buildings, such as policy rules, insulation level, energy equipment technology, occupant behavior, climate conditions, and energy mix [60,61].

This study relied on calculating the operating energy in the use stage during the life cycle of building on the diversity of energy mix scenarios in Belgium, as shown in Table 3. The current energy mix scenario 2020 and the future scenario of 2040 were adopted in the calculations [62,63]. Belgium is transitioning to phase out nuclear energy sources and will rely on renewables by 2060. However, during the transition period, natural gas will be used. Therefore, we focused our study on a calculation interval of 20 years during the next 60 years. As shown in Figure 6, another future energy mix scenario for the years 2060 and 2080 was proposed based on the future indicators of energy production in Belgium. There are no data yet available on the energy mix in Belgium from 2050 onwards [64].

Nuclear radioactive waste has been considered in Belgium's 2020 energy mix scenario. Radioactive waste is classified into three categories: A, B, or C as follows:

1. A: low- and intermediate-level short-lived waste (working clothes, gloves, safety shoes, masks, laboratory waste, etc.).
2. B: low- and intermediate-level long-lived waste (residual products from the processing of fuel, filters from the primary cooling circuit, etc.).
3. C: high-level waste (irradiated fuel).

According to ENGIE Electrabel [65], the total amount of nuclear waste per person per year (category A, B, and C combined) corresponds to 0.5 kg. Therefore, it was imperative to provide the project with 100% green electricity during its lifespan. The project relies on an off-site 100% green electric energy provider named the *Vlaams Energiebedrijf VEB* [66]. VEB is an energy company approved by the Flemish government to supply green electricity and natural gas to all public services and supervise energy efficiency projects [67].

Table 3. kg CO₂ emissions according to Belgium's current and future energy mix scenarios for the four different construction system materials.

Construction System	Calculation Period	CO ₂ Emissions		
		Embodied	Operation	Total
Timber	20 years	−385,810	323,448	−62,362
	40 years	−507,077	646,895	244,528
	60 years	−628,344	970,343	487,609
Steel	20 years	542,269	323,448	865,717
	40 years	436,804	646,895	1,083,699
	60 years	331,794	970,343	1,302,137
Concrete	20 years	331,483	323,448	654,930
	40 years	226,473	646,895	873,368
	60 years	121,007	970,343	1,091,350

Table 3. Cont.

Construction System	Calculation Period	CO ₂ Emissions		
		Embodied	Operation	Total
Hybrid	20 years	394,989	323,448	718,437
	40 years	289,524	646,895	936,419
	60 years	184,059	970,343	1,154,402

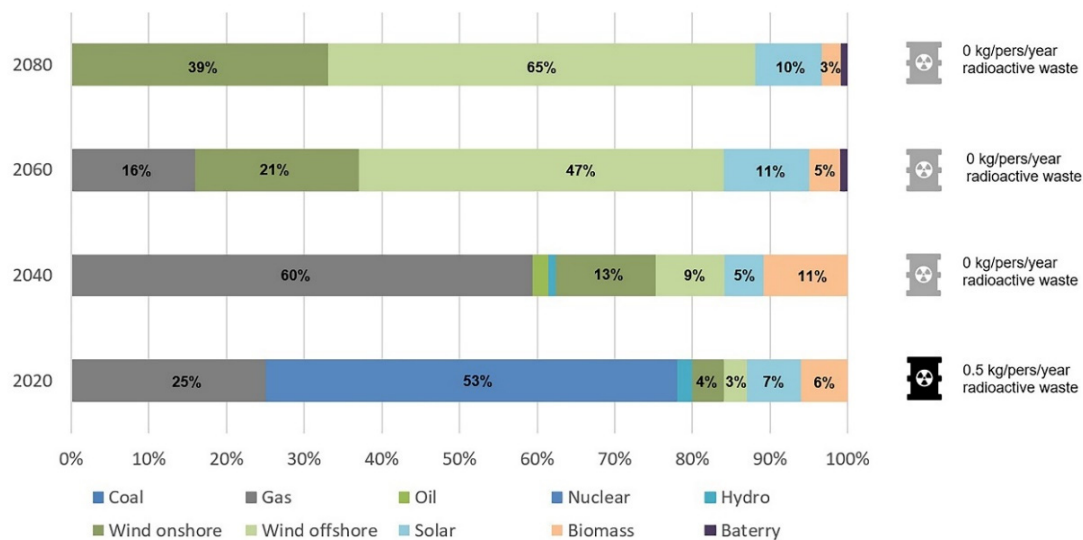


Figure 6. Current and future energy mix scenarios in Belgium [62,63].

2.7. Data Quality and Validation

2.7.1. Data Sources

Necessary data regarding the building materials and the construction system, including drawings, technical documents, and other details, were collected. Meetings and regular site visits have been done from the first stage of the project construction to the final stage to follow up the construction operation in detail. The materials specifications and the environmental impact data source have been based on the EPDs and available information on the One-Click LCA database. We compiled an open-access dataset that comprises all EPDs used in this study [68].

2.7.2. Data Quality Assessment

One-Click LCA contains two tools to record data quality in life cycle assessment. The first tool is the Plausibility Checker, which checks the plausibility of all the building material inputs to count the life cycle assessment for the project. The second tool is Completeness Checker, which checks if all required elements of the project are in place regarding the applicable standard or certification in question [69]. According to One-Click LCA and as shown in Table 4, the data Quality Policy (DQP) of One-Click LCA is explicitly designed for ensuring data fit for construction sector applications, using attributional LCA models and standardized life-cycle impact results in line with EN 15804+A2 [43].

Table 4. One-Click LCA data quality principles were implemented in this study [69].

Principle	Meaning in Practice
Availability	Revise and integrate all publicly and freely available LCA data that meet One Click LCA's Data Quality Policy (DQP).

Table 4. Cont.





Principle	Meaning in Practice
Plausibility (ref. EN 15978) [29]	Any market-based LCA data have to satisfy the Data Quality Policy (DQP) of One Click LCA to be included and used in the software. It covers ten steps and over 40 different checks.
Consistency (ref. EN 15978) [29]	LCA data consistency is ensured. If data include biogenic carbon storage, it is homogenized to ensure consistency of calculations (–) in One Click LCA's non-regulated LCA tools, biogenic carbon is always reported as a separate set of results to ensure transparency and clarity.
Representativeness (UN Guidelines)	All data are comprehensively classified on geographical and time representativeness. The data are documented based on available information for technological representativeness as a textual description.
Transparency	The data are enriched with metadata and information, allowing for a better understanding of the data point and its quality.

The environmental data provided by any assessment tool should be valid regarding the time and the location. If regional data are unavailable, the factors to adapt to regional conditions can be used [70]. In addition, Figure 7 illustrates the additional measures taken by the authors to reach the highest possible degree of data verification. Figure 7 was developed based on the ISO 14040 standard and was used to self-assess the data quality and intensive our research effort were necessary. The criteria adopted in the project data quality assessment included the following:

- Credibility (verified data based on measurements, assumptions, or estimation).
- The holistic briefing (representative data from the sites relevant for the market considered, over an adequate period to even out normal fluctuations).
- Temporality (the difference of the period of the dataset).
- Geographic distance (the difference of the geographic distance that allows verification and observation to ensure the validity of the dataset).

Scores for evaluation have been set as follows; Any information based on personal observation and a recent EPD receives the highest rating . Any information based on an only recent EPD receives an average rating of ++. Any other information receives an acceptable rating +. All composite materials and elements that contain different materials have been taken with caution. In addition to the above, we have carried out a self-check to assess the data quality through the following:

1. Conducting focus group discussions and workshops.
2. Intensive contact with suppliers and visits to manufacturers to determine the stages of production and transportation methods based on self-observations.
3. Contacting members of the TOTEM database and the Belgian Building Research Institute (BBRI) members to learn more about the innovative materials used in the project and search for EPDs.
4. Conducting site observations and regular site visits of the construction site every week.

Materials	Indicators			
	 Credibility	 Holistic briefing	 Temporal period	 Geographic distance
Timber	+++	+++	+++	++
Steel	++	++	+++	+++
Galvanized steel (Ventilation)	+++	+++	++	+++
Concrete	+++	+++	+++	+++
Gypsum	+++	++	++	++
Carton grey boards	++	++	++	+++
Aluminium	+++	+++	++	++
Glass (partitions)	++	++	++	+++
Glass (windows & doors)	++	++	++	++
Wall insulation (Cellulose)	+++	++	++	+++
Wall & floor insulation (Rockwool)	++	++	++	++
Wall insulation (Polystyrene)	+	++	++	++
Roof insulation (Pavatex)	++	++	+	+++
Roof insulation (Steico)	++	+	+	++
Other plastic items	++	++	++	+
Floor insulation (Shells)	+++	++	+	+++

Key:

+++	High quality	+++	Medium quality	+++	Acceptable quality
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Figure 7. Data quality assessment indicators of timber construction (Kamp C scenario).

2.7.3. Sensitivity analysis

Sensitivity analyses are used to check the impact of critical assumptions on models results [71]. Regarding sensitivity analyses, this study focused on the sensitivity of results of the most carbon-emitting material used in the building according to the construction material pyramid [72], such as; aluminum, galvanized steel, and copper, in addition to the materials that had the most significant weight share, such as timber and concrete, as a larger quantity of materials can lead to higher environmental impacts [73]. A sensitivity analysis was also conducted for the building lifespan after increasing it by 20 and 40 years, as designers often ignore the building's lifespan while it can have a significant environmental impact [74]. These parameters are considered to most affect the results regarding their environmental impact and the carbon emissions they cause (see Section 3.5).

2.7.4. Uncertainty Analysis

According to Huijbregts et al. (2003), uncertainty comes from mathematical models (model uncertainty), data uncertainty (parameter uncertainty), the output used to compare (output variable), and normative choices (scenario uncertainty) [75]. The results of a building's LCA can be affected by several uncertainty sources, mainly due to the system boundaries, the quality of the available data, and other factors [76]. In this study, uncertainty analysis addressed the materials with a large weight share in the building, such as; timber, concrete, glass, and shells insulation (see Section 3.5).

3. Results

Table 5 and Figure 8 present the carbon emissions of the four construction system scenarios. As illustrated in Figure 9, the environmental impact of construction materials also played a significant role in the life cycle assessment of the four different construction systems, (see Videos S1 and S2).

Table 5. kg CO₂ emissions (operational) for the four different construction system scenarios.

Life Cycle Stages EN 15978	Timber Construction	Steel Construction	Concrete Construction	Hybrid Construction
	20 Years Kamp C Scenario	20 Years Proposed Scenario	20 Years Proposed Scenario	20 Years Proposed Scenario
Biogenic carbon storage *	−385,086	−11,506	−11,506	−30,686
Product stage A1–A3	156,197	623,380	425,884	507,889
Construction Stage A4–A5	108,503	111,608	110,319	110,290
Use Stage B1–B7	323,448	323,448	323,448	323,448
End-of-life Stage C1–C4	34,056	8314	8223	8112
Re-use D *	−299,479	−189,527	−201,438	−200,617
Total life cycle	−62,362	865,717	654,930	718,436

* Note: One Click LCA leaves the values of Biogenic carbon storage and reuse content indicators for the user to be included in the overall results of carbon emissions.

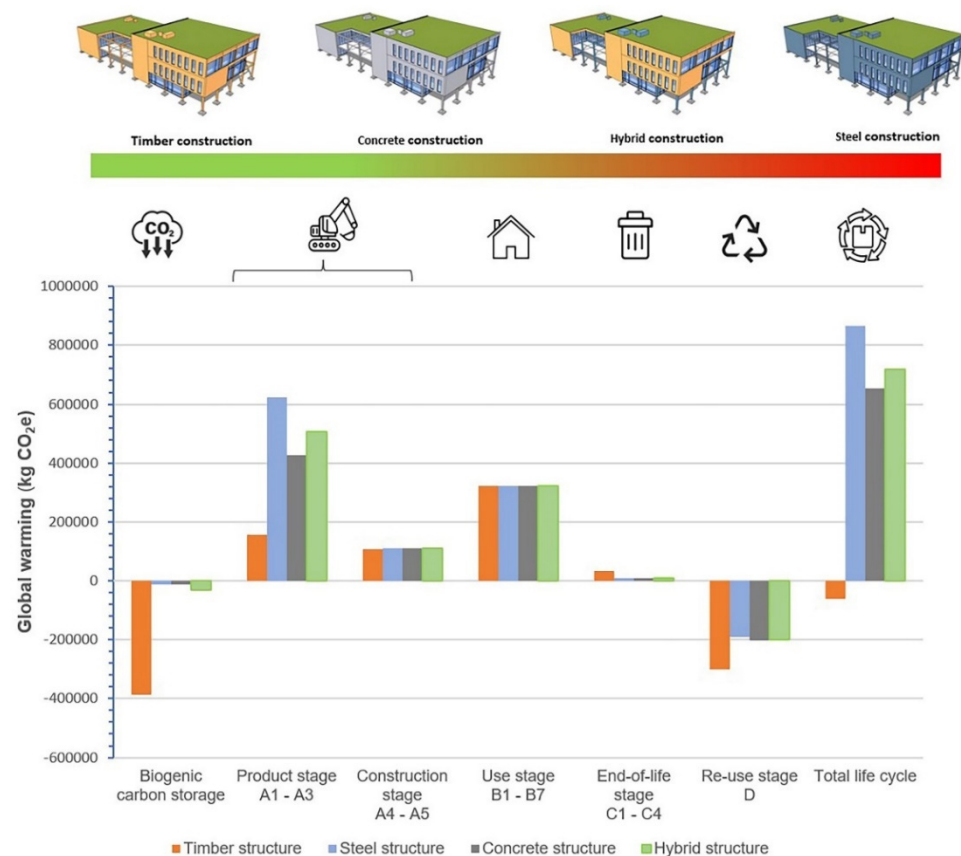


Figure 8. Comparison of the global warming potential during life cycle stages for the four different construction system materials.

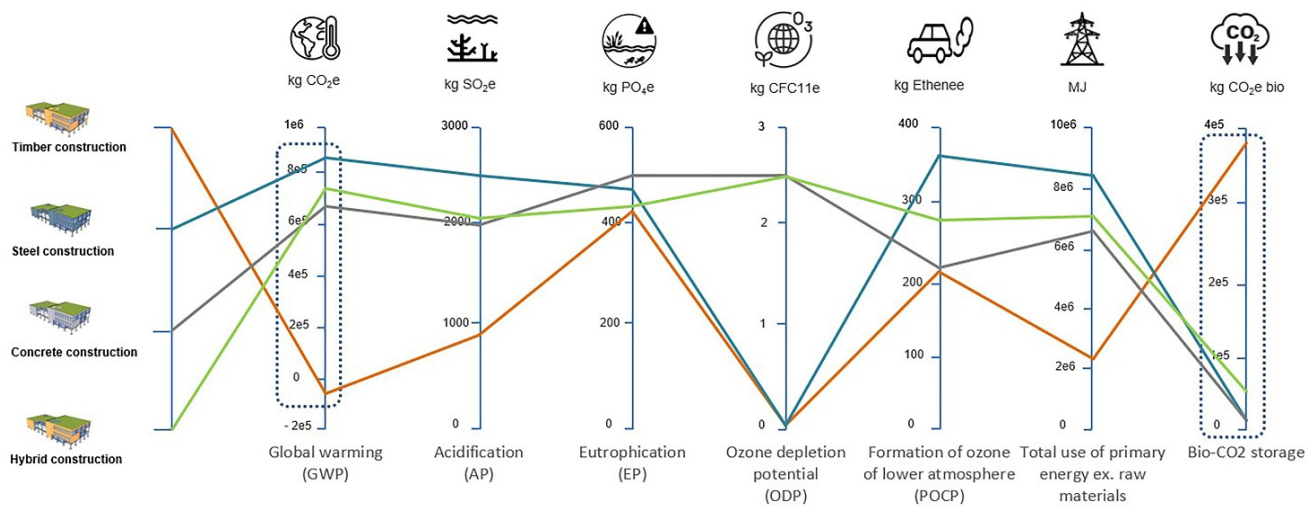


Figure 9. Parallel coordinated graph for the environmental impact of the four different construction system materials.

3.1. Environmental Impact and Carbon Footprint

Most of the building carbon emissions occur during the product stage (A1–A3). As shown in Table 5, carbon emissions in timber construction are four times less than steel construction and three times less than concrete and hybrid construction during this stage.

No significant difference was found concerning the carbon emissions during the construction stage (A4–A5) and use stage (B1–B7) for the four different scenarios. In the end-of-life stage (C1–C4), the carbon emissions of the timber construction were three times more than the other construction systems. As shown in Figure 10, the total carbon emissions indicate the effectiveness of implanting a timber construction. Biogenic carbon storage substantially affected these results favoring timber construction in this comparison.

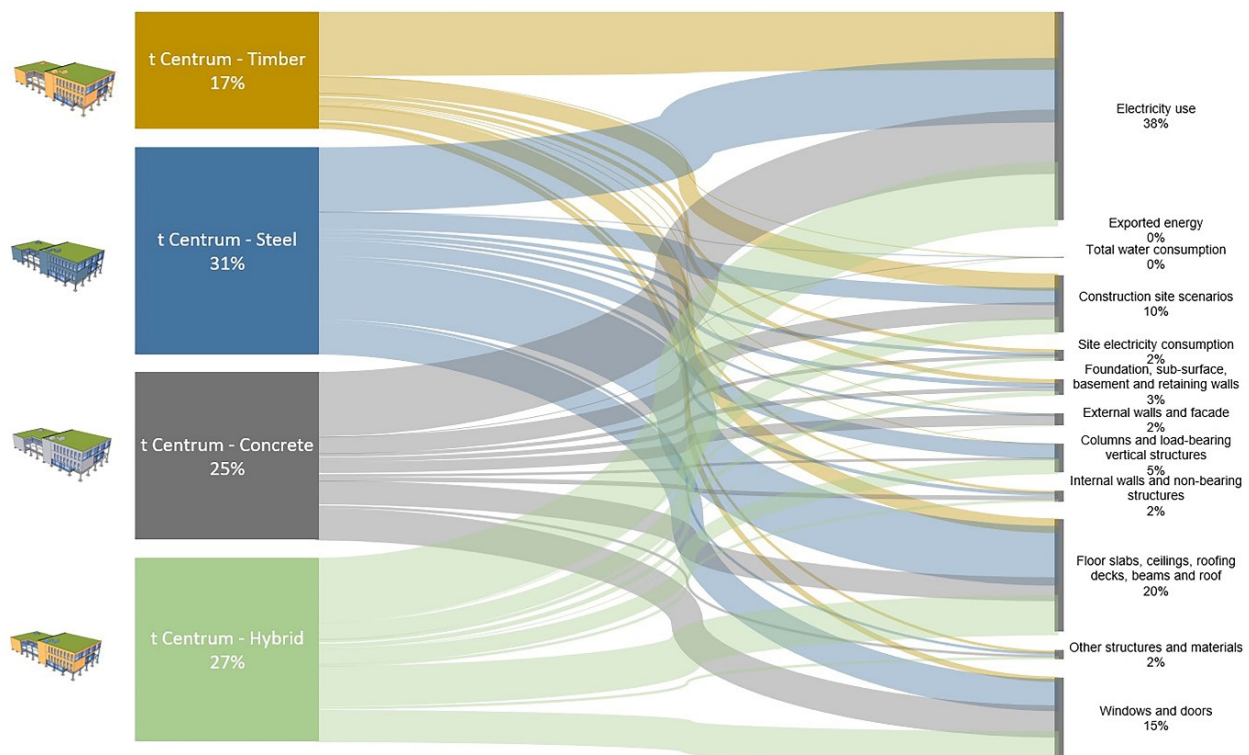


Figure 10. Comparison of the four construction systems regarding the carbon emissions according to energy usage and construction elements.

3.2. Reuse Content

One-Click LCA treats reused content as recycled materials, not as reused elements or components mentioned in Section 2.3.

According to One Click LCA, the reuse content score represents the total materials circularity in materials for the project and the end-of-life handling. It is calculated as the average of Materials Recovered (representing use of circular materials in the project) and Materials Returned (representing how effectively materials are returned, instead of disposed of or downgraded in value). The calculation is purely mass-based without material weighing.

Thus, the reused timber construction content scenario achieved a score of up to 73%, followed by 49% for the hybrid scenario, 41% for steel, and 39% for the concrete scenario. It was accompanied by a negative value of carbon emissions in timber construction reaching $-299,479$ kg CO₂e, while the carbon emissions resulting from the reused content in the steel, concrete, and hybrid construction reach $-189,527$, $-201,438$, $-200,617$ kg CO₂e, respectively.

On the other hand, regarding the realistic future scenario of 't Centrum project after dismantling and rebuilding it, several projects in which building elements or components were reused, such as Circular Retrofit Lab [77], Joseph Bracops Hospital [78], and the Institute of Botany in Liege university [79] were visited to evaluate the reused content. AGC glass company was visited to understand better the manufacturing process and reuse of building elements [80]. Additionally, ROTOR company that trades in reused building components was visited [81]. The evaluation of the reuse of building elements was discussed to reach a simulation closer to reality to explore and evaluate the reused content potential in the future scenario.

According to the European standard EN 15978 [29] for Life Cycle Assessment of construction products and buildings, the number of replacements for a part of the building can be obtained by applying the following equation (Equation (3)):

$$N_R(j) = \frac{ReqSL}{ESL(j)} - 1 \quad (3)$$

where ($N_R(j)$) presents the number of replacements of the part, ($ReqSL$) presents the Required Service Life of the building, and ($ESL(j)$) presents the Estimated Service Life of the part, rounded up and minus 1, to exclude the initial installation of the part at the construction of the building [29]. Therefore, the number of replacements for the main building elements during the proposed building lifespan of 20 years is 0.

To explore the reused content future scenarios and the ability for dismantling and rebuilding the building elements, we had to explore two stages:

1. Before construction will be 80% of total reuse content.
2. After the end of life will be 20% of total reuse content.

The calculation method is based on the weight of the building elements' material. The total reuse content percentage will be aggregated of these two sections. 't Centrum project will be dismantled and rebuilt in the future, the project aims to reuse more than 95% of its components as a material bank, taking into account a 5% material loss for LCA studies in the Belgian construction sector set [42,82]. The calculation period of this study is 20 years as a new building. Therefore, illustrated in Figure 11, the reused content before the construction is not with a large percentage, but it will be that after the end of life and the project is rebuilt in the other place. Therefore we can not call it a reused building, but we can call it a reusable building after dismantling it in the future more than once, and this is the main aim of this project, according to Kamp C [83].

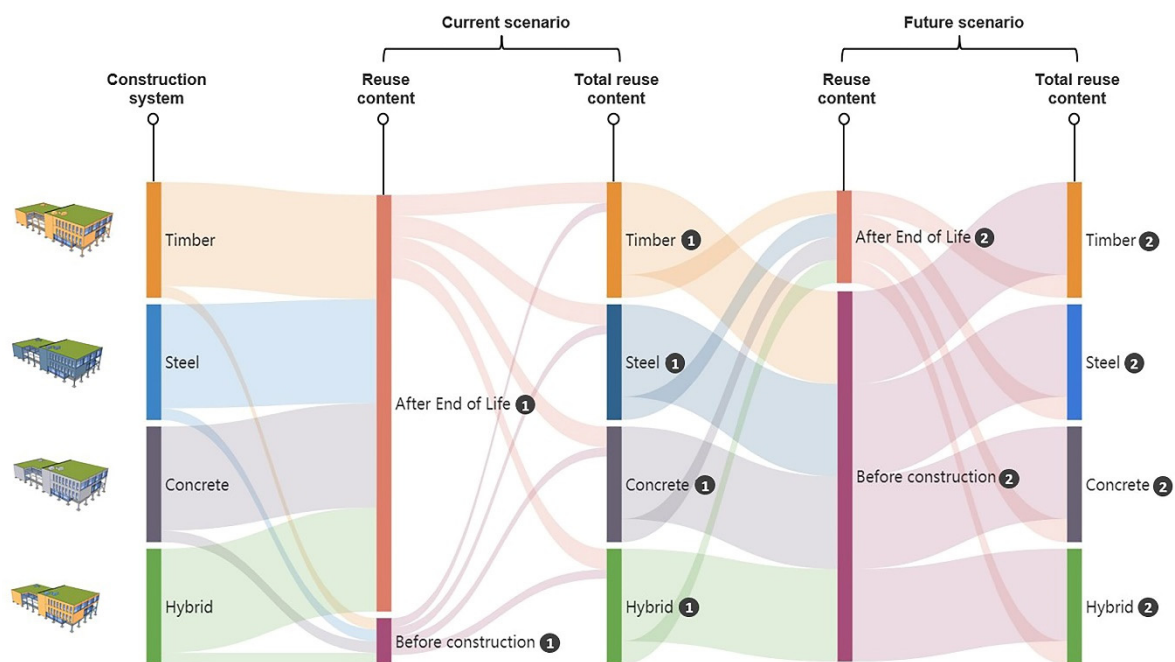


Figure 11. 't Centrum reuse content in the current and future scenario.

The results show a precise match in the reuse content indicator for the different building systems as they are designed primarily for future disassembly. Therefore, we can see that the reuse content indicator reaches approximately 25% in the current scenario as a new building, while the content reuse rate reaches up to 95% after dismantling and rebuilding.

3.3. Land Use Footprint

The land-use footprint was calculated based on the available data on the EDPs of the materials in the One-Click LCA database. In addition, from the other information of the project in general, as shown in Figure 12, the results prove the superiority of timber construction also by achieving ($-1.3 \text{ kg CO}_2\text{e/m}^2/\text{year}$), followed by concrete ($13.5 \text{ kg CO}_2\text{e/m}^2/\text{year}$), then hybrid ($15 \text{ kg CO}_2\text{e/m}^2/\text{year}$), and then steel ($18 \text{ kg CO}_2\text{e/m}^2/\text{year}$), (see Video S3).

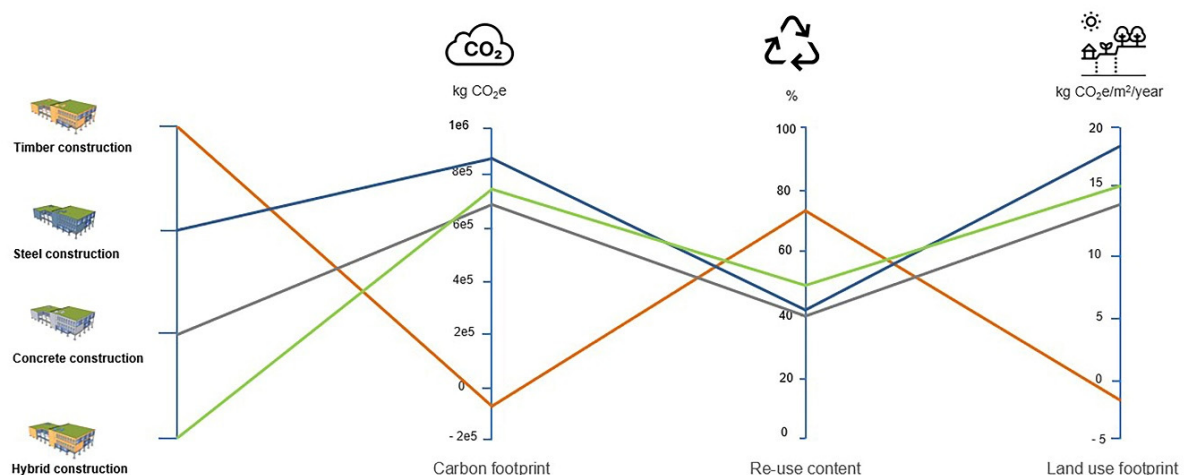


Figure 12. Comparison of the four construction systems according to the study indicators and One-Click LCA results.

3.4. Sensitivity Analysis

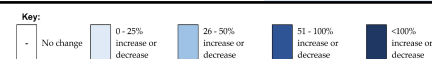
Sensitivity analysis can be defined as the study of how the uncertainty in the calculation and model results (outputs) can be explained and quantified by the uncertainty of the model inputs (parameters and/or boundary conditions) that are used in the study [84]. The choice of a sensitivity analysis method is based on the model complexity, computational time, required extractable information, and the usability and accessibility of the algorithm [85].

The global sensitivity approach has been considered by the use of analysis of variance (ANOVA). The good practice in sensitivity analysis and simulation that computes the intuitive Sobol first-order sensitivity index (SI) [86]. This sensitivity measure is based on the input variability and provides a value between 0 and 1. For example, an input with a SI equal to 0.75 is responsible for 75% of the output variability, and so on for the rest of the output.

Regarding this study, as illustrated in Table 6, the results are recalculated for a 10% increase/decrease in the most carbon-emitting material used in the building, such as; aluminum, galvanized steel, and copper. In addition to timber and concrete, they are the more sensitive categories of the current scenario (timber construction) and the most significant weight share of the materials after the shells insulation, which was excluded because it is a natural material and does not require manufacturing. In addition, all data and assumptions for the process parameters of building lifespan or calculation period were assessed. Specifically, the calculation period of the building was assessed in the sensitivity analysis by increasing the assumed lifespan or calculation period of 20 years by 20 and 40 years more. The sensitivity analysis results indicate that Global Warming Potential (GWP) is the most sensitive to the assumed building lifespan, with a focus on the use stage and energy consumption, where the electricity has been calculated according to the Federal Planning Bureau 2017 [63], and the Belgian energy landscape by 2050.

Table 6. Sensitivity analysis of more sensitive categories of the current scenario—timber construction.

Impact Category	Unit	Alum ± 10%	Galv. Steel ± 10%	Copper ± 10%	Timber ± 10%	Concrete ± 10%	Building Lifespan	
							+ 20 Years	+ 40 Years
Global Warming (GWP)	kg CO ₂ e	±0.8%	±0.9%	±0.3%	±60%	±01%	+392%	+781%
Acidification (AP)	kg SO ₂ e	±0.8%	±0.4%	±0.9%	±2.5%	±0.2%	+12%	+38%
Eutrophication (EP)	kg PO ₄ e	±0.01%	±0.01%	±0.17%	±2.7%	-	+4.3%	+15%
Ozone depletion potential (ODP)	kg CFC11e	-	-	-	±25%	-	-	+25%
Formation of ozone of lower atmosphere (POCP)	kg Ethenee	±0.02%	-	±0.02%	±7%	-	+2.8%	+21%
Total use of primary energy ex. raw materials	MJ	±1.6%	±1.4%	±1.4%	±3.8%	-	+0.4%	+65%
Bio-CO ₂ storage	kg CO ₂ e bio	-	-	-	±8.6%	-	-	-
Land use footprint	kg CO ₂ e/m ² /year	±0.08%	±0.1%	±0.03%	±54%	-	+300%	+360%



3.5. Uncertainty Analysis

Uncertainty analysis aims to estimate the uncertainty in model results prediction without identifying which model input is responsible for this in the study. It also aims to optimize the extractable information from model output variability [84].

In this study, the uncertainty analysis focuses on the heaviest materials used in the original design or the Kamp C scenario: Timber, concrete, glass, and insulation shells. According to the Revit model, timber constitutes 27% of the building weight share, expressed in (kg or m³). Through the EPD in the One-Click LCA database, the weight of the total timber used was calculated, with a density of 450 kg/m³, global warming potential (A1–A3) before local compensation of 0.43 kg CO₂e/kg, and Biogenic CO₂ storage of 1.54 kg CO₂e/kg. While the project's timber specifications talk about different densities of timber such as 460 kg/m³ and 470 kg/m³ produced by the factory, including the types that are used in this project [87], which will not significantly affect the results of the analysis.

Regarding the concrete, the URBCON foundation technology was used to manufacture the foundations and the rest of the concrete parts of the project, a technology that guarantees the manufacture of foundations from the concrete slag provided by ResourceFull [50].

For the life cycle assessment of concrete, EPD available on the One Click LCA database was used. According to ResourceFull, 13,000 kg of CO₂ emissions has been saved compared to traditional foundations [50].

AGC glass [80] has been used in this project. In the calculation method, the weight of the glass and its environmental impact was calculated according to the One-Click database, which has a fixed thickness and may allow, in certain types, changing the thickness of the glass to obtain an analysis close to reality. With AGC glass experts in Belgium, the different weights of glass per square meter were verified, and it appeared that there are differences of 10% to 15% between the actual weight of the square meter and the weight resulting from LCA calculations.

Shells insulation is a natural material provided by Ecoschelp [88]. Despite the significant weight share of shell insulation used in the building, there is not enough information about its environmental impact and carbon emissions. The available information about shells does not indicate more than the ability of the material to be highly insulating and resist mechanical pressure. Therefore, it was considered natural and unmanufactured material collected and transported to the construction site. However, the materials were not found in the One-Click LCA database. One-Click LCA was contacted to include this type of shell insulation in its database for future use.

4. Discussion

4.1. Summary of Main Findings and Recommendations

This study implemented a multicriteria approach to evaluate a unique case study's carbon neutrality and circularity. This study focused on the carbon footprint and the reused content in addition to the land-use footprint. The most relevant parametric analysis outcomes are described below:

- Timber construction is better than other construction systems; carbon emissions of timber construction are three times less than concrete, and hybrid construction and four times less than steel construction (see Table 5).
- The biogenic carbon storage capacity of timber had the most significant effect in achieving this result based on a cradle to cradle calculation approach.
- The timber construction's carbon emissions are lower than the requirements of the new French Building Regulation RE2020, which introduces a new threshold of 4 kg CO₂e/m² for new buildings [24].
- According to the circularity definition, this building is not a "reused building", but we can call it a "reusable building" because the reused content before the construction is reaching 5%, but it will be 95% after the end of life and rebuilt in the other location.
- Regarding the land-use footprint, the timber construction achieved a negative value reaching (−1.3 kg CO₂e/m²/year) for 20 years, unlike the other construction systems as shown in Figure 12.
- The consumption of electrical energy during the operation stage was one of the most influencing factors in increasing carbon emissions and global warming. As shown in Table 5, carbon emissions during the operational stage (B1–B7) reached 323,447.58 kg CO₂ in the original Kamp C scenario (Timber construction). The sensitivity analysis and uncertainty analysis indicate that operational energy use significantly contributes to the environmental life cycle impact, in line with studies found in the literature [89,90].

This research develops a workflow and parametric approach (see Section 2.1) to apply to several projects. Below are some recommendations for future circular building designs:

- Designers should increase the materials reused content to achieve the highest circularity value. In Belgium, for example, it is challenging to use reclaimed and reused materials because of the lack of compliance and certification of those second-life ma-

materials. The construction industry in Belgium is heavily standardized and does not encourage building designers to use reclaimed building elements or materials.

- LCA must be based on dynamic environmental impact characterization factors and combined with circularity principles [91]. For 't Centrum project a digital twin will be created to allow for a digital twins-based LCA.
- To avoid falling into the greenwashing trap, we advise not to use any material that does not have an EPD. Many industrial manufacturers claim the sustainability of new and green materials, including low-impact concrete or products that have no EPDs.
- Scientists should develop simple evaluation methods and audits for reusing building elements, which can characterize building components or structural elements based on fatigue, durability, and duration of its second or third extended life.

4.2. Strengths and Limitations of This Research

This study has developed a parametric methodology for environmental performance analysis of four different construction systems. An analytic workflow was created and applied for 21 alternate designs and 630 iterations. The strength of the parametric approach presented allowed the evaluation of four different design alternatives based on circular building design principles. The multicriteria evaluation approach provides an evaluation process used during the early design stages. By choosing and evaluating the construction materials, the study succeeded in evaluating to what extent a building is circular. The methodology brought operational carbon and embodied carbon into a whole life-cycle carbon assessment workflow by combining building energy modeling with LCA and considering changes in the energy mix affecting operational carbon. As indicated in Section 2.1 and shown in Figure 2, this methodology used tools already continuously used by researchers, engineers, and architectural companies. Using One Click LCA and Revit software with average expertise is enough to apply this methodology.

Also, a system of unique criteria was developed to reach the highest possible degree of data verification (see Figure 7). Self-checks have been done to assess the data quality through focus group discussions, workshops, intensive contact with suppliers, visits to manufacturers, personal observations, and weekly site visits to the construction site. Sensitivity and uncertainty analysis was conducted for the most carbon-emitting materials and the building's heaviest materials, as shown in Table 6. The sensitivity and uncertainty analysis allowed identify the hot spots and carbon profiles of different building materials and construction elements. Moreover, EPDs used in this study were compiled and made available in an open-access dataset [68]. Thus, the study findings align with similar studies investigating the influence of structural and construction system design on the green house emissions [92].

On the other hand, life cycle assessment programs like One-Click LCA do not include EPDs of the new innovative materials in its databases, such as green concrete and shells insulation used in this project. Therefore, their environmental impact was calculated with caution and under high uncertainty. Additionally, the One-Click LCA program deals with reusing content based on recycling materials rather than reusing building elements, according to Module D of EN 15978. Therefore, future work should test this novel workflow to calculate the reused content as building elements or components and not recycled materials.

It is worth noting that the transportation impact associated with dismantling and re-assembling the building in this project is almost negligible because it will be done on the same project site during the following years. It is planned to dismantle and re-assemble the building three times by 2037, on a new site around 20 m away from the original location. However, in reality, the associated transportation charges will be higher because the building elements will be expected to be transported far, for example, from one city to another; therefore, they should be considered.

4.3. Future Work and Possible Applications

This study provides a novel incremental contribution to the body of knowledge on circular economy principles for buildings' design towards circular construction and carbon-neutral buildings. The workflow developed in this study could be applied to other projects in several regions and climate conditions. We believe that the future carbon tax schemes proposed by the EU can increase the market uptake of circularity principles and create a real demand for design workflows and early design decision support tools. The presented case study proves the feasibility of implementing zero-carbon buildings. The use of bio-sourced materials such as timber and hemp can make it easy to neutralize the embodied carbon emissions [93,94]. However, for the reduction in whole life carbon of buildings, operational carbon will remain the most considerable challenge to the 2050 climate target [95]. On the other hand, the circularity gap is still wide. Circularity principles require further development to create simple key performance indicators for the construction sector. Despite the development of the European Frameworks for building sustainability evaluation—including Level(s)—there is a need for a rating system for circular buildings [96]. There is a need for independent certification and audits to distinguish low carbon materials from carbon-intensive materials and recycled materials from reused and reclaimed materials. Awareness should be raised regarding the difference between reclaimed materials, recycled materials, and reused content or elements. There is a real difficulty in using the reclaimed materials because they may contradict the required specifications or are not included in the database of environmental product declaration [57]. For example, the Public Waste Agency of Flanders OVAM funded a new project carried out by the Flemish Institute for Technological Research VITO. The project is a demolition guide that recognizes building materials for recycling or reuse [97]. According to Gobbo et al. (2021) [57], most environmental impact assessment tools hinge on databases of environmental declarations, which do not include any data for reclaimed materials. Therefore, many new low-impact materials/products are not found in environmental impact declarations databases. There is still a need for methods and tools to accurately calculate the reused content as elements or components when working on the life cycle assessment of the building, which can be easily combined with design modeling software. Thus, it is not easy to find a good balance between user-friendliness and the consistency of the approach, which needs to be transparent and verifiable [57].

Finally, carbon footprint and EPDs remain the most valuable tools for classifying building materials and evaluating circular projects in the future. Other LCA tools could be used and coupled with this workflow to evaluate the circularity for each scenario, thus expanding the broad environmental indicators and the circularity criteria and addressing and optimizing this workflow. This study is considered as the foundation for future work. Designers and researchers can quickly expand it to more detailed and specific studies using parametric tools. Digital twins can play a significant role in performing digital twins-based LCA. Another possible extension of this study would be developing a new tool or a plug-in to calculate the reused content as building elements, not as recycled materials, which would add a more realistic aspect to the analysis process. Also, the new standards of CEN/TC 350 [98] and ISO/TC 323 [99], which are under development, are expected to proliferate the CE principles in the construction sector and build on the EC initiatives.

5. Conclusions

As part of the EU's goals towards a circular economy, this paper presented a workflow to evaluate the impact of building materials on environmental performance. Capitalizing on the new possibilities offered by the environmental parametric tools like One Click LCA and the building information modeling BIM software like Revit, a wide range of input design parameters were systematically evaluated for four different design scenarios, timber, steel, concrete, and hybrid, with doing the energy performance simulations for the original scenario (timber construction). The results reveal a correlation between the

building materials choices and the carbon emissions. The results reveal a clear superiority of wood in construction to reduce carbon emissions and achieve circularity.

The use of steel, concrete, or hybrid constructions is associated with a remarkable negative environmental impact compared to timber. According to Kamp C, the reuse content indicator showed high potential to be an effective indicator to achieving circularity in terms of reusing the content as components or elements that will be achieved after dismantling and reconstructing the building in the future. The land-use footprint indicator also confirmed the superiority of the timber construction scenario. Finally, there is a need to develop other multicriteria approaches (quantitative and qualitative) and early design workflows with general and specific indicators to evaluate the circularity.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/su14063370/s1>, Video S1: Life Cycle Assessment; Video S2: Environmental Impact; Video S3: Performance Indicators.

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Conflicts of Interest: The authors declare no conflict of interest.

References

1. Ellen MacArthur Foundation. Completing the Picture: How the Circular Economy Tackles Climate Change. Available online: <https://ellenmacarthurfoundation.org/completing-the-picture> (accessed on 9 December 2021).
2. Sánchez-Garrido, A.J.; Navarro, I.J.; Yepes, V. Multi-criteria decision-making applied to the sustainability of building structures based on Modern Methods of Construction. *J. Clean. Prod.* **2022**, *330*, 129724. [\[CrossRef\]](#)
3. Attia, S. *Regenerative and Positive Impact Architecture*; Springer International Publishing: Cham, Switzerland, 2018. [\[CrossRef\]](#)
4. Heisel, F.; Rau-Oberhuber, S. Calculation and evaluation of circularity indicators for the built environment using the case studies of UMAR and Madaster. *J. Clean. Prod.* **2019**, *243*, 118482. [\[CrossRef\]](#)
5. Cottafava, D.; Ritzen, M. Circularity indicator for residential buildings: Addressing the gap between embodied impacts and design aspects. *Resour. Conserv. Recycl.* **2021**, *164*, 105120. [\[CrossRef\]](#)
6. Çimen, Ö. Construction and built environment in circular economy: A comprehensive literature review. *J. Clean. Prod.* **2021**, *305*, 127180. [\[CrossRef\]](#)
7. Al-Obaidy, M.; Santos, M.C.; Baskar, M.; Attia, S. Assessment of the circularity and carbon neutrality of an office building: The case of ‘t Centrum in Westerlo, Belgium. *IOP Conf. Ser. Earth Environ. Sci.* **2021**, *855*, 012025. [\[CrossRef\]](#)
8. Honic, M.; Kovacic, I.; Rechberger, H. Concept for a BIM-based Material Passport for buildings. *IOP Conf. Ser. Earth Environ. Sci.* **2019**, *225*, 012073. [\[CrossRef\]](#)
9. Durmišević, E. Reversible building design. In *Designing for the Circular Economy*, 1st ed.; Charter, M., Ed.; Routledge: Abingdon, UK; New York, NY, USA, 2018; pp. 344–359. [\[CrossRef\]](#)
10. Nuñez-Cacho, P.; Górecki, J.; Molina-Moreno, V.; Corpas-Iglesias, F.A. What Gets Measured, Gets Done: Development of a Circular Economy Measurement Scale for Building Industry. *Sustainability* **2018**, *10*, 2340. [\[CrossRef\]](#)

11. Tallini, A.; Cedola, L. A review of the properties of recycled and waste materials for energy refurbishment of existing buildings towards the requirements of NZEB. *Energy Procedia* **2018**, *148*, 868–875. [CrossRef]
12. Passer, A.; Lasvaux, S.; Allacker, K.; De Lathauwer, D.; Spirinckx, C.; Wittstock, B.; Kellenberger, D.; Gschösser, F.; Wall, J.; Wallbaum, H. Environmental product declarations entering the building sector: Critical reflections based on 5 to 10 years experience in different European countries. *Int. J. Life Cycle Assess.* **2015**, *20*, 1199–1212. [CrossRef]
13. Baldo, G.L.; Cesarei, G.; Minestrini, S.; Sordi, L. 6—The EU Ecolabel scheme and its application to construction and building materials. In *Eco-Efficient Construction and Building Materials*; Pacheco-Torgal, F., Cabeza, L.F., Labrincha, J., de Magalhães, A., Eds.; Woodhead Publishing: Cambridge, UK, 2014; pp. 98–124. [CrossRef]
14. Cambier, C.; Galle, W.; De Temmerman, N. Research and Development Directions for Design Support Tools for Circular Building. *Buildings* **2020**, *10*, 142. [CrossRef]
15. Rios, F.C.; Chong, W.K.; Grau, D. Design for Disassembly and Deconstruction—Challenges and Opportunities. *Procedia Eng.* **2015**, *118*, 1296–1304. [CrossRef]
16. Cordero, A.S.; Melgar, S.G.; Márquez, J.M.A. Green Building Rating Systems and the New Framework Level(s): A Critical Review of Sustainability Certification within Europe. *Energies* **2020**, *13*, 66. [CrossRef]
17. Attia, S.; Al-Obaidy, M. *Design Criteria for Circular Buildings*; Zuyd University: Parkstadt, The Netherlands, 2021; p. 11.
18. Smol, M.; Duda, J.; Czaplicka-Kotas, A.; Szoldrowska, D. Transformation towards Circular Economy (CE) in Municipal Waste Management System: Model Solutions for Poland. *Sustainability* **2020**, *12*, 4561. [CrossRef]
19. Smol, M. Inventory and Comparison of Performance Indicators in Circular Economy Roadmaps of the European Countries. *Circ. Econ. Sustain.* **2021**. [CrossRef]
20. Grover, R. Towards Zero Carbon Buildings: Reducing the Embodied Carbon Footprint of a Construction. 2020. Available online: <https://repository.tudelft.nl/islandora/object/uuid%3A98e2c46c-7321-4eab-9f88-c3d10912003a> (accessed on 19 July 2021).
21. Huberman, N.; Pearlmutter, D. A life-cycle energy analysis of building materials in the Negev desert. *Energy Build.* **2008**, *40*, 837–848. [CrossRef]
22. WGBC. Bringing Embodied Carbon Upfront. *World Green Building Council*. Available online: <https://www.worldgbc.org/news-media/bringing-embodied-carbon-upfront> (accessed on 26 July 2021).
23. Dezeen. French Public Buildings to Be Built with 50 Per Cent Wood. Available online: <https://www.dezeen-com.cdn.ampproject.org/c/s/www.dezeen.com/2020/02/12/france-public-buildings-sustainability-law-50-per-cent-wood/amp/> (accessed on 27 July 2021).
24. Ministère de la Transition Écologique. RE2020: Une Nouvelle Étape vers une Future Réglementation Environnementale des Bâtiments Neufs Plus Ambitieuse Contre le Changement Climatique. *Ministère de la Transition Écologique*. Available online: <https://www.ecologie.gouv.fr/re2020-nouvelle-etape-vers-future-reglementation-environnementale-des-batiments-neufs-plus> (accessed on 26 July 2021).
25. Rossi, B.; Marique, A.-F.; Reiter, S. Life-cycle assessment of residential buildings in three different European locations, case study. *Build. Environ.* **2012**, *51*, 402–407. [CrossRef]
26. Ellen MacArthur Foundation. What Is a Circular Economy? Available online: <https://ellenmacarthurfoundation.org/topics/circular-economy-introduction/overview> (accessed on 9 January 2022).
27. ISO. ISO 14040:2006: Environmental Management—Life Cycle Assessment—Principles and Framework. Available online: <https://www.iso.org/cms/render/live/en/sites/isoorg/contents/data/standard/03/74/37456.html> (accessed on 19 July 2021).
28. ISO. ISO 14044:2006: Environmental Management—Life Cycle Assessment—Requirements and Guidelines. Available online: <https://www.iso.org/cms/render/live/en/sites/isoorg/contents/data/standard/03/84/38498.html> (accessed on 19 July 2021).
29. EN 15978:2011. Sustainability of Construction Works—Assessment of Environmental Performance of Buildings—Calculation Method. *iteh Standards Store*. Available online: <https://standards.iteh.ai/catalog/standards/cen/62c22cef-5666-4719-91f9-c21cb6aa0ab3/en-15978-2011> (accessed on 19 July 2021).
30. One Click LCA. Calculate Your Environmental Impacts in Minutes. *One Click LCA® Software*. Available online: <https://www.oneclicklca.com/> (accessed on 19 July 2021).
31. OVAM. Totem: Tool to Optimise the Total Environmental Impact of Materials. Available online: <https://www.ovam.be/materiaalprestatie-gebouwen-0> (accessed on 24 July 2021).
32. OVAM. Annex. Monetisation of the MMG Method. Update 2017. Available online: <https://www.vlaanderen.be/publicaties/annex-monetisation-of-the-mm-g-method-update-2017> (accessed on 21 July 2021).
33. EnergyPlus. Available online: <https://energyplus.net/> (accessed on 21 July 2021).
34. EPB-Eisen. Available online: <https://www.energiesparen.be/epb-pedia/epb-eisen> (accessed on 21 July 2021).
35. Reap, J.; Roman, F.; Duncan, S.; Bras, B. A survey of unresolved problems in life cycle assessment. *Int. J. Life Cycle Assess.* **2008**, *13*, 374–388. [CrossRef]
36. One Click LCA. LCA Database of Building Products: Local and Global Data for Your LCA. *One Click LCA® software*. Available online: <https://www.oneclicklca.com/support/faq-and-guidance/documentation/database/> (accessed on 19 July 2021).
37. Rakhshan, K.; Morel, J.-C.; Alaka, H.; Charef, R. Components reuse in the building sector—A systematic review. *Waste Manag. Res. J. A Sustain. Circ. Econ.* **2020**, *38*, 347–370. [CrossRef]
38. Ritzen, M.; Van Oorschot, J.; Cammans, M.; Segers, M.; Wieland, T.; Scheer, P.; Creugers, B.; Abujidi, N. Circular (de)construction in the Superlocal project. *IOP Conf. Ser. Earth Environ. Sci.* **2019**, *225*, 012048. [CrossRef]

39. Akinade, O.O.; Oyedele, L.O.; Ajayi, S.O.; Bilal, M.; Alaka, H.A.; Owolabi, H.A.; Bello, S.A.; Jaiyeoba, B.E.; Kadiri, K.O. Design for Deconstruction (DfD): Critical success factors for diverting end-of-life waste from landfills. *Waste Manag.* **2017**, *60*, 3–13. [CrossRef]
40. Tingley, D.D.; Davison, B. Design for deconstruction and material reuse. *Proc. Inst. Civ. Eng. Energy* **2011**, *164*, 195–204. [CrossRef]
41. Kalyun, M.; Wodajo, T. Application of a Design Method for Manufacture and Assembly, Flexible Assembly Methods and Their Evaluation for the Construction of Bridges. *Undefined*. 2012. Available online: <https://www.semanticscholar.org/paper/Application-of-a-Design-Method-for-Manufacture-and-Kalyun-Wodajo/17f0e56185797c39d9789c07544a4fdab9212bed> (accessed on 28 October 2021).
42. Vandervaeren, C.; Galle, W.; Stephan, A.; De Temmerman, N. More than the sum of its parts: Considering interdependencies in the life cycle material flow and environmental assessment of demountable buildings. *Resour. Conserv. Recycl.* **2022**, *177*, 106001. [CrossRef]
43. Standards, E. EN 15804+A2. Available online: <https://www.en-standard.eu/csn-en-15804-a2-sustainability-of-construction-works-environmental-product-declarations-core-rules-for-the-product-category-of-construction-products/> (accessed on 18 August 2021).
44. One Click LCA. How Do I Model Module D for Recycled Material? *One Click LCA Help Centre*. Available online: <https://oneclicklca.zendesk.com/hc/en-us/articles/36002222720-How-Do-I-Model-Module-D-For-Recycled-Material-> (accessed on 15 December 2021).
45. EEA. The European Environment—State and Outlook 2020: Knowledge for Transition to a Sustainable Europe—European Environment Agency. Available online: <https://www.eea.europa.eu/soer> (accessed on 29 July 2021).
46. European Committee for Standardization. Standard NBN EN 15221-6:2011. Available online: https://www.nbn.be/shop/en/standard/nbn-en-15221-6-2011_20688/# (accessed on 23 July 2021).
47. Beneens. We Build Camp Circular. *Beneens*. Available online: <https://www.beneens.be/circulair> (accessed on 19 July 2021).
48. Binderholz GmbH. WOOD The Intelligent and Versatile Raw Material. *binderholz.com*. Available online: <https://www.binderholz.com/?klenk=> (accessed on 15 November 2021).
49. ResourceFull. Low Carbon Concrete ResourceFull Houthalen-Helchteren. Available online: <https://www.resourcefull.eu> (accessed on 9 January 2022).
50. ResourceFull. Foundationst Centrum Built without Cement. *ResourceFull.eu*. Available online: <https://www.resourcefull.eu/tcentrum-kampe-cementless-foundations> (accessed on 4 August 2021).
51. Eurostat, *Cooling and Heating Degree Days by NUTS 3 Regions—Annual Data*; European Commission: Brussels, Belgium, 2021. Available online: https://ec.europa.eu/eurostat/databrowser/view/nrg_chddr2_a/default/table?lang=en (accessed on 8 January 2022).
52. RMI. Royal Meteorological Institute of Belgium. 2021. Available online: <https://www.meteo.be/en/belgium> (accessed on 8 January 2022).
53. Taleghani, M.; Marshall, A.; Fitton, R.; Swan, W. Renaturing a microclimate: The impact of greening a neighbourhood on indoor thermal comfort during a heatwave in Manchester, UK. *Sol. Energy* **2019**, *182*, 245–255. [CrossRef]
54. Caeys, L. Comparing the Energy Performance and Sustainability of Vacuum Insulated Glass vs. Triple Glass in an Office Building: A Case Study in Belgium. Master's Thesis, Liege University, Liege, Belgium, 2022.
55. Meex, E. Early Design Support for Material Related Environmental Impact Assessment of Dwellings. 2018. Available online: <https://documentserver.uhasselt.be/handle/1942/27512> (accessed on 31 July 2021).
56. Roos Servaes, TOTEM & Circulariteit. Roos Servaes Masterclass Kamp C, 4 Oktober PDF Gratis Download. Available online: <https://docplayer.nl/131574855-Totem-circulariteit-roos-servaes-masterclass-kamp-c-4-oktober-2018.html> (accessed on 24 October 2021).
57. Gobbo, E.; Ghyoot, M.; Paduart, A.; Nasserredine, M. Reuse in Environmental Impact Assessment Tools. 2021. Available online: https://www.nweurope.eu/media/15802/reuse_in_environmental_impact_assessment_tools_2021.pdf (accessed on 10 December 2021).
58. E-Peil: Eis Voor Niet-Residentiële Gebouwen, Vlaanderen is Energie. 2021. Available online: <https://www.energiesparen.be/epb-pedia/e-peil/eis-niet-residentieel-2021> (accessed on 19 July 2021).
59. Attia, S. *Net Zero Energy Buildings (NZEB): Concepts, Frameworks and Roadmap for Project Analysis and Implementation*; Elsevier: Amsterdam, The Netherlands, 2018. [CrossRef]
60. Blom, I.; Itard, L.; Meijer, A. Environmental impact of building-related and user-related energy consumption in dwellings. *Build. Environ.* **2011**, *46*, 1657–1669. [CrossRef]
61. Collinge, W.O.; Landis, A.E.; Jones, A.K.; Schaefer, L.A.; Bilec, M.M. Dynamic life cycle assessment: Framework and application to an institutional building. *Int. J. Life Cycle Assess.* **2012**, *18*, 538–552. [CrossRef]
62. EnergyVille. Belgian Long Term Electricity System Scenarios. Available online: <https://www.energyville.be/belgian-long-term-electricity-system-scenarios> (accessed on 29 September 2021).
63. Federaal Planbureau—Publicatie—Het Belgische Energielandschap Tegen 2050—Een Projectie Bij Ongewijzigd Beleid. Available online: <https://www.plan.be/publications/publication-1728-nl-het-belgische-energielandschap-tegen-2050-een-projectie-bij-ongewijzigd-beleid> (accessed on 4 September 2021).
64. Ramon, D.; Allacker, K. Integrating long term temporal changes in the Belgian electricity mix in environmental attributional life cycle assessment of buildings. *J. Clean. Prod.* **2021**, *297*, 126624. [CrossRef]

65. ENGIE Electrabel. Radioactive Waste. *ENGIE Electrabel*. Available online: <https://nuclear.engie-electrabel.be/en/nuclear-energy/nuclear-power-plants-and-climate/radioactive-waste> (accessed on 26 October 2021).
66. VEB. Vlaams Energiebedrijf, Efficiënt in Energie. Available online: <https://www.veb.be/> (accessed on 17 October 2021).
67. Vlaanderen. Vlaams Energiebedrijf. Available online: <https://www.vlaanderen.be/organisaties/administratieve-diensten-van-de-vlaamse-overheid/beleidsdomein-omgeving/vlaams-energiebedrijf> (accessed on 28 October 2021).
68. Al-Obaidy, M.; Attia, S. Environmental Product Declaration Dataset of 't Centrum Circular Building in Westerlo, Belgium. Harvard Dataverse, 23 January 2022. Available online: <https://dataverse.harvard.edu/dataset.xhtml?persistentId=doi:10.7910/DVN/Z1CS97> (accessed on 23 January 2022).
69. One Click LCA. How We Work with Data at One Click LCA. *One Click LCA® Software*. Available online: <https://www.oneclicklca.com/how-we-work-with-data-at-one-click-lca/> (accessed on 21 July 2021).
70. Meex, E.; Hollberg, A.; Knapen, E.; Hildebrand, L.; Verbeeck, G. Requirements for applying LCA-based environmental impact assessment tools in the early stages of building design. *Build. Environ.* **2018**, *133*, 228–236. [CrossRef]
71. Li, Y.; Allacker, K.; Feng, H.; Heidari, M.D.; Pelletier, N. Net zero energy barns for industrial egg production: An effective sustainable intensification strategy? *J. Clean. Prod.* **2021**, *316*, 128014. [CrossRef]
72. Byggeriets Materialepyramide. Available online: <https://www.materialepyramiden.dk/> (accessed on 7 December 2021).
73. Larivière-Lajoie, R.; Blanchet, P.; Amor, B. Evaluating the importance of the embodied impacts of wall assemblies in the context of a low environmental impact energy mix. *Build. Environ.* **2022**, *207*, 108534. [CrossRef]
74. Grosso, M.; Thiebat, F. Life Cycle Environmental Assessment of Temporary Building Constructions. *Energy Procedia* **2015**, *78*, 3180–3185. [CrossRef]
75. Huijbregts, M.A.J.; Gilijsse, W.; Ragas, A.M.J.; Reijnders, L. Evaluating Uncertainty in Environmental Life-Cycle Assessment. A Case Study Comparing Two Insulation Options for a Dutch One-Family Dwelling. *Environ. Sci. Technol.* **2003**, *37*, 2600–2608. [CrossRef] [PubMed]
76. Cellura, M.; Longo, S.; Mistretta, M. Sensitivity analysis to quantify uncertainty in Life Cycle Assessment: The case study of an Italian tile. *Renew. Sustain. Energy Rev.* **2011**, *15*, 4697–4705. [CrossRef]
77. Vlaanderen Circulair. Circular Retrofit Lab. *Vlaanderen Circulair*. Available online: <https://vlaanderen-circulair.be/en/cases/detail/circular-retrofit-lab> (accessed on 5 November 2021).
78. Archipelago. Joseph Bracops Hospital, Anderlecht: An Urban Hospital Based on Circular Economy Principles. *Archipelago*. Available online: <https://archipelago.be/en/projects/how-can-we-design-an-urban-hospital-according-to-circular-economy-principles/> (accessed on 5 November 2021).
79. OPALIS. L'Institut de Botanique de l'ULg. *Opalis*. Available online: <https://opalisis.eu/fr/projets/linstitut-de-botanique-de-lulg> (accessed on 5 November 2021).
80. AGC Glass, AGC Glass Belgium. AGC Belgium—Glas—Beglazing—Pyrobel—WBDBO. Available online: <https://www.agcglassbelgium.be/> (accessed on 5 November 2021).
81. ROTOR, Rotor—Brussels Rotor. Available online: <http://rotordb.org/en> (accessed on 5 November 2021).
82. Allacker, K.; Debacker, W.; Delem, L.; De Nocker, L.; De Troyer, F.; Janssen, A.; Peeters, K.; Servaes, R.; Spirinckx, C.; Van Dessel, J. Environmental Profile of Building Elements [Update 2020], Danny Wille, OVAM; Stationsstraat 110, 2800 Mechelen, 2020. Available online: <https://lirias.kuleuven.be/1954287> (accessed on 9 November 2021).
83. Kamp, C. Circular Building: 't Centrum. Available online: <https://www.kampc.be/tcentrum/circulair-bouwen-t-centrum> (accessed on 19 July 2021).
84. Goffart, J.; Woloszyn, M. EASI RBD-FAST: An efficient method of global sensitivity analysis for present and future challenges in building performance simulation. *J. Build. Eng.* **2021**, *43*, 103129. [CrossRef]
85. Saltelli, A.; Aleksankina, K.; Becker, W.; Fennell, P.; Ferretti, F.; Holst, N.; Li, S.; Wu, Q. Why so many published sensitivity analyses are false: A systematic review of sensitivity analysis practices. *Environ. Model. Softw.* **2019**, *114*, 29–39. [CrossRef]
86. Saltelli, A.; Sobol', I.M. Sensitivity analysis for nonlinear mathematical models: Numerical experience. *Mat. Modelirovanie* **1995**, *7*, 16–28.
87. Baubook. Binderholz Brettsperrholz BBS (Fichte). Available online: https://www.baubook.at/vlbg/?URL_R=https%3A%2F%2Fwww.baubook.at%2Fm%2FPHP%2FInfo.php%3FSI%3D2142705769%26SW%3D2&SW=2 (accessed on 15 November 2021).
88. Ecoschelp. Bouw en Bescherm Met Schelpen. Available online: <https://www.ecoschelp.be/nl/> (accessed on 14 November 2021).
89. Decorte, Y.; Steeman, M.; Bossche, N.V.D. Effect of a one-dimensional approach in LCA on the environmental life cycle impact of buildings: Multi-family case study in Flanders. *Build. Environ.* **2021**, *206*, 108381. [CrossRef]
90. Giordano, R.; Serra, V.; Demaria, E.; Duzel, A. Embodied Energy Versus Operational Energy in a Nearly Zero Energy Building Case Study. *Energy Procedia* **2017**, *111*, 367–376. [CrossRef]
91. Levasseur, A.; Lesage, P.; Margni, M.; Deschênes, L.; Samson, R. Considering Time in LCA: Dynamic LCA and Its Application to Global Warming Impact Assessments. *Environ. Sci. Technol.* **2010**, *44*, 3169–3174. [CrossRef]
92. Helal, J.; Stephan, A.; Crawford, R.H. The influence of structural design methods on the embodied greenhouse gas emissions of structural systems for tall buildings. *Structures* **2020**, *24*, 650–665. [CrossRef]
93. Manfren, M.; Tagliabue, L.C.; Cecconi, F.R.; Ricci, M. Long-Term Techno-Economic Performance Monitoring to Promote Built Environment Decarbonisation and Digital Transformation—A Case Study. *Sustainability* **2022**, *14*, 644. [CrossRef]

94. Churkina, G.; Organschi, A.; Reyer, C.P.O.; Ruff, A.; Vinke, K.; Liu, Z.; Reck, B.K.; Graedel, T.E.; Schellnhuber, H.J. Buildings as a global carbon sink. *Nat. Sustain.* **2020**, *3*, 269–276. [[CrossRef](#)]
95. Robati, M.; Oldfield, P.; Nezhad, A.A.; Carmichael, D.G.; Kuru, A. Carbon value engineering: A framework for integrating embodied carbon and cost reduction strategies in building design. *Build. Environ.* **2021**, *192*, 107620. [[CrossRef](#)]
96. Akadiri, P.O.; Chinyio, E.A.; Olomolaiye, P.O. Design of A Sustainable Building: A Conceptual Framework for Implementing Sustainability in the Building Sector. *Buildings* **2012**, *2*, 126–152. [[CrossRef](#)]
97. VITO. Demolition Guide Recognizes Building Materials for Recycling or Reuse. Available online: <https://vito.be/en/news/demolition-guide-recognizes-building-materials-recycling-or-reuse> (accessed on 9 December 2021).
98. CEN/TC 350, CEN/TC 350/SC 1—Circular Economy in the Construction Sector. *iTeh Standards Store*. Available online: <https://standards.itih.ai/catalog/tc/cen/51316ef3-3dea-4483-8aab-cd1a8033cd41/cen-tc-350-sc-1> (accessed on 12 December 2021).
99. ISO, ISO/TC 323—Circular Economy (under Development). *ISO*. Available online: <https://www.iso.org/cms/render/live/en/sites/isoorg/contents/data/committee/72/03/7203984.html> (accessed on 12 December 2021).