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Comparative life cycle and energy performance analysis of a circular office building in a temperate climate

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Abstract

This study evaluates the whole-life environmental and energy performance of cross-laminated timber (CLT) versus reinforced concrete in office buildings, using ’t Centrum (Westerlo, Belgium), Belgium’s first certified circular CLT office building, as a real-world case study. Life cycle assessment (LCA) was conducted following ISO 14040/44 and EN 15978 (stages A1–A5, B4, B6, C3–C4; 50-year horizon), combined with dynamic energy simulation in DesignBuilder. Four construction material scenarios and four heating, ventilation, and air conditioning (HVAC) configurations were assessed. Net life cycle global warming potential (GWP) for the CLT reference scenario is 9.97 kg $CO_2e/(m^2{\cdot}year)$, representing a 30% reduction compared to the best-performing concrete alternative (14.34 kg $CO_2e/(m^2{\cdot}year)$), reported using the EN 15804 + A2 – 1/ + 1 biogenic carbon convention with fossil and biogenic flows disaggregated separately. Although CLT’s lower thermal mass increased overheating risk, adding bio-based thermal inertia materials reduced thermal discomfort hours by up to 25% per EN 16798–1 adaptive comfort criteria, with negligible carbon impact (< 1%). Operational energy consumption was comparable across structural systems. HVAC equipment accounts for 68% of material-related emissions in CLT buildings due to repeated replacement cycles over the building lifespan. Sensitivity analysis (Morris method) identified the electricity mix and HVAC system type as dominant uncertainty sources. In high-performance Belgian buildings, embodied carbon, not operational energy, is the decisive lifecycle factor, and CLT combined with bioclimatic design and low-carbon HVAC systems represents a credible circular pathway toward carbon–neutral construction in temperate climates.

Keywords Life cycle assessment, Embodied carbon, Cross-laminated timber, Circular building, Energy optimization, HVAC system, Thermal comfort

1 Introduction

The building sector accounts for 34% of global CO_2 emissions and 34% of total final energy demand, with emissions rising 5% since 2015 [1, 2]. Decarbonising construction, therefore, requires addressing both operational energy and embodied carbon across the full building life cycle. The European Union has responded through the revised Energy Performance of Buildings Directive (EPBD), the Construction Products Regulation, and mandatory lifecycle carbon reporting from January 2026 [3, 4]. Denmark already enforces a whole-life carbon cap of 8.6 kg $CO_2e/(m^2{\cdot}year)$ for new buildings [5]. Belgium, which ranks 35th out of 67 countries in climate

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performance [6] and where embodied carbon accounts for 18% of construction-sector emissions [2], remains structurally dependent on reinforced concrete and has yet to mandate lifecycle carbon assessment.

Within this regulatory context, cross-laminated timber (CLT) has emerged as a structurally viable, bio-based alternative to reinforced concrete. CLT panels sequester biogenic carbon during forest growth, are prefabricated with low construction waste, and are designed for disassembly and reuse at the end of life, aligning with circular economy principles [7–9]. Life cycle assessments (LCAs) of CLT buildings consistently report 30% to 50% lower whole-life global warming potential (GWP) compared to concrete equivalents in Northern European contexts [7, 10]. Meta-analyses across 18 international case studies confirm that substituting conventional structural materials with mass timber reduces construction-phase emissions by an average of 69% [11]. However, the reported net GWP of CLT depends critically on the biogenic carbon accounting convention applied: the EN 15804 + A2 − 1/+ 1 method, which credits biogenic CO_2 uptake at harvest and records its release at the end of life, can shift results by 16% at the building scale and up to 200% at the component scale [12]. This methodological variability has rarely been addressed in studies combining LCA with energy simulation.

A further knowledge gap concerns heating, ventilation, and air conditioning (HVAC) system interactions with CLT construction. CLT's low thermal mass relative to reinforced concrete accelerates indoor temperature response, increasing overheating risk in temperate climates with warm summers [13, 14]. Belgian projections estimate summer temperature increases of 2.4 to 6.6 ℃ by 2080 [15], intensifying this risk. Although passive strategies such as bio-based thermal mass additions and night ventilation can reduce thermal discomfort hours significantly [16], the combined effect of structural material choice, HVAC configuration, and passive mitigation on whole-life GWP has not been systematically quantified for circular office buildings in Belgium's climate. Existing comparative LCA and building energy simulation studies are largely limited to residential buildings, cold climates, or single HVAC configurations [10, 17–20], and none address a certified circular office building where design-for-disassembly and material reusability are explicit design constraints.

A prior study examined 't Centrum in Westerlo, the case study building used here, focusing on structural circularity and material reusability under steel and timber scenarios [21]. That study did not assess operational energy performance, HVAC interactions, or thermal comfort, nor did it compare multiple construction material scenarios. The present study addresses these gaps through a multi-criteria framework integrating LCA (ISO 14040/44, EN 15978; stages A1–A5, B4, B6, C3–C4; 50-year reference period) with dynamic energy simulation in DesignBuilder, applied to four construction material scenarios and four HVAC configurations. Biogenic and fossil carbon flows are disaggregated in accordance with EN 15804 + A2:2019 [12].

Three research questions structure this study:

(1) What is the whole-life GWP of CLT compared to reinforced concrete across construction and HVAC scenarios, and how sensitive are results to electricity mix and material service life assumptions?
(2) How do HVAC system type and thermal mass strategies interact with CLT's low thermal inertia to affect operational energy performance and occupant thermal comfort?
(3) Does the circular design of 't Centrum deliver measurable lifecycle carbon benefits relative to conventional concrete construction in Belgium's temperate climate?

This study makes three original contributions. First, it provides the first integrated LCA and building energy simulation of a certified circular CLT office building in Belgium, combining four materials and four HVAC scenarios in a single calibrated framework. Second, it explicitly disaggregates biogenic and fossil carbon flows, addressing a recognised transparency deficit in timber building LCA [12]. Third, it quantifies the carbon cost and thermal comfort benefit of bio-based thermal mass strategies, generating design-relevant evidence applicable to Belgium's forthcoming mandatory lifecycle carbon framework and to European EPBD implementation more broadly.

2 Literature review

2.1 The whole-life carbon imperative: from operational to embodied emissions

The dominant paradigm in building energy policy for three decades focused on operational energy as the primary decarbonisation lever. This framing is now demonstrably insufficient. Röck et al. [22] analysed 238 building case studies globally and established that in high-performance and near-zero energy buildings, embodied carbon can represent 45% to 100% of whole-life greenhouse gas emissions over a 50-year reference period. As operational performance improves through better insulation, airtightness, and low-carbon energy systems, the relative weight of embodied carbon intensifies rather than diminishes. Bertini et al. [23] confirmed this dynamic in a 2025 Belgian residential renovation context: nearly zero energy scenarios shifted the dominant emission source entirely to embodied impacts, making material selection the decisive design variable. The Royal Institution of Chartered Surveyors (RICS) Whole Life Carbon Assessment guidance [24], updated in 2024, formalises this shift by requiring mandatory reporting across all lifecycle stages A through C, signalling professional consensus that operational-only metrics are no longer defensible.

At the regulatory frontier, Denmark's 2025 whole-life carbon cap of 8.6 kg $CO_2e/(m^2 \cdot year)$ [5] represents the most stringent national threshold in Europe, encompassing both embodied and operational emissions. The European Union's revised EPBD and mandatory lifecycle carbon reporting from January 2026 extend this logic to all member states [3, 4]. Belgium, ranked 35th globally in climate performance [6], has not enforced equivalent standards, and its construction sector remains structurally dependent on reinforced concrete whose embodied carbon constitutes 18% of sectoral emissions [2]. This regulatory gap defines the urgency of identifying viable low-carbon structural alternatives for the Belgian context.

2.2 CLT as a low-carbon structural material: evidence, variability, and limitations

Cross-laminated timber has emerged as the most studied mass timber alternative to reinforced concrete in whole-life carbon assessments. Its environmental advantage derives from two concurrent mechanisms: its manufacturing process requires significantly less fossil energy than concrete or steel production [25], and biogenic carbon captured during forest growth remains stored in the material throughout its service life [7]. A systematic review by Younis and Dodoo [26] confirmed substantial and consistent GWP reductions across CLT LCA studies, with most reporting 30% to 60% lower whole-life impacts relative to equivalent concrete structures. Himes and Busby [11] quantified this advantage across 18 international comparisons, finding an average 69% reduction in construction-phase emissions when mass timber substitutes for conventional structural materials.

However, this literature contains a critical methodological fracture that renders direct cross-study comparisons unreliable: the treatment of biogenic carbon. Three conventions coexist. The carbon–neutral (0/0) approach ignores biogenic flows entirely, treating wood as inherently carbon–neutral. The EN 15804 + A2 − 1/+ 1 method credits biogenic CO_2 uptake at harvest as a negative emission and records its atmospheric release at the end of life as a positive, and is currently mandated in European Environmental Product Declarations. Dynamic LCA methods further account for the timing of sequestration and release relative to radiative forcing. Hoxha et al. [12] demonstrated that the choice between these conventions produces deviations of up to 16% at the building scale and up to 200% at the component scale, making biogenic carbon accounting the single largest source of methodological variability in CLT LCA. A systematic review of 79 wooden building LCA studies covering 226 scenarios found that only 12% incorporated dynamic biogenic carbon approaches, and fewer than 2% explicitly reported biogenic carbon impacts separately from fossil GWP, a transparency deficit that impedes reproducibility and policy comparability [27]. Andersen et al. [7] applied the − 1/+ 1 method to a Danish CLT office building and reported a 45% net whole-life GWP reduction versus a concrete equivalent, consistent with the findings of the present study.

CLT is not without environmental trade-offs. Synthetic adhesives in panel fabrication elevate eutrophication potential and ozone depletion impacts relative to concrete in some assessments [25, 28]. Fire protection requirements and acoustic performance layers add material with their own embodied carbon costs [29]. Nakano et al. [25] documented these trade-offs in a Japanese CLT research building, finding that CLT is competitive on GWP and primary energy but less favourable on toxicity and resource depletion indicators. Structural span constraints and adhesive bond service life uncertainty further limit applicability in large commercial programmes. These limitations are rarely foregrounded in climate-benefit-centred literature; the present study addresses them directly in the discussion.

2.3 HVAC performance, thermal mass, and the temperate climate challenge

The interaction between CLT's structural properties and HVAC system performance is an underdeveloped area of the literature, yet one with major consequences for both whole-life carbon and occupant comfort. CLT's lower thermal mass compared to reinforced concrete accelerates indoor temperature response to external and internal heat loads, increasing overheating risk in temperate climates during warm periods [13, 14]. In Belgium, summer temperatures are projected to rise by 2.4 to 6.6 ℃ by 2080 [15], intensifying this risk. Attia and Gobin [13] demonstrated that high-performance tertiary buildings in Belgium face persistent overheating despite superior insulation, with indoor temperatures above 25 ℃ causing an average 2% productivity loss. Amaripadath et al. [30] extended this analysis to a carbon–neutral CLT office building near Brussels, confirming that lower thermal mass spaces experienced greater heat stress under projected 2050 climate scenarios.

Two complementary mitigation pathways are documented. Bio-based thermal mass additions, particularly clay-based materials integrated within CLT wall assemblies, improve summer thermal performance: Paul [16] showed clay block additions reduced daily maximum indoor temperatures by 3 ℃ and cooling energy by up to 16%, while Kang et al. [31] confirmed enhanced Predicted Mean Vote indices through wall composition optimisation. HVAC system selection is equally consequential: Artun and Alemdağ [18] established that heating and cooling loads in temperate-humid CLT buildings are sensitive to both envelope composition and system configuration. Critically, the literature on HVAC interactions specific to CLT commercial buildings in temperate European climates is sparse. Existing studies are limited to residential buildings [19, 32], cold-climate contexts [17, 18], or single HVAC configurations [10, 20, 33]. None addresses a certified circular office building where design-for-disassembly constraints affect material composition and system integration simultaneously.

2.4 Circular economy principles and the limits of current LCA boundaries

The circular economy framework requires moving beyond recycling toward design-for-disassembly, material reusability, and component longevity. CLT construction is structurally compatible with these principles: panels connected mechanically rather than adhesively enable deconstruction and reuse at the end of life [26, 34]. Li et al. [34], reviewing 60 modular timber building case studies, identified reversible connection systems and material passports as the dominant circularity enablers, provided they are integrated from the design stage. Pomponi and Moncaster [35] established that circular economy benefits in construction require explicit LCA assessment of reuse potential; excluding Module D systematically undervalues circular designs. Younis and Dodoo [26] found that CLT buildings generate approximately three times less end-of-life waste than concrete equivalents, and that panel reuse under optimistic scenarios reduces whole-life GWP by a further 15% to 20%. The tension between EN 15978's exclusion of Module D from mandatory comparative reporting and the circular economy's emphasis on end-of-life value is directly relevant to certified circular buildings such as 't Centrum. The present study addresses this tension explicitly, providing a qualitative circular design assessment alongside the quantitative LCA results and disaggregating biogenic from fossil carbon flows throughout.

Cumulatively, this review establishes that CLT offers measurable whole-life carbon benefits over reinforced concrete, but that the magnitude depends critically on biogenic carbon accounting convention, HVAC system integration, climate context, and the depth of circular design assessment. No study has yet applied an integrated LCA and energy simulation framework to a certified circular CLT office building in a temperate Belgian climate, across multiple material and HVAC configurations, with explicit biogenic carbon disaggregation. This is the gap the present study fills.

More specifically, the contribution of this research relative to the current state of the art is threefold. First, unlike conventional LCA studies limited to static comparisons of embodied carbon, this study combines whole-life carbon assessment with operational energy and thermal comfort analysis, allowing the interactions between structural material choice, HVAC configuration, and indoor environmental performance to be evaluated simultaneously. Second, whereas existing studies on CLT buildings in Europe generally focus either on environmental impacts or on energy performance separately, this research integrates LCA, energy simulation, and comfort assessment within a single methodological framework applied to the same case study. Third, the study contributes new evidence for the Belgian temperate climate context, where integrated assessments of CLT tertiary buildings remain scarce, particularly for certified circular office buildings. By explicitly separating biogenic and fossil carbon flows while coupling carbon, energy, and comfort performance, the article advances current practice beyond conventional operational-versus-embodied carbon comparisons and provides a more holistic evaluation framework for low-carbon office buildings.

3 Methodology

The methodology used in this study is based on a four-phase structure defined by the ISO 14040: 2006 standard and is illustrated in Fig. 1 [1, 36]. This approach allows for a rigorous and systematic evaluation of the environmental impacts linked to the entire life cycle of a building.

The first phase concerns the definition of the objectives and the scope of the study. It consists of determining the goals of the analysis, the functional unit, and the system boundaries. In this research, the focus was placed on office buildings. A building archetype was defined based on its geometry, the materials used, the performance of its envelope, the HVAC systems, the renewable energy sources available on site, as well as its overall energy and environmental performance. This archetype was used as a reference for the development of three construction scenarios: a reinforced concrete scenario with bio-based insulation, a reinforced concrete scenario with polyurethane insulation, and a cross-laminated timber scenario integrating thermal inertia in the walls. From these base scenarios, combinations were developed by associating different HVAC system variants (heating, ventilation, and air conditioning), with the aim of identifying the best matches between construction materials and the energy performance of the systems.

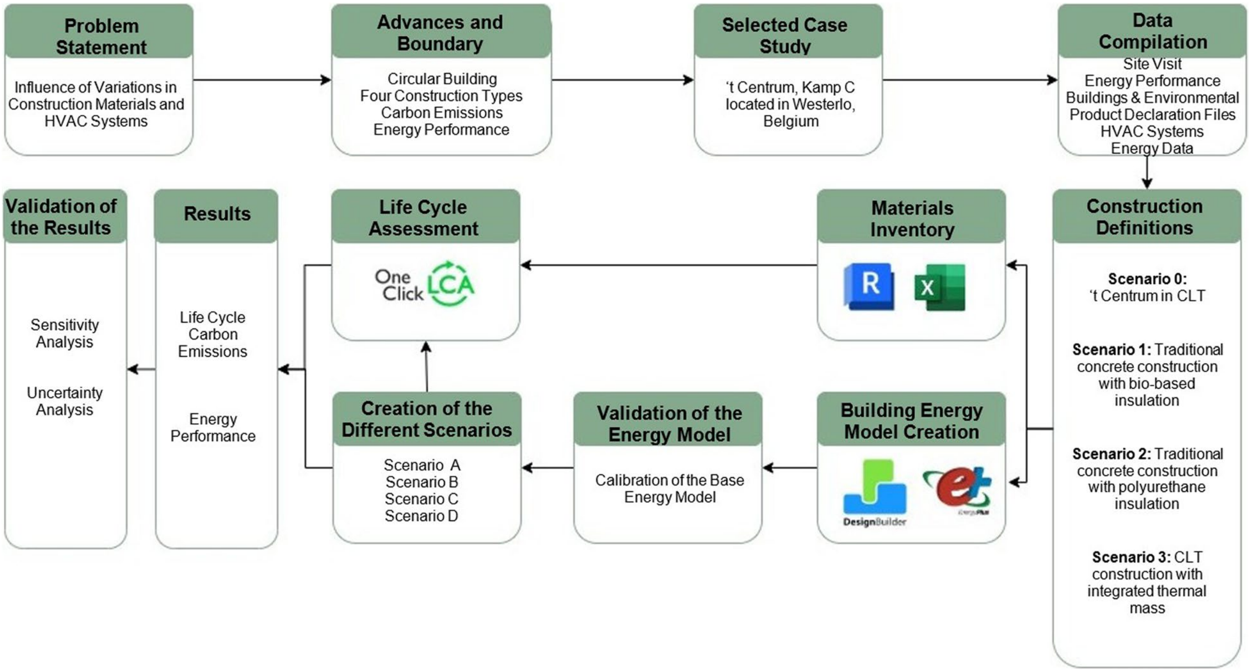


Fig. 1 Research conceptual framework

The second phase, called life cycle inventory, consists of collecting and quantifying all input data of the study, from materials and systems to the energy used. This data collection was carried out using digital modeling, specialized tools, and certified databases. The OneClick LCA tool, combined with the INIES database INIES version 5.6.0, provided impact data specific to materials, while Revit software was used for the detailed inventory of building components [37, 38]. The energy models linked to the different scenarios were developed in the DesignBuilder software.

The third phase focuses on the evaluation of environmental impacts. It converts the inventory flows into environmental impact indicators, such as GWP. The results were expressed in CO_2 equivalent emissions per square meter per year (kg CO_2e/(m^2·year)), over an analysis period of fifty years, in line with EN 15804 + A2: 2019 and EN 15978 standards [39, 40]. This functional unit allows a consistent comparison of the results across scenarios.

The interpretation of results makes up the fourth phase of the methodology. It brought together the results from the previous phases, analyzed them critically, and drew relevant conclusions. This step also made it possible to identify the limits of the study and to propose recommendations.

3.1 Phase of defining objectives and scope of study

The first phase of the methodology consists of defining the research objectives as well as the scope of the study. The main objective of this research is to measure and compare the environmental and energy performance of a building made of CLT with that of an equivalent building in conventional reinforced concrete. This comparison aims to assess to what extent bio-sourced materials and innovative construction solutions can help reduce the environmental impact in the building sector, while maintaining good energy performance and satisfactory indoor comfort.

To achieve this objective, three main parameters were defined and studied throughout the analysis: GWP, energy efficiency, and indoor thermal comfort. Their characteristics are presented in Table 1. This comparison aims to evaluate to what extent bio-sourced materials and innovative construction solutions can contribute to reducing the environmental impact in the building sector, while maintaining good energy performance and satisfactory indoor comfort.

The three indicators were evaluated using a combination of software tools and standards. GWP was calculated with OneClick LCA, which estimates greenhouse gas emissions over the building's life cycle. Energy efficiency was assessed using DesignBuilder, summing

Table 1 Key variables and their sub-variables

Variables	Carbon emissions	Energy performance	Thermal comfort
Sub-variables	GWP	Annual energy efficiency	Hours of discomfort
Indicator	kg $CO_2e/(m^2 \cdot year)$	$kWh/(m^2 \cdot year)$	hours
Standard	EN 15804 + A2: 2019	[41]	EN 16798–1: 2019 ASHRAE Standard 55
Tools	OneClick LCA	DesignBuilder	DesignBuilder

simulated energy use for heating, cooling, lighting, office equipment, and hot water. Thermal comfort was also evaluated in DesignBuilder according to ASHRAE Standard 55, counting only hours of discomfort when the cooling system is active, to focus on summer periods when comfort is not ensured.

The approach began with the selection of the case study. The chosen building had to be, imperatively, a CLT construction to serve as a reference in the comparison with concrete alternatives. The choice was made for the building 't Centrum, located in Westerlo, Belgium. It is the first circular building built in CLT, inaugurated in 2022. This building presents a particular interest because it integrates both energy and environmental aspects, which makes it a relevant and representative case study for the intended cross-analysis. The building is represented in Fig. 2.

In order to deepen research on new construction methods, the building will undergo a process of deconstruction and progressive reconstruction, divided into three successive phases until 2037. This approach will allow the identification of potential obstacles throughout the process. This trajectory has already been awarded by the jury of the Procura + Awards [42].

From an architectural point of view, the building develops over three levels and was designed to adapt to different uses over time. It mainly houses modular office spaces, made possible thanks to modular partitions. The main structure is based on a column-beam system combined with footings, offering flexibility for interior layout. The building is shown in Fig. 3.

In addition, each material used is provided with a specific passport, in the form of a small label that, once scanned, gives access to all its properties. This tool is designed to optimize the reuse of the different materials. These passports gather detailed digital data on the materials and products used in the building: their history, their potential for reuse, the conditions for reusing each of them, as well as their ability to be recycled or biodegraded. In case of disassembly, this information will make it easier to identify the materials and indicate the most suitable reuse solutions [43].

These materials can indeed be resold in the future. For example, CLT beams can be used in another structure. In addition, all the insulation materials in the building can be easily removed thanks to a disassembly system without glue.

Fig. 2 South-West Facade of 't Centrum

Fig. 3 Architectural plans of ’t Centrum

From a technical point of view, all HVAC installations, such as radiators, ventilation ducts, and electrical circuits, are installed and left visible at ceiling level. This configuration goes beyond the simple reuse of construction materials, as it also allows the recovery and reuse of the technical systems themselves. The only element that, according to the site visit, will not have a second life in the building is the lighting. The building characteristics are listed in Table 2.

The circular design of ’t Centrum integrates several key principles aligned with circular economy practice. The CLT structural panels are assembled using reversible mechanical connections, enabling disassembly and reuse at the end of life. The building’s open floor plan and modular layout facilitate future adaptation or reprogramming.

Module D, which covers the potential for reuse, recovery, and recycling beyond the system boundary, was excluded from the primary LCA results in accordance with EN 15978 mandatory reporting scope. However, given the circular design of ’t Centrum, including reversible mechanical connections and CLT panel reusability, the qualitative end-of-life potential is discussed in Sect. 3.3. This exclusion does not diminish the circular value of the building; rather, it reflects standard practice in comparative LCA studies where Module D assumptions can introduce significant variability.

The CLT structural panels are assembled using dry and screw connections throughout the core and shell, with no adhesive or hard chemical connections in the primary structure. An expert assessment of 1 387 connection systems in the building using the DeCon disassembly evaluation system returned a total disassembly potential of 92%, with connection accessibility at 97% and zero design barriers recorded, confirming that ’t Centrum is among the most thoroughly designed-for-disassembly office buildings currently documented in the literature [44].

3.2 Lifecycle inventory phase

Once this building was identified, it was necessary to collect the energy and technical data required for modeling and evaluating its performance. A site visit was carried out to directly observe the installations, technical systems, and configuration of the building. The collected data included wall compositions, architectural plans, material datasheets (EPD), energy performance data (EPB file), as well as detailed information on the installed HVAC systems. To collect the building’s energy data in real time, the Calculus platform was used. This platform enables continuous monitoring of the building’s energy and water consumption. It was designed to be flexible and to minimize resource use as much as possible. The climate data from Antwerp were used for this project. This choice was made because these data better reflect the actual climatic conditions of the building, unlike the data from Brussels Airport, which are not representative. This decision was confirmed by measurements from the weather station installed on

Table 2 Site location data of the case study

	Year of construction	Location	Climate zone	Floor area (m^2)	Number of floors	Occupants
’t Centrum	2022	Westerlo	Tempered	2 087	3	115

the building's roof. Since this station is not an official Belgian meteorological station, the Antwerp data were imported into the software.

Unlike conventional building management systems, Calculus goes further by integrating smart algorithms that account for user presence, behavioral patterns, and weather forecasts. For instance, heating and cooling systems automatically shut down when there is no demand, reducing unnecessary energy use. Water consumption is also continuously monitored, along with the recovery and treatment of greywater. The overarching goal is to limit the use of potable water [45]. A detailed inventory of materials and systems is shown in Table 3.

The embodied carbon factor for CLT used in this study, sourced from the INIES database via OneClick LCA, yields a notably low net value (approximately 0.22 kg $CO_2e/(m^2 \cdot year)$ over 50 years). This figure warrants explicit explanation, as it is the result of two distinct mechanisms that must not be conflated.

First, the gross fossil emissions associated with CLT manufacturing (modules A1–A3), covering timber harvesting, kiln drying, adhesive application, and panel pressing, amount to approximately 60–130 kg CO_2e/m^3 of CLT, depending on the EPD source and the electricity mix used in production [7]. For this study, the EPD selected from INIES reflects a European average manufacturing context. It should be acknowledged that not all EPDs for CLT include full transport distances (A4) or factory energy use in the same way; where specific data were unavailable, OneClick LCA default assumptions were applied.

Second, and critically, CLT stores biogenic carbon captured by trees during forest growth. Per EN 16449 and following the EN 15978 −1/+1 accounting convention, biogenic carbon uptake is counted as a negative emission at the point of harvest (approximately −700 to −985 kg CO_2e/m^3), offsetting the fossil A1–A3 emissions in the net reported value [11]. This is standard practice in comparative LCA studies of timber buildings and is consistent with the methodology applied here [7, 11]. However, biogenic carbon storage is a temporary benefit: it is released at end of life (C3–C4) when the timber is incinerated or decomposes. Both flows are reported separately in Appendix A in accordance with EN 15978 and EN 15804 + A2: 2019.

Excluding biogenic storage, the gross embodied carbon of the CLT structure (A1–A5) is approximately 130–160 kg CO_2e/m^2 for the building, which remains substantially lower than the reinforced concrete alternative. The net value reported in results integrates biogenic storage and should be read alongside Appendix A, which disaggregates fossil GWP, biogenic uptake, and end-of-life biogenic release. This approach is consistent with recent guidance on transparent carbon accounting in timber buildings [7, 11, 12].

3.2.1 Creation of the base model

To simulate the energy performance of these scenarios, a base model was created from the 't Centrum building. The initial energy model, developed by Claeys [46], was adopted, calibrated, and adjusted based on actual consumption data, in accordance with ASHRAE 14–2002 [47]. This model was developed using DesignBuilder, which uses the EnergyPlus simulation engine.

This simulation includes all the technical aspects of the building, such as inverters, photovoltaic panels, lighting, HVAC systems, domestic hot water (DHW) production and office equipment. Energy demand profiles were defined to realistically reflect the daily operation of the building and the use of the different equipment. This approach ensures consistency between the simulated energy data and the environmental modeling carried out in OneClick LCA.

In parallel, a digital model of the building was created in Revit, allowing for the extraction of precise material quantities needed for the life cycle assessment in OneClick LCA. This modeling ensures uniformity between the energy data and the environmental data. The EPDs were selected from the OneClick LCA database based on the actual materials used on-site to best reflect real construction conditions. For CLT specifically, the selected EPD (EPD reference number: 2000102_002_EN) reports a net A1–A3 GWP that includes biogenic carbon offset; the gross fossil value and the biogenic storage component are disaggregated and reported separately in Appendix A, in accordance with EN 15804 + A2: 2019.

During the data entry process in OneClick LCA, an energy mix was selected to reflect the specific characteristics of the building study.

For this purpose, the Belgian energy mix for 2024 was used, with a value of 0.132 kg CO_2/kWh, in accordance with the data published by the Association of Issuing Bodies (AIB) in the Residual Mixes and European Attribute Mix 2024 report [48].

This choice is justified by the technical characteristics of the building, which is fully powered by electricity. It features high-performance and advanced technologies, such as a geothermal heat pump and a double-flow ventilation system, that contribute to optimized energy consumption. Moreover, the large area of photovoltaic panels installed on the building allows for partial self-consumption, with the Photovoltaic (PV) electricity production deducted from the net energy demand.

The use of the 2024 Belgian energy mix therefore aims to realistically reflect the building's energy strategy and to integrate a greener and more sustainable energy profile into the environmental assessment.

Table 3 Summary table of the different quantities of materials

Quantities of materials	Units	Reference scenario Quantities	Scenario 1 Quantities	Scenario 2 Quantities	Scenario 3 Quantities
Building materials					
Wood cladding	m^3	23.75	23.75	23.75	23.75
CLT	m^3	468.74	-	-	468.74
Timber frame	m^3	19.54	-	-	19.54
Cement-free concrete	m^3	68.21	-	-	68.21
Reinforced concrete	m^3	-	760.18	760.18	-
Concrete blocks	m^3	-	84.53	84.53	-
Seashells	m^3	548.47	548.47	548.47	548.47
Lime screed	m^3	91.41	-	-	91.41
Fermacell dry screed	m^3	29.68	-	-	29.68
Cement screed	m^3	-	165.1	165.1	-
Fermacell wall	m^3	5.29	5.29	5.29	5.29
Rigidur	m^3	-	-	-	12.61
Clay blocks	m^2	-	-	-	480.68
FINEO vacuum-sealed glass	m^2	258.92	258.92	258.92	258.92
Thermobel TG Glass	m^2	509.69	509.69	509.69	509.69
Glass partitions	m^2	186.76	186.76	186.76	186.76
Plant substrate	m^3	2.43	2.43	2.43	2.43
JUUNOO partitions	m^3	73.23	73.23	73.23	73.23
OSB panels	m^3	20.17	20.17	20.17	20.17
Softwood battens	m^3	2.41	2.41	2.41	2.41
Tiles	m^3	32.14	32.14	32.14	32.14
Window frames	m^3	9.15	9.15	9.15	9.15
Bituminous membrane	m^3	2.57	2.57	2.57	2.57
Rainproof membrane	m^3	2.95	0.38	0.38	2.95
frame infill panels	m^3	4.32	4.32	4.32	4.32
Slag concrete pavers	m^2	209.04	-	-	209.04
Concrete pavers	m^2	-	209.04	209.04	-
Hemp bricks	m^3	228.53	-	-	228.53
Rigid wood fiber	m^3	23.76	387.22	-	23.76
Blown cellulose insulation	m^3	82.67	-	-	82.67
Linen panels	m^3	91.95	-	-	91.95
Cellular glass	m^3	111.28	-	-	111.28
Polyurethane	m^3	-	-	260.53	-
HVAC systems					
Galvanized steel	kg	1 916	1 916	1 916	1 916
Inverters	Unit	4	4	4	4
High-density polyethylene	kg	1 000	1 000	1 000	1 000
Aluminium	kg	1 905	1 905	1 905	1 905
Steel	kg	164	164	164	164
Reinforced concrete	kg	30 116	30 116	30 116	30 116
Copper tubes	kg	1 262	1 262	1 262	1 262
Photovoltaic panels	m^2	213	213	213	213
Mineral wool	kg	2 270	2 270	2 270	2 270
Heat pump	Unit	1	1	1	1
Acoustic radiator panels	m^3	14.42	14.42	14.42	14.42

3.2.2 Core calculation formulas

The GWP is calculated in Eq. (1) per EN 15978 as:

$$\mathrm{GWP}_{\mathrm{total}} = (1/A_{\mathrm{ref}} \bullet T) \times \sum (m_i \bullet \mathrm{EF}_i) \qquad (1)$$

where m_i is the quantity of material or energy flow i (kg or kWh), EF_i is the corresponding emission factor (kg $\mathrm{CO_2e}$/unit) sourced from EPD data, A_{ref} is the reference floor area (m^2), and T is the building reference study period (years, here $T = 50$). Summing across all lifecycle modules included (A1–A5, B4, B6, C3–C4) yields the total GWP expressed in kg $\mathrm{CO_2e/(m^2 \cdot year)}$.

Operational energy performance is expressed as the Energy Use Intensity (EUI) in Eq. (2):

$$\mathrm{EUI} = E_{\mathrm{delivered}}/A_{\mathrm{ref}} \qquad (2)$$

where $E_{\mathrm{delivered}}$ is the annual delivered energy (kWh/year) extracted from DesignBuilder simulation outputs, covering heating, cooling, ventilation, domestic hot water, lighting, and plug loads. EUI is expressed in kWh/(m^2·year) and benchmarked against the Belgian Energy Performance of Buildings (EPB) regulatory requirements.

Thermal discomfort hours are calculated per EN 16798-1 using the adaptive comfort model. The upper comfort limit for Category II spaces (normal level of expectation, recommended for new buildings) is defined in Eq. (3) as:

$$T_{\mathrm{comfort\_max}} = 0.33T_{\mathrm{rm}} + 18.8 + 2 \qquad (3)$$

where T_{rm} is the running mean outdoor temperature (°C), calculated as an exponentially weighted mean of preceding daily outdoor temperatures. An occupied hour is classified as a discomfort hour when the operative indoor temperature exceeds $T_{\mathrm{comfort\_max}}$. The building is considered to have an overheating problem when discomfort hours exceed 5% of total occupied hours during the cooling season (May to September), in accordance with EN 16798-1 Category II criteria.

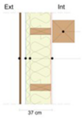
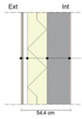
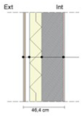
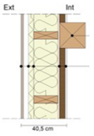
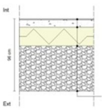
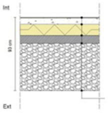
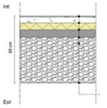
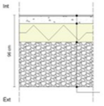
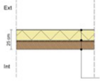
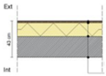
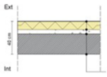
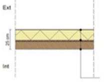
3.2.3 Creation of the different study scenarios

Based on this data, four construction scenarios were defined to allow a coherent comparative analysis. The first scenario corresponds to the actual building, built in CLT, which serves as the reference scenario. The second scenario represents a traditional reinforced concrete construction using bio-based insulation. The third scenario is similar to the previous one but with a synthetic polyurethane insulation. Finally, the fourth scenario also relies on a CLT construction but with a specific integration of thermal inertia in the walls, aimed at improving the comfort and thermal regulation of the building. All the different wall compositions of the different scenarios are listed in Table 4. The alternative concrete scenarios are based on real construction practices. The wall assemblies were defined using realistic layer thicknesses in order to achieve equivalent U-values across scenarios, ensuring a fair comparison of thermal performance. In addition, the dimensions of the structural elements were selected based on typical real-world configurations, allowing the scenarios to accurately reflect practical construction conditions.

These scenarios were defined to represent both common traditional practices in Belgium and innovative alternatives that could be implemented as part of the environmental transition of the sector.

For this study, four HVAC scenarios were defined to analyze and compare the impact of different technical configurations on the building's energy performance, indoor comfort and environmental impacts. The choice of these scenarios was made to represent high-tech efficient systems, simplified solutions and specific variations that help to better understand the influence of certain

Table 4 Details of the different study scenarios

	Scenario 0		Scenario 1		Scenario 2		Scenario 3	
External wall		1. 20 mm Cladding 2. 50 mm Air cavity 3. 1 mm Rain screen 4. 50 mm Wood fibre 5. 235 mm Timber frame + cellulose insulation 6. 2.5 mm Vapour layer 7. 12.5 mm Gypsum fibre board		1. 20 mm Cladding 2. 50 mm Air cavity 3. 1 mm Rain screen 4. 220 mm Wood fibre 5. 250 mm Concrete block 6. 2.5 mm Vapour layer 7. 12.5 mm Gypsum fibre board		1. 20 mm Cladding 2. 50 mm Air cavity 3. 1 mm Rain screen 4. 140 mm Polyurethane 5. 250 mm Concrete block 6. 2.5 mm Vapour layer 7. 12.5 mm Gypsum fibre board		1. 20 mm Cladding 2. 50 mm Air cavity 3. 1 mm Rain screen 4. 50 mm Wood fibre 5. 235 mm Timber frame + cellulose insulation 6. 2.5 mm Vapour layer 7. 12.5 mm Gypsum fibre board 8. 56 mm Clay blocks 9. 12.5 mm Gypsum fibre board
Foundation		1. 10 mm Tiles 2. 100 mm Cement-free screed 3. 250 mm Hemp bricks 4. 600 mm Sea shell		1. 10 mm Tiles 2. 80 mm Cement screed 3. 140 mm Wood fibre 4. 100 mm Concrete slab 5. 600 mm Sea shell		1. 10 mm Tiles 2. 80 mm Cement screed 3. 90 mm Polyurethane 4. 100 mm Concrete slab 5. 600 mm Sea shell		1. 10 mm Tiles 2. 100 mm Cement-free screed 3. 250 mm Hemp bricks 4. 600 mm Sea shell
Roof		1. 3 mm Bitumen layer 2. 130 mm Cellular glass 3. 1 mm Rain screen 4. 18 mm OSB board 5. 100 mm CLT		1. 3 mm Bitumen layer 2. 18 mm OSB board 3. 106 mm Wood fibre 4. 250 mm Concrete slabs		1. 3 mm Bitumen layer 2. 100 mm Polyurethane 3. 50 mm Cement screed 4. 250 mm Concrete slabs		1. 3 mm Bitumen layer 2. 130 mm Cellular glass 3. 1 mm Rain screen 4. 18 mm OSB board 5. 100 mm CLT

parameters, such as the ventilation strategy or the type of heating emitters.

The first scenario A corresponds to the systems installed in the case study building, namely a geothermal heat pump combined with a mechanical ventilation system with heat recovery and radiators. This scenario represents a high-tech solution and serves as the reference. The second scenario B explores the impact of natural ventilation on the building's energy behavior and comfort. In this case, the mechanical ventilation was deactivated, leaving only the geothermal heat pump and radiators as the heating system. The third scenario C introduces a floor heating system in order to study its effect on different construction typologies as well as on occupant comfort. Finally, the fourth scenario D proposes a simpler alternative, with an air-to-water heat pump, mechanical ventilation, and radiators. This scenario makes it possible to evaluate the performance and environmental impact of less complex systems requiring more standard equipment. The comparative results of these scenarios are presented in Fig. 4.

3.3 Life cycle impact assessment phase

After creating the different HVAC scenarios, each of them was simulated in DesignBuilder in order to obtain the energy performance results for each combination. These results were then entered into OneClick LCA to account for the changes in energy use and their impact on the life cycle assessment. The input data used in OneClick LCA included material quantities and energy performance extracted from the Revit and DesignBuilder models, as well as Environmental Product Declarations (EPDs) for CLT and reinforced concrete. The operational energy data from DesignBuilder, expressed in (kWh/(m^2·year)), were converted into primary energy and entered as annual electricity consumption for module B6 in OneClick LCA. This approach ensures that the operational phase (B) and the actual energy performance (B6) of the building are accurately represented in the life cycle analysis.

The life cycle assessment of the different scenarios begins with the selection of the life cycle stages considered in the study. The main strength of this study lies in the integration of carbon emissions over the entire life cycle, including stages A1–A5, B4, B6, and C3–C4, in accordance with Danish standards (Nordic Sustainable Construction, 2024). The different calculations were carried out for modules A1–A3, A4–A5, B4–B5, B6–B7, and C2–C4, as shown in Fig. 5. The life cycle study was conducted over a period of 50 years. The results of the study will be compared to the total global warming potential threshold of 8.6 kg CO_2e/(m^2·year). This value includes an independent limit for the construction process, corresponding to 1.5 kg CO_2e/(m^2·year), which covers life cycle modules A4–A5.

As mentioned earlier, the software used for the assessment of global warming potential impacts is OneClick LCA. This tool is specifically designed for carrying out LCA and provides access to several environmental databases of construction materials. For example, the INIES

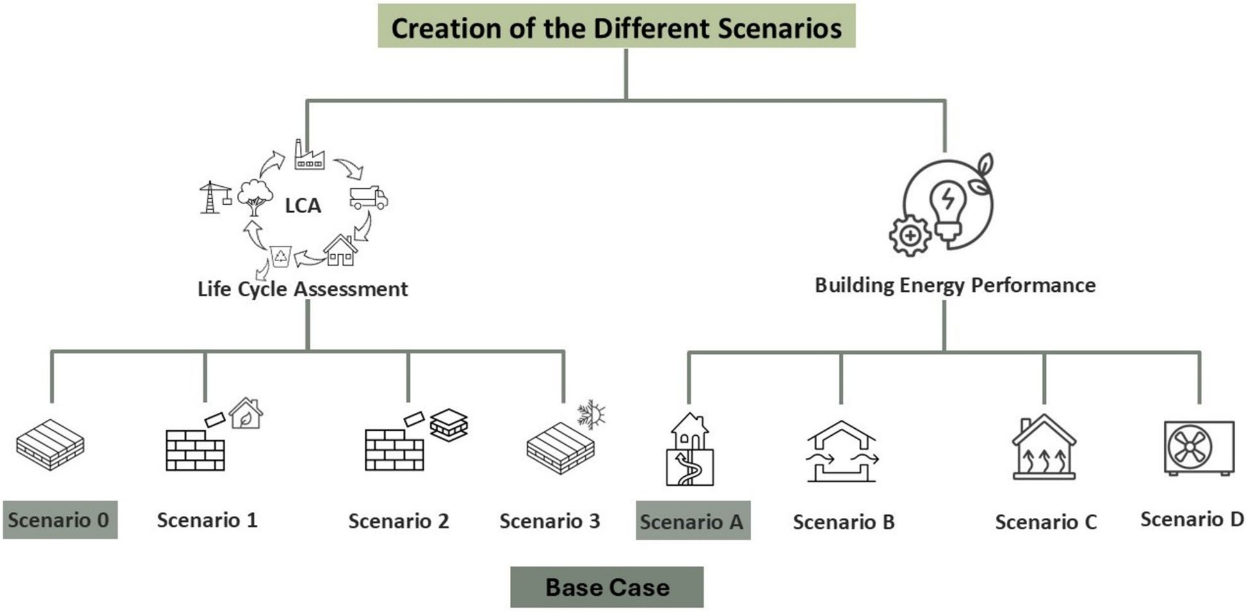


Fig. 4 Various scenarios of the study

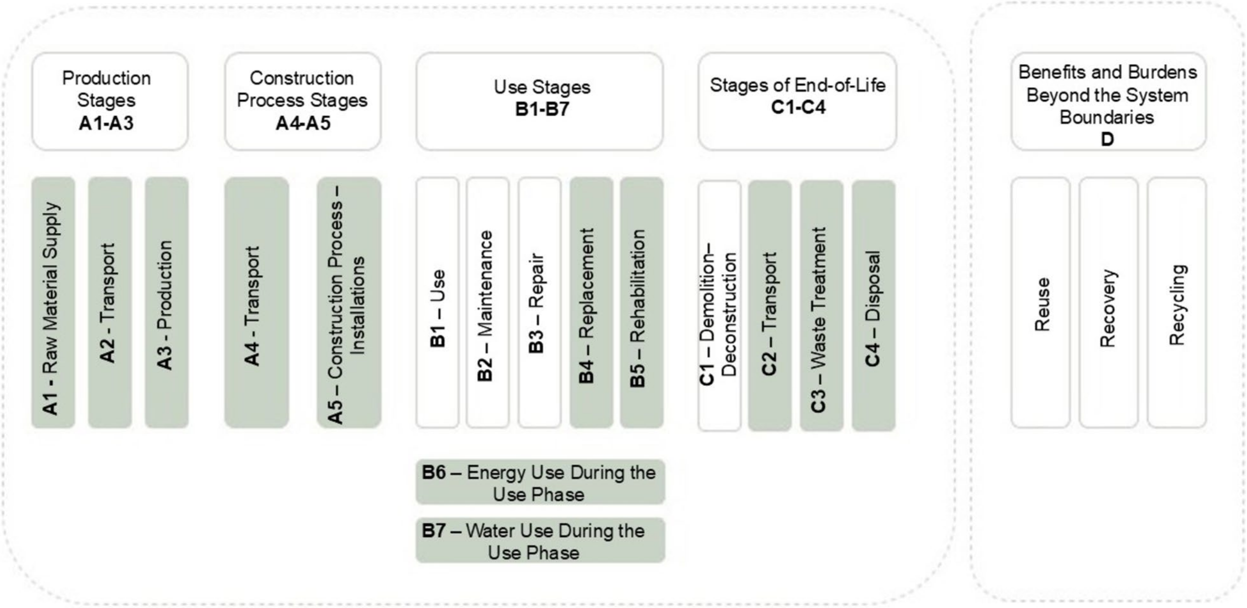


Fig. 5 Considered life cycle stages in the study

database is used in this study for data selection. These EPDs are directly integrated into the LCA tool. For each module included in the analysis, data sources and specific assumptions were carefully defined to ensure the consistency and reliability of the scenarios. Environmental data were primarily sourced from the EPDs of the various materials used. The INIES database was used to supplement default values in the absence of specific data. In addition, on-site measurements and technical documentation were used to validate energy consumption and system performance data.

- Modules A1–A5 cover raw material extraction and processing, transportation to the manufacturing site, product manufacturing, and on-site construction processes. For these modules, environmental impact values were extracted directly from the EPDs of the materials used on site. In the absence of a product-specific EPD, generic data from the OneClick LCA database were used to complete the inventory. Transportation distances and construction waste ratios are based on project documentation and default assumptions provided by the software.
- Modules B1–B7 represent the use phase, including maintenance, repair, and replacement (B4–B5), as well as operational energy and water use (B6–B7). Data for these modules were obtained through the Calculus platform, which monitors real-time energy and water consumption, combined with HVAC performance data and user behavior assumptions. The maintenance and replacement of technical systems such as the heat pump, ventilation units, and other mechanical equipment were also considered over the 50-year life cycle, in accordance with typical service lives recommended by manufacturers and the OneClick LCA database.
- Modules C1–C4 account for the end-of-life phase, including deconstruction, transportation of waste, processing, and final disposal. Default datasets from OneClick LCA were used for these modules, complemented by waste management assumptions consistent with regional practices. At the end of life, it was assumed that 70% of the materials are directed to recycling pathways, including material recovery as aggregates and the recycling of metals and glass. Additionally, 21% of the materials are disposed of in landfills, while 9% are sent to incineration.
- Module D was not included in the scope of this study. This choice is justified, because the variability of end-of-life scenarios makes results difficult to generalize and compare across studies, and because EPD databases for Module D are often less complete or reliable than those for modules A–C.

The LCA was structured sequentially according to EN 15804 + A2 (modules A–C). The operational energy use (B6) was derived from DesignBuilder simulations using the projected Belgian electricity mix for 2024. Photovoltaic self-production was subtracted from the net electricity demand, representing approximately 20 000 kWh/year. Sensitivity analysis was conducted by varying material service life (± 20%) and HVAC efficiency (coefficient of performance (COP) ± 10%) to evaluate the robustness of results.

3.4 Interpretation phase

The last phase concluded with the processing and detailed analysis of the results obtained. The interpretation of the results was based on several axes of analysis. First, a hot spot identification was carried out in order to distinguish the most significant contributions between the embodied emissions of materials and the operational emissions related to the building's use. Then, a cross-analysis with the energy simulation results made it possible to link environmental and energy performance. A sensitivity analysis was also conducted with two key parameters: the lifespan of the materials and the efficiency of the HVAC systems, in order to assess their influence on the overall results. In addition, the share of renewable energy in the electricity mix was varied to evaluate its impact on module B6, which represents the operational energy consumption during the use phase. Also, uncertainties were characterized using the Morris method, which made it possible to define variability ranges around the results.

The Morris method is a one-at-a-time (OAT) screening technique that generates r trajectories through the parameter space, computing elementary effects for each input parameter. In this study, $r=10$ trajectories were used, resulting in $10(k+1)$ model evaluations, where $k=10$ is the number of parameters assessed. The Morris method was employed to perform the sensitivity and uncertainty analysis. This approach consists in varying one input parameter at a time while keeping all others constant [49]. This method was selected because it is well adapted to the characteristics of the present study, in which the input parameters are explored within fixed bounds and treated with equal probability. It enables an efficient screening and prioritization of influential variables while maintaining a reasonable computational effort. For each parameter, five simulations were performed. For each simulation, only one parameter is assigned a new value, allowing the identification of which parameters have the greatest influence on the study outcomes. Parameter ranges are detailed in Table 5. The propagation of uncertainties was quantified by analyzing the dispersion of the results

Table 5 Parameters for sensitivity and uncertainty analysis

Parameters for sensitivity analysis	
Quantity of materials	− 10%, − 20%, 10%, 20%, 30%
Share of renewable energy	25%, 40%, 75%, 100%
Wall composition	Hemp brick (0.25 → 0.15 m), cellular glass (0.13 → 0.15 m), flax insulation (0.08 → 0.12 m), individually or in combination
Building lifespan	25–100 years
Types of HVAC systems	Ventilation (mechanical/natural), system (geothermal heat pump/gas boiler), emitters (radiators), PV (with/without)
Heat pump COP	2–5
Heat pump lifespan	10–35 years
Glazed surfaces	300–450 m^2
Heating setpoint temperature	19–21.5 ℃
Airtightness	0.3–1.2 air changes per hour
Parameters for uncertainty analysis	
Choice of materials (change of EPDs)	Belgium and European country or bordering country
Recycling rate and end-of-life recovery	10%, 25%, 50%
Building lifespan	25, 35, 50, 75, 100 years
Material lifespan	5%, 10%, 20% on the lifespan
Choice of energy mix	Europe (wind), Belgium (2022), 2030 scenario, Belgium residual (GWP only, 2023), Denmark (2023), Denmark consumption without renewables (2022)
Site impacts	2030 and 2050 projections (± 15% on the emission factor)
Choice of climate file	Antwerpen, BEL_BRUSSELS_IWEC, BEL_SAINT HUBERT_IWEC
Number of simulation years	2020–2025
Lighting schedule	− 5% – + 25%
User behavior	± 20%

obtained from all simulations. This was expressed either as a standard deviation providing a clear indication of the model's sensitivity to each input variable.

Finally, the calibration of the energy model was carried out using actual monthly consumption data and validated according to the criteria of the ASHRAE 14 guideline, with a mean bias error (MBE) lower than 5% and a coefficient of variation of the root mean square error (CV(RMSE)) lower than 15%. The results were also compared with the regulatory requirements for building energy performance (EPB), with the Danish standard for the evaluation of carbon impacts, as well as with the maximum admissible hours of discomfort for occupants. This comparison makes it possible to position the studied scenarios both in relation to current obligations and to emerging sustainability standards.

The following section presents the results of the model validation, life cycle impact calculations, and the comparison of the different scenarios. A particular attention is given to the trade-offs between embodied and operational impacts, as well as to the sensitivity of the results to the main parameters investigated.

4 Results

4.1 Energy performance

The analysis of the energy performance of different scenarios shows that CLT constructions can compete with traditional buildings in terms of energy consumption and indoor comfort, provided they are paired with appropriate technical systems. The combination of a geothermal heat pump, mechanical ventilation and radiators allows for the optimization of both energy use and occupant comfort. This best-performing combination is illustrated in Fig. 6. The addition of thermal mass, through the integration of high-inertia materials in the wall, further improves performance by stabilizing indoor temperatures and reducing summer overheating by 25%. In this study, passive strategies to mitigate overheating in CLT constructions include the integration of clay blocks within wall assemblies. These elements increase thermal inertia by absorbing heat during the day and releasing it at night, when the building can be ventilated with cooler outdoor air, thereby improving indoor thermal conditions. This strategy enables CLT buildings to compete with traditional constructions while maintaining the environmental benefits associated with bio-based materials.

These results suggest that the energy performance of CLT buildings in temperate climates depends less on the structural material itself than on the coherence between envelope composition, thermal inertia, and HVAC system selection. The findings therefore challenge the common assumption that lightweight timber buildings are inherently less suitable for thermal comfort in

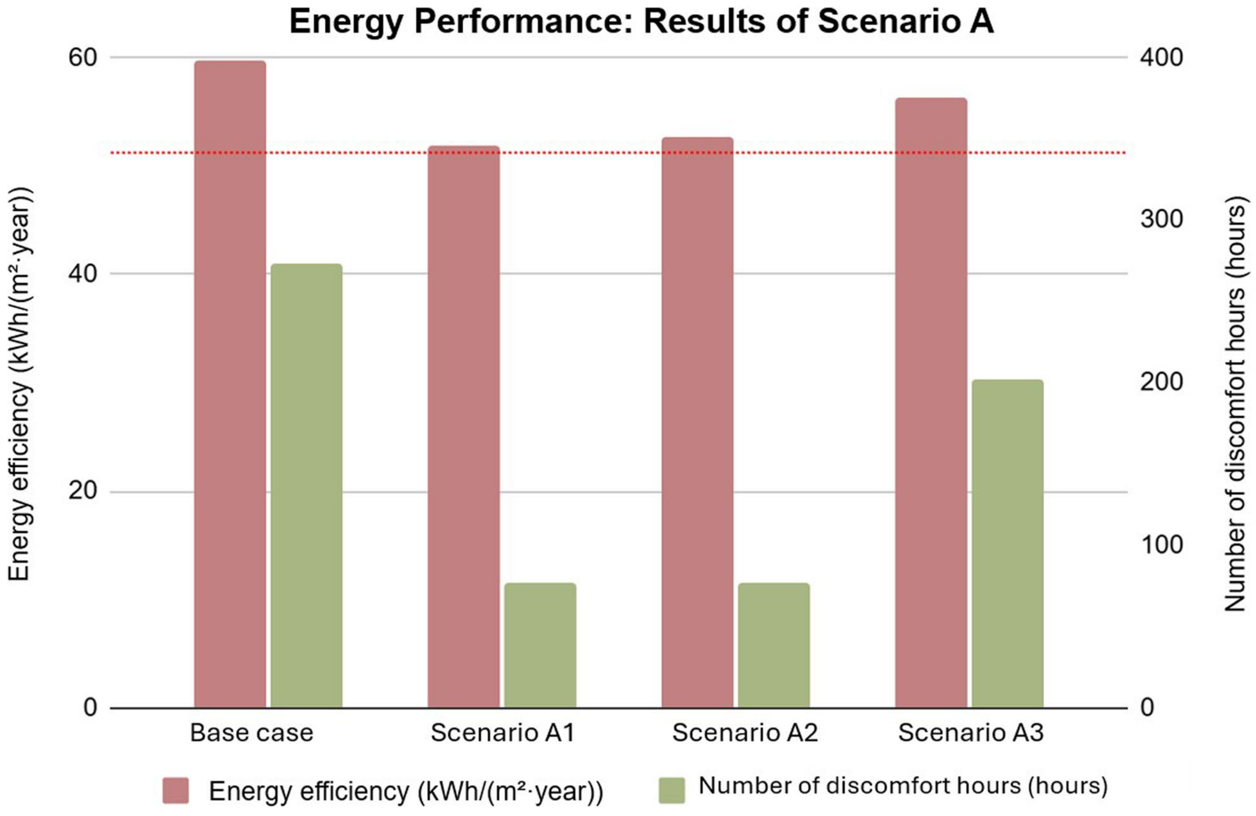


Fig. 6 Energy performance – results of Scenario A

office applications. Instead, the study demonstrates that overheating risks can be significantly mitigated through targeted passive design strategies and adapted HVAC configurations.

In contrast, the use of natural ventilation in CLT buildings proves to be less suitable due to a high rate of thermal discomfort. Underfloor heating leads to increased cooling demands over 60%, while the adoption of an air-to-water heat pump reduces overall energy efficiency. This is because underfloor heating stores heat in the floor and releases it slowly. While this is useful in winter, it becomes a problem during warm periods or mid-season. When there is more heat from the sun or from inside (people, equipment), the system reacts slowly and keeps releasing heat even when it is no longer needed. This can cause overheating and increase the need for cooling. In addition, underfloor heating is not very effective for cooling, as it has a low cooling capacity and a risk of condensation. A particularly important finding is that systems traditionally considered energy-efficient in conventional buildings, such as underfloor heating, may become counterproductive in low-inertia CLT offices because of their slow thermal response. This highlights that HVAC solutions cannot be directly transferred from concrete-based buildings to timber structures without adaptation. For building design practice, the results imply that early-stage integration between structural, envelope, and HVAC decisions is essential to avoid performance trade-offs between operational energy, comfort, and embodied carbon reduction.

These results highlight the need to balance energy performance and environmental impact, by combining simulation outcomes with life cycle assessment results. Achieving this balance is essential to establish CLT constructions as a sustainable and high-performing building solution.

4.2 Life cycle analysis

The carbon emissions results for the different scenarios are presented in Table 6. Scenarios 1 and 2, which rely on the use of a concrete structure combined with polyurethane or bio-based insulation, show the highest impact on global warming. The main carbon emissions in these scenarios come from the manufacturing phases (A1–A3) and replacement phases (B4–B5). Compared to other differences observed, the impacts associated with the replacement phase (B4–B5) for Scenarios 1 and 2 are lower than those for Scenarios 0 and 3. This difference is explained by the service life of the materials. In scenarios using CLT, some components require more frequent replacement than those in traditional constructions. For example, the lime screed needs to be replaced every 30 years.

These results highlight a key general insight: the environmental performance of CLT systems is primarily driven by the trade-off between reduced embodied carbon in the structure and increased replacement frequency of certain finishing layers. This means that material substitution alone is not sufficient to minimise lifecycle impacts; service life assumptions play a decisive role in the final outcome.

Regarding the end-of-life phase, the life cycle assessment results reveal that the environmental impact of waste disposal (C4) is approximately three times higher for concrete constructions than for CLT buildings. This difference is due to the limited possibilities for concrete

Table 6 Life cycle assessment results (kg $CO_2e/(m^2\cdot year)$)

Life cycle analysis (50 years)	Scenario 0	Scenario 1	Scenario 2	Scenario 3
Production stage: A1–A3	0.22	5.07	5.90	0.19
Transport stage: A4	0.11	0.14	0.14	0.11
Construction-installation stage: A5	1.20	1.22	1.08	1.26
Use stage: B1	Not considered			
Maintenance stage: B2	Not considered			
Repair stage: B3	Not considered			
Replacement and rehabilitation stage: B4–B5	4.39	3.91	3.91	4.38
Use of energy stage: B6	3.12	2.71	2.75	2.95
Use of water stage: B7	0.03	0.03	0.03	0.03
Deconstruction-demolition stage: C1	Not considered			
Waste transport stage: C2	0.05	0.09	0.09	0.05
Waste treatment stage: C3	0.63	0.60	0.60	0.63
Disposal: C4	0.22	0.73	0.75	0.25
Benefits and loads beyond the system boundary: D	Not considered			
Total climate change	**9.97**	**14.5**	**15.25**	**9.85**

reuse, which generate large amounts of waste. In contrast, CLT structures benefit from a more developed reuse and recycling pathway: panels can be dismantled, reused in other projects, or recycled. This reinforces the idea that CLT constructions are better aligned with a circular economy approach and the overall reduction of the building's carbon footprint.

A key implication for design practice is that end-of-life benefits depend strongly on actual dismantling feasibility rather than theoretical recyclability. In other words, the advantage observed for CLT in module C4 is only realised if reversible connections and deconstruction-oriented detailing are implemented from the design stage. This makes structural detailing a critical design lever with direct consequences on lifecycle emissions.

When operational energy (module B6) is combined with embodied impacts (modules A1–C4), the total GWP ranges from 6.85 to 9.97 kg CO_2e/(m^2·year). This highlights that the use of this LCA module is essential, as it allows for the assessment of all environmental impacts of a building over its entire life cycle. Limiting the analysis to material impacts alone could underestimate the main sources of emissions. Integrating modules A1–C4 with B6 therefore enables the prioritization of key carbon reduction levers, the identification of the most critical components, systems, guides design decisions toward constructive and technical solutions that are truly effective for decarbonization.

In terms of overall greenhouse gas emissions, a significant difference of 45% is observed between concrete structures and cross-laminated timber structures. It should be noted that this figure reflects the net life cycle GWP including biogenic carbon storage in CLT. When only fossil emissions are considered (excluding biogenic offset), the reduction is approximately 28%, confirming that the advantage of CLT over reinforced concrete holds regardless of the carbon accounting convention applied. Within the CLT scenarios, however, the differences between the baseline case and the one integrating thermal mass through the addition of clay remain small. This proximity in impacts is encouraging as it shows that optimizing energy performance through improved thermal inertia can be achieved without significantly increasing greenhouse gas emissions.

When comparing these results with the current Danish carbon benchmark for buildings, all case studies exceed the established threshold. However, a more detailed analysis of the CLT scenario shows that the use of bio-based materials allows for a gradual reduction in the carbon footprint, bringing it closer to the benchmark.

This observation highlights the importance of combining low-carbon material choices with optimized energy design. Although CLT constructions do not yet fully meet the Danish standard within the current Belgian energy context, the results demonstrate that the integration of bio-based materials and high-performance technical systems represents an effective lever for reducing environmental impacts.

The reference case exhibits the lowest carbon emissions impacting global warming, closely followed by Scenario 3 over a 50-year period. The analysis shows that the most impactful materials mainly come from special techniques, particularly during the replacement phase. These results are illustrated in Fig. 7.

The influence of different HVAC systems on the energy performance of a Belgian building is particularly

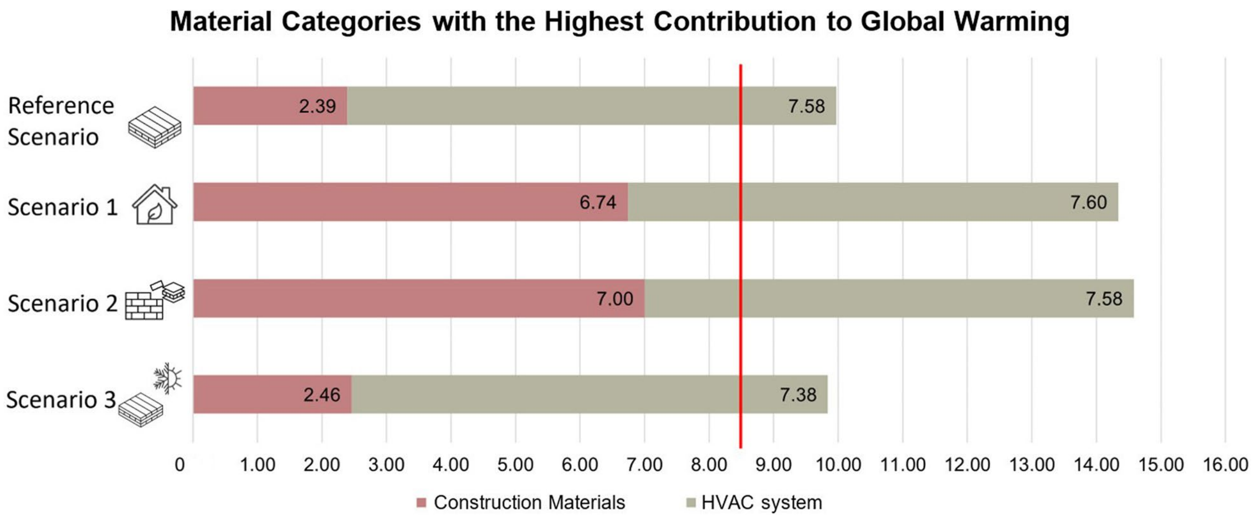


Fig. 7 Most climate-impacting material categories

significant in CLT constructions. Although the choice of timber materials substantially reduces the building's initial carbon footprint, it increases after the integration of HVAC systems. Indeed, 68% of the material-related emissions are associated with the HVAC equipment used as shown in Fig. 7. These systems involve the use of numerous materials with a high environmental impact, which affects the overall carbon balance. Secondly, the life cycle assessment assumes a building lifespan of 50 years, during which major HVAC components (e.g., heat pumps and photovoltaic panels) are replaced twice. This implies that their production and end-of-life impacts are accounted for multiple times, in contrast to most construction materials, which are considered only once over the building's lifetime. This repeated replacement substantially increases the cumulative environmental impact of HVAC systems.

In comparison, for traditional concrete constructions, HVAC systems represent a smaller share of total emissions (43%), while construction materials contribute the majority (57%) of the carbon footprint. This difference highlights the importance of considering HVAC system choice when evaluating the environmental impact of buildings. Similar conclusions were reported by de Paula Filho et al. [19].

The thermal mass of CLT constructions has a direct impact on energy performance, summer overheating, and occupant comfort. Due to their low initial thermal mass, these buildings respond more quickly to temperature variations, which can be a disadvantage during summer, particularly in the presence of solar or internal gains (e.g., office equipment).

Simulation results show that, in scenarios with mechanical double-flow ventilation, the addition of bio-based materials with high thermal inertia, such as clay blocks, can reduce overheating hours by up to 25%, as illustrated in Fig. 8. This improvement directly enhances

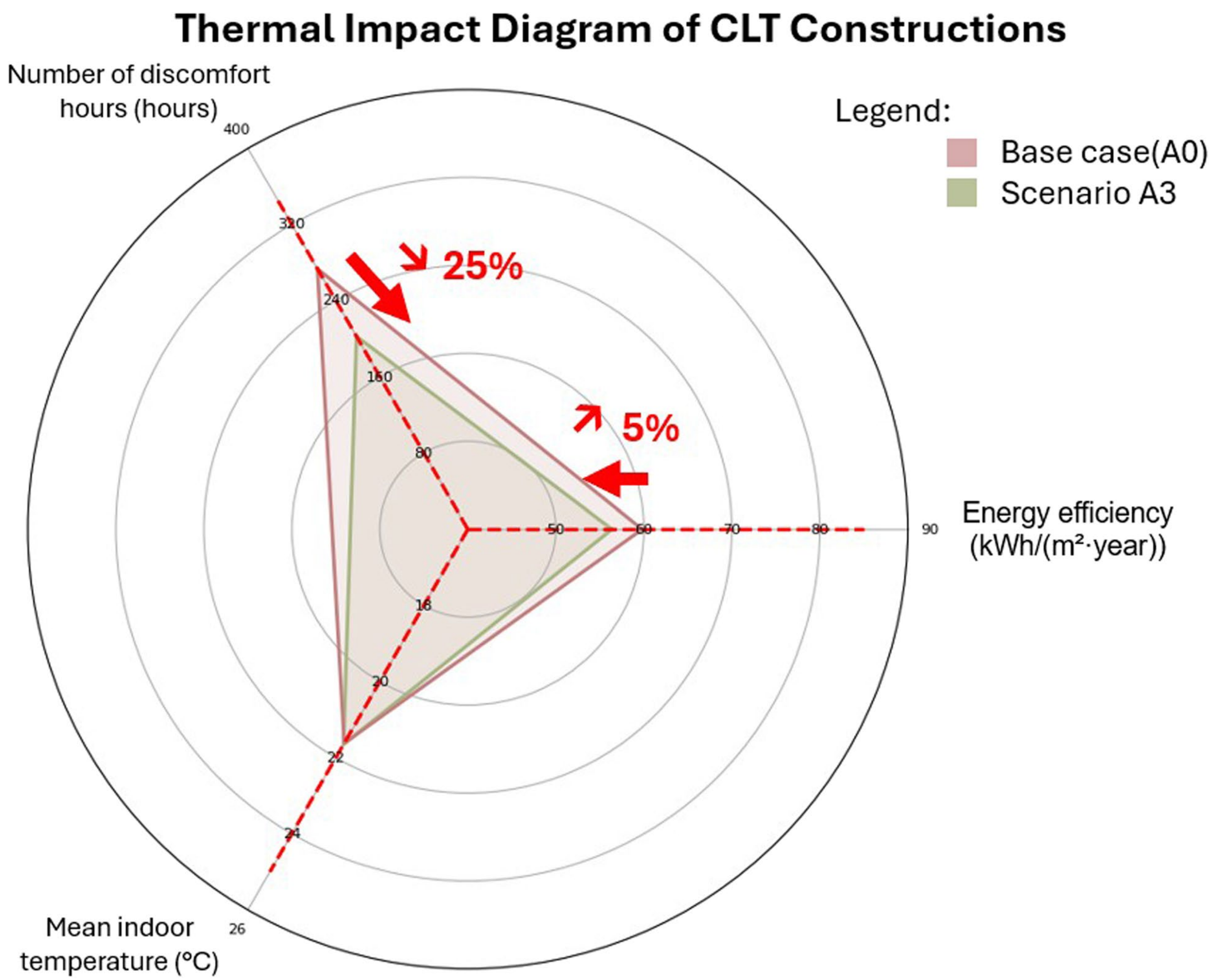


Fig. 8 Diagram of the thermal impact of CLT buildings

thermal comfort in office spaces. However, in configurations without mechanical ventilation, this thermal mass can become counterproductive. In the absence of sufficient air renewal, heat stored in the walls is released more slowly, leading to prolonged indoor temperature increases and occupant discomfort.

In the context of climate change, air pollution, noise and urban heat island effects, summer comfort becomes a priority. To address this, hydraulic systems are preferable to air-based systems, as water enables faster and more stable thermal regulation in low-inertia buildings.

Furthermore, the choice of heat emission system strongly influences occupant comfort in CLT constructions. Slow-response emitters, such as underfloor heating, are poorly suited to rapid temperature variations. This limitation increases cooling energy demand and occupant discomfort in commercial buildings during summer. Conversely, fast-response emitters, such as radiators, allow for quicker adjustments of indoor temperature. Their ability to rapidly increase or decrease temperature provides better management of comfort and overheating in office buildings. These findings align with the results of Artun and Alemdağ [18] and Dong et al. [33], who highlight this performance gap.

Finally, the results show that a balance can be achieved between thermal comfort and carbon footprint. The addition of clay blocks significantly improves summer comfort without causing a substantial increase in environmental impacts; the additional emissions remain below 1%. This solution is particularly effective when combined with a high-performance system comprising a geothermal heat pump, mechanical double-flow ventilation, and radiators. It provides a balanced approach between energy performance, user comfort, and environmental sustainability.

In conclusion of these results, Table 7 provides a summary of the different parameters studied in this research. The CLT scenarios consistently perform around the average across the three criteria—energy performance, environmental impact, and user comfort—making them the best-performing option overall. Their main drawback is summer comfort, which can be effectively mitigated with appropriate thermal inertia and HVAC strategies. In contrast, traditional constructions exhibit significant environmental shortcomings, despite potentially higher thermal comfort, highlighting the advantage of CLT as a balanced and sustainable building solution.

The number of symbols represents the relative performance level of each scenario. A higher number of symbols indicates better performance.

4.3 Validation of the energy model, sensitivity and uncertainty analysis

4.3.1 Model validation

For model validation, a calibration was performed to ensure the reliability of the results. The calibration was carried out in accordance with the ASHRAE Guideline 14 criteria, using the energy data of the existing building for the years 2023 and 2024, including the production of photovoltaic panels and indoor temperature measurements. This standard allows the calculation of the two indicators MBE and CV(RMSE) [47].

For validation, the MBE and CV(RMSE) indicators were computed. Table 8 presents the comparison between on-site measured data and the numerical model. According to ASHRAE criteria, the model is considered validated when MBE < 5 % and CV(RMSE) < 15 % for monthly comparisons. All results obtained meet these thresholds, confirming that the model reliably reproduces the energy performance of the existing building.

4.3.2 Sensitivity and uncertainty results

The results of the sensitivity analysis applied to the building LCA model highlight the most influential parameters on the annual environmental impacts. All variations observed in this analysis are summarized in Table 9. Among the factors studied, HVAC systems appear as the most sensitive parameter, with impacts

Table 7 Comparative analysis of scenarios

Criterion	Reference CLT scenario	Scenario 1: concrete structure with bio-based insulation	Scenario 2: concrete structure with polyurethane insulation	Scenario 3: CLT structure with integrated thermal inertia
Environmental impacts	🍃 🍃 🍃	🍃	🍃	🍃 🍃 🍃
Energy performance	⚡ ⚡ ⚡	⚡ ⚡ ⚡	⚡ ⚡ ⚡	⚡ ⚡ ⚡
Thermal comfort	⌂ ⌂	⌂ ⌂ ⌂	⌂ ⌂ ⌂	⌂ ⌂

Table 8 Results of the energy model calibration

Item	Real data	Model data	MBE (%)	CV(RMSE) (%)
Total annual energy consumption (kWh)	65 071.38	65 187.10	0.18	13.97
Total annual production (kWh)	55 618.70	53 182.66	− 4.38	12.22
Average indoor temperature (℃)	21.25	21.62	1.72	3.30

Table 9 Results for sensitivity analysis

Parameters for sensitivity analysis

Item	Variation	Δ GWP (%)	Sensitivity rank
Quantity of materials	± 20%	± 17	3
Share of renewable energy	25%, 40%, 75%, 100%	± 31	2
Wall composition	Change of material thickness	± 1	6
Building lifespan	25–100 years	± 13	4
Types of HVAC systems	Change of HVAC system	± 56	1
Heat pump COP	2–5	± 5	5
Heat pump lifespan	10–35 years	± 0	10
Glazed surfaces	300–450 m^2	± 0.7	7
Heating setpoint temperature	19–21.5 ℃	± 0.3	9
Airtightness	0.3–1.2 air changes per hour	± 0.8	8

ranging from 7.83 to 11.24 kg $CO_2e/(m^2·year)$. This sensitivity is explained by the composition of these systems, which include numerous metal components (copper, aluminum, stainless steel) that are highly energy-intensive and generate significant greenhouse gas emissions. Therefore, the selection, design, and lifespan of HVAC systems represent an important lever for reducing the carbon footprint of buildings.

The second most influential parameter identified in the sensitivity analysis concerns the share of renewable energy used for building operation. The study shows that increasing the proportion of renewable energy in the building's energy mix can significantly reduce its annual carbon footprint. Specifically, the use of renewable energy can lead to a reduction of approximately 30% in the building's environmental impact. This influence is due to the fact that operational energy consumption constitutes a large portion of greenhouse gas emissions over the building's life cycle. The cleaner and more renewable the electricity source, the lower the emissions associated with heating, ventilation, air conditioning and electrical equipment use. Conversely, a fossil-fuel-dominated energy mix would directly increase the building's annual environmental pressure.

Parameters related to wall compositions, glazed surfaces and other construction characteristics show much smaller variations, indicating that these elements have a limited effect on the overall LCA results in the studied scenarios.

Overall, the sensitivity analysis confirms that the results do not depend excessively on a single uncertain parameter and that the model remains robust to plausible variations of key parameters. This approach allows for a better understanding of uncertainty sources and helps identify the priority levers for improving the environmental and energy performance of buildings.

Regarding the uncertainty analysis, the results indicate that the parameter with the highest level of uncertainty is the energy mix encoded in the OneClick LCA platform. This uncertainty arises mainly from the variability of electricity generation sources between countries, as well as from the temporal evolution of the energy mix. Indeed, depending on whether electricity is primarily generated from renewable sources (wind, solar) or fossil fuels (coal, gas, oil), the associated environmental impact can vary significantly. All variations observed are summarized in Table 10.

The second most uncertain parameter concerns the choice of materials, particularly the data obtained from EPDs. The availability, quality, and accuracy of EPDs directly influence the assessment of the environmental

Table 10 Results for uncertainty analysis

Parameters for uncertainty analysis

Item	Variation	Δ GWP (%)	Sensitivity rank
Choice of materials (change of EPDs)	Belgium and European country or bordering country	± 40	2
Recycling rate and end-of-life recovery	10%, 25%, 50%	± 0.7	7
Building lifespan	25, 35, 50, 75, 100 years	± 13	3
Material lifespan	5%, 10%, 20% on the lifespan	0	10
Choice of energy mix	± 15%	± 250	1
Site impacts	2030 and 2050 projections (± 15% on the emission factor)	± 7	4
Choice of climate file	Antwerpen, BEL_BRUSSELS_IWEC, BEL_SAINT HUBERT_IWEC	± 2	6
Number of simulation years	2020–2025	± 0.4	8
Lighting schedule	− 5% – 25%	± 4	5
User behavior	± 20%	± 0.2	9

impacts of the materials used, especially for new or non-standardized materials.

The third parameter contributing to uncertainty is the service life of materials. The lifespan affects how the initial environmental impacts are distributed over the building's operational period. A longer service life allows for the annual environmental impacts to be diluted, while a shorter lifespan increases the annual environmental pressure. This uncertainty is particularly relevant for bio-based or innovative materials, whose actual durability can vary depending on usage conditions and maintenance practices.

5 Discussion

5.1 Findings and recommendations

The life cycle assessment, conducted in accordance with ISO 14040 and EN 15978 across stages A1–A5, B4, B6, and C3–C4, shows that CLT can reduce the total lifecycle global warming potential by 45% compared to the best-performing reinforced concrete scenario (9.97 vs. 14.34 kg $CO_2e/(m^2 \cdot year)$). This figure is consistent with the range of 20% to 60% reported across CLT LCA studies in the literature, depending on system boundaries, biogenic carbon accounting convention, and building typology [11, 26]. Studies applying full cradle-to-grave boundaries with the EN 15804 + A2 − 1/+ 1 biogenic convention, as in this study, tend toward the upper half of that range. Andersen et al. [7] reported a 45% reduction for a comparable Danish CLT office building under identical accounting conventions, providing the closest methodological analogue in the literature. Allan and Phillips [17] found 30% to 40% reductions for low and mid-rise mass timber buildings compared to structural steel, confirming that CLT's lifecycle advantage is robust across different structural comparison types. Duan et al. [10] and Iuorio et al. [20] similarly report reductions of 30% to 50% in Chinese and Italian contexts, respectively, demonstrating geographic consistency in CLT's embodied carbon advantage even when operational energy profiles differ. This reduction mainly results from the substitution of carbon-intensive materials with bio-based materials capable of storing atmospheric carbon throughout their service life, with a significant influence concentrated in the manufacturing phases A1–A3.

A key finding is that construction and maintenance phases, not operational energy, dominate lifecycle GHG emissions in 't Centrum. This contrasts with conventional office buildings where the operational phase accounts for 50% to 70% of whole-life emissions [22]. The inversion is explained by two compounding factors: the high energy performance standard of 't Centrum substantially reduces operational carbon, while CLT's biogenic carbon uptake under the − 1/+ 1 convention further suppresses net embodied emissions relative to concrete. Similar patterns have been reported in near-zero energy buildings across Europe [6], confirming that as operational carbon decreases, embodied carbon becomes the decisive lifecycle variable. All CLT scenarios in this study remain slightly above the Danish regulatory threshold of 8.6 kg $CO_2e/(m^2 \cdot year)$ [5]. This finding, corroborated by studies comparing results against Swiss Environmental Impact Assessment benchmarks [22], highlights that even well-designed circular CLT buildings face a genuine challenge in meeting the most ambitious European whole-life carbon standards under current Belgian electricity conditions.

Annual operational energy consumption is generally similar across all tested construction systems, confirming that structural material choice has limited influence on operational energy demand when envelope performance is held constant. The dominant variable is HVAC system configuration. The mechanisms driving performance differences between systems are rooted in the interaction between response time and CLT's low thermal mass. Underfloor heating stores thermal energy in the floor slab and releases it slowly: effective during steady winter conditions, but a liability during transitional seasons and summer, when internal and solar gains fluctuate rapidly and the system continues emitting heat after comfort conditions are exceeded, increasing cooling energy demand by over 60%. Fast-response emitters such as radiators decouple thermal output from floor mass, enabling rapid adjustment to variable loads and reducing overheating risk. Geothermal heat pumps provide a stable, low-carbon source for both heating and cooling; their high coefficient of performance under Belgian ground temperatures makes them the most lifecycle-efficient system tested, consistent with findings by Artun and Alemdağ [18], who established that HVAC performance in temperate-humid CLT buildings is highly sensitive to emitter type. The air-to-water heat pump performs at lower efficiency during peak summer periods when outdoor temperatures are highest, compressing the performance advantage that makes heat pumps attractive in heating-dominated contexts. These mechanism-level distinctions are critical for design practice and are rarely disaggregated in published CLT LCA studies.

The integration of bio-based thermal mass additions, specifically clay blocks within CLT wall assemblies, reduces thermal discomfort hours by up to 25% with a negligible additional carbon impact of less than 1%. Clay blocks absorb heat during the day and release it progressively at night when cooler outdoor air is available, moderating indoor temperature amplitude without adding fossil carbon. This solution is particularly effective when combined with geothermal heat pumps and mechanical double-flow ventilation, and represents the most efficient comfort-carbon trade-off identified across all scenarios tested. In addition to enhancing summer comfort, these natural materials carry a favourable carbon balance, further contributing to the building's environmental performance.

HVAC equipment accounts for 68% of material-related emissions in CLT buildings in this study, driven by repeated replacement cycles over the 50-year reference period rather than unit-level carbon intensity. De Paula Filho et al. [19] similarly found that structural design choices propagate to embodied carbon through their effects on technical system sizing and replacement frequency. Beyond HVAC, fire protection requirements, and acoustic performance layers in CLT buildings add material with their own embodied carbon costs that are frequently overlooked in headline GWP comparisons [37]. Adhesive bond service life introduces a further structural uncertainty not fully resolved by this study's sensitivity analysis. CLT panels in 't Centrum are connected using melamine-urea–formaldehyde and polyurethane adhesives whose long-term bond integrity under sustained moisture and load cycling remains incompletely characterised beyond 30 to 40 years in European temperate climates [50]. The 50-year reference period adopted here implicitly assumes that no structural adhesive failure triggers panel replacement within the B4–B5 modules. Should bond degradation occur earlier, replacement cycles would be activated that would increase total B4–B5 embodied carbon and narrow the 45% lifecycle GWP advantage over reinforced concrete reported here. This limitation is compounded by the fact that EN 15978 replacement assumptions for adhesive connections are based on manufacturer-declared service lives rather than in-situ performance data, which Vandervaeren et al. [51] demonstrated can underestimate actual material flux by up to 162% in demountable buildings. Specifying mechanically fastened rather than adhesively bonded CLT connections wherever structurally feasible, as implemented at 't Centrum for its primary connections, therefore carries a direct lifecycle carbon benefit beyond its contribution to disassembly potential.

Taken together, these trade-offs reinforce the need to assess CLT buildings as integrated material-energy systems rather than structural substitutions alone. The long-term environmental performance of CLT buildings in Belgium is strongly sensitive to the electricity mix, which the sensitivity analysis ranks as the largest single source of GWP uncertainty at ± 250%. If the Belgian energy mix evolves towards renewable sources in line with national decarbonisation trajectories, operational emissions will decrease further, widening CLT's lifecycle advantage and bringing results closer to the Danish threshold. Material selection and energy system decarbonisation are therefore complementary rather than alternative strategies.

The circular design of 't Centrum reinforces these lifecycle gains. Reversible mechanical connections in timber structures, systematically documented in terms of connection typology, geometric parameters, and reversibility potential by the Sustainable Building Design (SBD) Lab at the University of Liège [52], are the enabling condition for end-of-life material recovery. Their implementation at 't Centrum, combined with digital material passports and exposed technical systems, yields a disassembly potential of 92% based on expert assessment of 1 387 connection systems [43]. This high reversibility potential is directly linked to the LCA results, as the reduced replacement needs and improved recoverability of structural components contribute to lowering lifecycle impacts beyond the operational phase. In parallel, the exposed technical systems facilitate future maintenance and HVAC adaptation, which may help preserve operational energy performance over time by reducing invasive refurbishment requirements.

Younis and Dodoo [26] found that CLT panel reuse under optimistic scenarios reduces whole-life GWP by a further 15% to 20% beyond the A to C scope of this study, and Pomponi and Moncaster [35] established that excluding Module D systematically undervalues circular designs. However, these potential benefits remain conditional on future reuse scenarios, material recovery logistics, market demand for reclaimed timber elements, and long-term preservation of panel mechanical integrity. Consequently, the present study does not quantify Module D benefits and the reported carbon reductions should not be interpreted as guaranteed future savings. Similarly, the biogenic carbon storage associated with CLT remains sensitive to end-of-life assumptions, since delayed release or material reuse can substantially modify long-term climate impacts.

The present results should therefore be read as a conservative lower bound on ’t Centrum’s true lifecycle advantage over reinforced concrete. More specifically, the study demonstrates that the observed reduction in embodied carbon is primarily attributable to material substitution toward CLT, while the operational energy and comfort results are additionally influenced by envelope composition, thermal inertia limitations, and HVAC configuration. Circular design strategies therefore act as complementary long-term mitigation mechanisms rather than the sole driver of environmental performance. Jointly, these findings confirm that CLT, when combined with bioclimatic design, appropriate HVAC system selection, and circular connection detailing, provides a credible pathway toward low-carbon construction in the Belgian and broader European context. Pylsy et al. [53] emphasised that the interconnection between buildings and the energy system must be considered holistically; this integrated approach is directly applicable to Belgium’s forthcoming mandatory lifecycle carbon framework from January 2026.

5.2 Methodological strengths and study limitations

This study presents five methodological strengths that distinguish it from comparable CLT LCA studies in the literature. First, the LCA follows ISO 14040/44 and EN 15978 across a full A to C lifecycle scope, covering stages A1–A5, B4, B6, and C3–C4, with Module D excluded in accordance with standard comparative practice. This scope is more comprehensive than many published CLT studies, which frequently limit boundaries to A1–A5 only or omit the operational phase [26, 27]. Second, four construction material scenarios and four HVAC configurations are assessed within a single calibrated framework, providing scenario resolution uncommon in published CLT office building research [19, 20]. Third, the energy model was calibrated against real monitored consumption data from the Calculus platform, achieving MBE below 5% and CV(RMSE) below 15% per ASHRAE Guideline 14, establishing model reliability at research-grade standard. Fourth, biogenic and fossil carbon flows are explicitly disaggregated in Appendix A per EN 15804 + A2: 2019, addressing a transparency deficit that affects the overwhelming majority of published CLT LCA studies, fewer than 2% of which report these flows separately [27]. Fifth, the case study is Belgium’s first certified circular office building, with an empirically assessed disassembly potential of 92% based on inspection of 1 387 connection systems [43], providing circular design grounding unavailable in studies using hypothetical reference buildings.

Several limitations must be acknowledged with specificity. The most significant is the single case study design: the results reflect the particular combination of CLT technology, Belgian temperate climate, INIES-based EPD data, and the 2024 electricity mix applied here. Transferability to other building types, structural configurations, or climates is constrained. In cold-dominated climates where heating demand is higher, CLT’s operational energy advantage over concrete is larger; in hot climates, the cooling penalty from low thermal mass is more severe. In large-span commercial buildings, CLT’s structural constraints require additional columns or hybrid systems that add embodied carbon. These boundary conditions limit the direct applicability of the 45% reduction figure to contexts that share a similar energy performance standard and electricity mix. Regional climate dependency is a further constraint: Belgian projections indicate summer temperature increases of 2.4 to 6.6 ℃ by 2080 [15], and the overheating vulnerability identified in this study will intensify under future climate scenarios, making current results optimistic for long-term performance assessment.

Uncertainty in life cycle inventory data constitutes a third category of limitation. The reliance on INIES database EPDs and OneClick LCA generic defaults for modules where product-specific data were unavailable introduces variability that the sensitivity analysis captures only partially. The uncertainty analysis ranks EPD choice as the second-largest source of GWP variation at ± 40%, confirming that database selection materially affects results. The end-of-life modeling remains simplified: the assumed 70% recycling and 9% incineration rates are regional defaults rather than building-specific projections. The absence of long-term monitoring data beyond the calibration period limits validation of simulated multi-year performance. Finally, the acoustic performance implications of CLT construction, which require additional material layers with their own embodied carbon costs, are not quantified in this study and represent a gap that future multi-impact CLT assessments should address.

5.3 Implications for practice, policy and future research

The integrated LCA and building energy simulation framework developed here is directly applicable to the Belgian and European policy context emerging from January 2026, when lifecycle carbon reporting becomes mandatory under the revised EPBD [3, 4]. This study provides a methodologically complete template for that transition: a calibrated DesignBuilder and OneClick LCA workflow applied to a real building with monitored energy data produces whole-life GWP results benchmarkable against the Danish 8.6 kg $CO_2e/(m^2 \cdot year)$ threshold [5] within a realistic design timeline. The fact that all CLT scenarios in this study slightly exceed that threshold, despite 't Centrum performing at the frontier of Belgian circular construction practice, signals that the Danish standard represents a genuine design challenge rather than a readily achievable target. Meeting it requires simultaneous action on HVAC equipment replacement cycles, EPD data quality, and the electricity mix.

For design practitioners, three findings are directly actionable. First, HVAC system selection is the largest single determinant of whole-life GWP among design-controlled variables, with a sensitivity range of ± 56%. Specifying geothermal heat pumps with mechanical double-flow ventilation and fast-response radiators over underfloor heating reduces lifecycle carbon substantially and should be treated as an LCA decision from the earliest design stage. Second, clay block integration within CLT wall assemblies reduces thermal discomfort hours by 25% at a carbon cost below 1%, making bio-based thermal mass the most efficient comfort-carbon trade-off available to designers of CLT office buildings in temperate climates. Third, digital material passports and reversible mechanical connections translate into measurable end-of-life performance: the 92% disassembly potential measured at 't Centrum [54] demonstrates that circular design is a quantifiable construction attribute that should be specified, assessed, and procured alongside structural and energy performance, not treated as a qualitative aspiration [55].

For policymakers, three European-scale priorities follow from this study. The Level(s) framework [56] and Green Public Procurement criteria should require explicit disaggregation of biogenic and fossil carbon flows in CLT project declarations, as net GWP figures alone prevent transparent comparison between projects using different accounting conventions. The European Union (EU) taxonomy's 90% construction and demolition waste recovery requirement should be supported by mandatory disassembly potential assessment using standardised tools [55] rather than self-reported design intent. The Belgian GRO sustainable buiding assessment tool for circular and carbon evaluation, and the forthcoming CEN/TC 350 circularity assessment standard, provide the national and European instruments through which the lifecycle carbon and circular performance evidence generated here can be mainstreamed into building procurement and regulation.

Future research should address three gaps this study could not resolve. First, dynamic LCA incorporating projected Belgian electricity mix evolution through 2050 would quantify the extent to which grid decarbonisation alone closes the gap between current CLT performance and the Danish threshold, without requiring further material or HVAC improvements. Second, multi-building CLT studies across temperate and continental European climates are needed to establish transferability bounds for the 45% GWP reduction and the ± 56% HVAC sensitivity finding, both of which are currently grounded in a single Belgian case. Third, long-term monitoring of 't Centrum's planned sequential deconstruction and reconstruction through 2037 [41] will generate the first empirical evidence on actual CLT panel condition after first use, in-situ disassembly times, reuse rates, and the carbon cost of the deconstruction process itself, closing the Module D gap that EN 15978 mandatory reporting scope requires all comparative LCA studies to leave open.

6 Conclusions

This study provides the first integrated LCA and building energy simulation of a certified circular CLT office building in Belgium, combining four construction materials and four HVAC scenarios in a calibrated framework with explicit disaggregation of biogenic and fossil carbon flows. Six findings of scientific and policy significance emerge.

CLT reduces total lifecycle GWP by 45% compared to the best-performing reinforced concrete alternative (9.97 vs. 14.34 kg $CO_2e/(m^2 \cdot year)$, 50-year reference period). This figure corresponds to the upper end of the 20% to 60% range reported in the literature and is directly contingent on applying full cradle-to-grave boundaries under the EN 15804 + A2 − 1/+ 1 biogenic carbon convention, confirming that accounting methodology determines the reported magnitude of CLT's climate benefit.

Construction and maintenance phases dominate lifecycle green house gas (GHG) emissions in 't Centrum, inverting the conventional pattern in which the operational phase accounts for 50% to 70% of whole-life impacts [22]. This inversion results from the compounding of high energy performance and low-carbon Belgian electricity, and constitutes direct evidence that Belgium's operational energy focus in building regulation systematically misdirects decarbonisation effort. The forthcoming mandatory lifecycle carbon framework from January 2026 [3, 4] is a structural correction, not an incremental refinement.

HVAC system configuration is the single largest determinant of whole-life GWP in CLT buildings, with a sensitivity range of ± 56%, exceeding material quantity variation (± 17%), building lifespan (± 13%), and renewable energy share (± 31%). The governing mechanism is the interaction between emitter response time and CLT's low thermal mass: underfloor heating increases cooling energy demand by over 60% through thermal lag, while geothermal heat pumps with fast-response radiators achieve the best lifecycle performance across all scenarios. HVAC specification is, therefore, a lifecycle carbon decision, not a comfort decision alone.

Bio-based thermal mass additions, specifically clay blocks within CLT wall assemblies, reduce thermal discomfort hours by 25% per EN 16798–1 adaptive comfort criteria at a carbon cost below 1%. This is the most efficient comfort-carbon trade-off identified across all scenarios and provides a directly applicable passive strategy for CLT office buildings in Belgium's temperate climate, where projected summer temperatures rise by 2.4 to 6.6 ℃ by 2080 [15].

HVAC equipment accounts for 68% of material-related emissions in CLT buildings, driven by replacement cycles over the 50-year reference period rather than manufacturing intensity. Sensitivity analysis ranks the electricity mix as the dominant source of GWP uncertainty at ± 31%. A transition to a fully renewable Belgian electricity mix would bring all CLT scenarios below the Danish 8.6 kg $CO_2e/(m^2{\cdot}year)$ benchmark [38], establishing that energy system decarbonisation and material selection are complementary, not competing, strategies.

't Centrum's reversible mechanical connections, digital material passports, and exposed technical systems yield a measured disassembly potential of 92% based on expert assessment of 1 387 connection systems [43], the highest value recorded in the literature for an office building of this typology. CLT panel reuse under optimistic end-of-life scenarios reduces whole-life GWP by a further 15% to 20% [26], a benefit excluded from EN 15978 mandatory scope but quantifiable through dedicated disassembly assessment tools [43, 51]. The EU taxonomy's 90% waste recovery requirement and Belgium's 2026 carbon framework create the regulatory conditions under which this end-of-life value becomes accountable.

Low-carbon circular construction is achievable in Belgium today, but requires simultaneous optimisation of structural material, HVAC system, connection design, and energy source. No single lever is sufficient. The calibrated LCA and building energy simulation workflow presented here is reproducible and directly applicable to the lifecycle carbon reporting obligations emerging across the 27 Member States of the European Union from 2026.

Appendix

Biogenic carbon reporting (EN 15978 – Module A1–A3 and B1)

Biogenic carbon storage is calculated per EN 16449 based on the dry mass of CLT and a carbon content of 50% by dry weight (approximately 1.83 kg CO_2 stored per kg of dry timber). It is reported separately from fossil GWP as required by EN 15978 and EN 15804+A2: 2019. Values are normalised per reference floor area (2 087 m^2) and 50-year study period.

Unit: kg $CO_2e/(m^2{\cdot}year)$

Indicator	Value	Scope
Fossil GWP (A1–A3)	**+4.25**	Fossil emissions only, from One-Click LCA
Biogenic carbon storage	**−4.03**	Carbon stored in CLT panels per EN 16449 (−897 kg CO_2e/m^3 CLT)
Net GWP including biogenic	**+0.22**	Per EN 15978 −1/+1 approach; consistent with Table 6 A1–A3
End-of-life biogenic release (C3–C4)	**+4.03**	Assumed incineration/landfill scenario

Authors' contributions

Marine Eliard: Conceptualization, Methodology, Formal analysis, Investigation, Visualization, Writing of the original draft. Aurora Bertini: Methodology, Validation, Review and editing. Muheeb Al-Obaidy: Data curation, Circularity assessment, Review and editing. Shady Attia: Conceptualization, Supervision, Methodology, Validation, Review and editing.

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Data availability

The datasets generated and analysed during the current study are available from the corresponding author upon reasonable request.

Declarations

Competing interests

Shady Attia is one of the Editorial Board Members for *Low-carbon Materials and Green Construction* and was not involved in the editorial review, or the decision to publish, this article. All authors declare that there are no other competing interests.

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