VALUTAZIONE DEL CICLO DI VITA DI UN EDIFICIO PER UFFICI E CONFRONTO TRA DIVERSI MATERIALI STRUTTURALI

BUILDING LIFE-CYCLE ASSESSMENT OF AN OFFICE BUILDING CONSIDERING DIFFERENT STRUCTURAL MATERIALS

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ABSTRACT

Building LCA (life-cycle analysis) is a science-based methodology for quantifying the lifetime environmental impacts of buildings. It is used to measure and provide insights to reduce the embodied, operational, and whole-life carbon of buildings. This paper presents the comparative results of a building LCA of a typical office building located in Luxembourg with 50 years of service life. Three structural systems are compared: a steel frame, a prefabricated reinforced concrete frame, and a timber frame. The boundaries of the Building LCA are the product stage (modules A1-A3), construction process (modules A4-A5), replacement (B4) end-of-life (modules C3-C4), and the benefits and loads beyond the system boundary (module D) (i.e., cradle-to-cradle). The life-cycle inventory (LCI) is composed of environmental product declarations (EPD) according to EN 15804 and EN 15978. All the LCA evaluations are performed using the software One Click LCA. Given the findings of the paper, the steel solution outperforms the prefabricated concrete frame in the overall GWP. Additionally, the steel frame performs better, in terms of overall GWP, than the timber frame solution when landfilling EOL scenario for wood is considered. Finally, steel and timber solutions have equivalent overall GWP when the wood is considered to be 100% incinerated, knowing this EOL applies only to 6% of wood CDW (Construction and demolition waste) [1].

SOMMARIO

L’approccio al ciclo di vita di un edificio (LCA) è una metodologia per quantificare gli impatti ambientali di un efidicio. L’LCA viene utilizzata per misurare e ridurre il carbonio incorporato, operativo durate l’intero ciclo di vita degli edifici. Questo articolo presenta i risultati di LCA comparative di un edificio per uffici “tipo”, situato in Lussemburgo con vita utile 50 anni. Vengono messi a confronto tre sistemi strutturali: struttura in acciaio, struttura prefabbricata in c.a e struttura in legno. L’LCA applicate ad un edificio prevede la fase di produzione dei materiali (moduli A1-A3), il processo di costruzione (moduli A4-A5), la fase di ristrutturazione (B4), il fine vita (modulo C) e il potenziale oltre il fine vita (modulo D- “cradle to cradle”). Uno studio LCA si divide in diverse fasi; definizione di scopi e obiettivi; analisi di inventario (LCI); valutazione degli impatti; interpretazione e miglioramento. Nella fase LCI sono fondamentali le dichiarazioni ambientali di prodotto (EPD- EN 15804+A1 e la EN 15978). Tutte le valutazioni LCA sono eseguite utilizzando il software commerciale One Click LCA*. I risultati presentati dimostrano che la soluzione in acciaio ha un impatto inferiore, in termini di GWP, rispetto alla soluzione in prefabbricato e rispetto alla soluzione in legno, se si considera come scenario di fine vita (EOL) la dismissione in discarica. Al contrario, le soluzioni (acciaio e legno) hanno un GWP comparabile quando a fine vita si considera il lengo incenerito al 100%. Va considerato però che questo scenario si applica solo al 6% dei CDW (rifiuti da demolizione) delle strutture in legno [1].

1 INTRODUCTION

To date, most of the efforts to reduce the environmental impact of the construction sector were mainly focused on the operational carbon by the improvement of the building’s energy efficiency. Global investment in energy efficiency in the buildings sector rose an unprecedented 11,4% in 2020 to around $184 billion, up from $165 billion in 2019, primarily through targeted government support in Europe [2]. In addition, important efforts have been put into the decarbonization of the energy sector highlighting embodied carbon as the dominant climate impact driver. In 2020, compared to other sectors, 37% of the global share of energy-related CO_2 emissions was attributed to buildings and the construction sector [2].

Considering this, emissions from materials and construction processes must be urgently addressed to ensure that the buildings being built today are optimized for low carbon solutions across the full life-cycle. This involves evaluating each design choice using a whole life-cycle approach and seeking to minimize upfront carbon impacts (e.g., low carbon materials), as well as taking steps to avoid future embodied carbon during the end of life (e.g., circularity). In addition, low carbon solutions do not only rely on selecting low embodied carbon materials, but also on an efficient structural design where engineers and architects play an important role.

In response, countries in Europe are currently accelerating their efforts to comply with climate change commitments and regulations as pressure grows for the construction sector to reduce its impact rapidly. Some European countries have introduced policies to reduce whole-life carbon emissions from buildings and construction. While a common EU policy on whole-life carbon is still in the making, Denmark [3], the Netherlands, and France have introduced CO_2 limits for a large share of new buildings, while Finland and Sweden have plans to do so. Germany, the UK, and Switzerland have life cycle assessment (LCA) requirements for certain public buildings; Belgium is planning similar requirements.

This paper presents the comparative results of a building LCA of a typical office building located in Luxembourg with 50 years of service life. Three structural systems are compared: a steel frame, a prefabricated reinforced concrete frame, and a timber frame. The building LCA focuses on the product stage (modules A1-A3), construction process (modules A4-A5), replacement (B4), end-of-life (modules C3-C4), and the benefits and loads beyond the system boundary (module D) (i.e., cradle-to-cradle). The operational energy (module B6) of the building is out of the scope of this building’s LCA assessment. The life cycle inventory (LCI) is composed of construction environmental product declarations (EPDs) published according to the EN 15804+A1 and the EN 15978 All the LCA evaluations are performed using the commercial software One Click LCA whose application is widely accepted for building LCA.

2 METHODOLOGY

2.1 Life cycle assessment framework

LCA is a scientific and quantitative method for determining and assessing environmentally relevant processes. It was first developed for assessing products, but it is also used today to assess industrial processes, services, behavioral patterns, and complete buildings.

The EN 15978 Sustainability of construction works - Assessment of environmental performance of buildings - Calculation method defines the steps that shall be followed for a building LCA:

A Purpose and object of assessment;
B Boundaries of the analysis;
C Life cycle inventory (LCI);
D Calculation of the environmental indicators.
E Interpretation of results
E Conclusions

2.2 Purpose and object of assessment

The goal of the present building LCA is to quantify the environmental performance of equivalent structural options, composed of different materials, of an office building located in Luxembourg. This comparative study can support the different construction chain players (e.g.: engineers, architects, real estate developers, etc.) in the decision-making process by providing comparisons of the environmental performance of different design options and by indicating the potential for environmental performance improvement.

To define a representative office building for the Luxemburgish construction context, a market analysis was performed by the company TBC (http://www.tbcinnovation.fr/). The selected office building type was configured in an “L” shape. Its most significant dimensions are listed in Table 1.

Table 1. Significant office building dimensions

Building depth [m]	13,60
Building length [m]	78,15
Superstructure the number of levels	R+8
Infrastructure number of levels	2
Free height on the ground floor [m]	3,5
Free height on the intermediate floors [m]	2,7

The layout of a typical floor (Fig. 1) is proposed by the architectural office ARCADIS on the recommendations of the market analysis performed. Table 2 shows the areas of a typical floor, listed by function. The required service life of the building was defined as 50 years being the same as the reference study period (RSP) for the building LCA. For purposes of analysis, the building was divided into building parts. The building parts that will be in the scope of the LCA are: foundations, retaining walls, core and bracings, framing, floors, and roof.

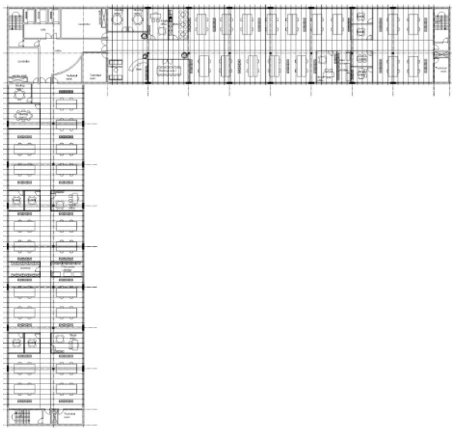

Fig. 1. Layout of a typical floor

Table 2. Area by function

Office [m^2]	1491
Closed office rooms [m^2]	100
Open space [m^2]	1111
Meeting room [m^2]	179
IT, archives, storage, etc. [m^2]	8
Circulation [m^2]	166

2.2 Presentation of the structural options

All the structural options assessed were designed and verified according to Eurocode's rules for safety and structural performance by independent design offices. Two grid options were adopted based on the best performance of the different structural options and materials: 8,1m by 13m (clear span) for the composite steel option, 8,1m by 5m +8m (with intermediate columns) for the prefab reinforced concrete option, and finally 5,4m by 5m + 8m (with intermediate columns) for the timber options. Fig. 2, Fig. 3, and Fig. 4 show the 3D representation of the considered structural options. Table 3 shows the floor and framing summary of the structural options analyzed.

Table 3. Reinforced concrete

Reinforced concrete	
Frame	Prefab Concrete principal beams 8m + 5m span Prefab Concrete façade beams 8,1m span
Floor	Pre-stressed concrete hollow slabs 8,1m span
Composite steel	
Frame	ArcelorMittal Angelina® 13m span S460 Hot rolled steel sections 8,1m span S460
Floor	ArcelorMittal Cofraplus® 60 composite floor 2,7m span
Timber	
Frame	Glulam GL24h beams 8m + 5m span Glulam GL24h façade beams5,4m span
Floor	CLT GL24h panel 5,4m span

Fig. 2 Reinforced concrete

Fig. 3. Composite steel

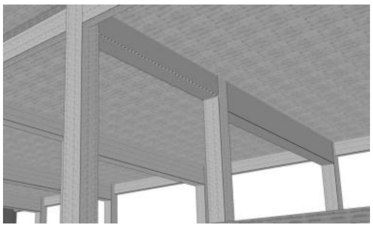

Fig. 4. Timber

2.3 Boundaries of the analysis

The setting of the system boundaries follows the modularity principle (Fig. 5 [4]) proposed by EN 15978: Sustainability of construction works – Assessment of environmental performance of buildings – Calculation method.

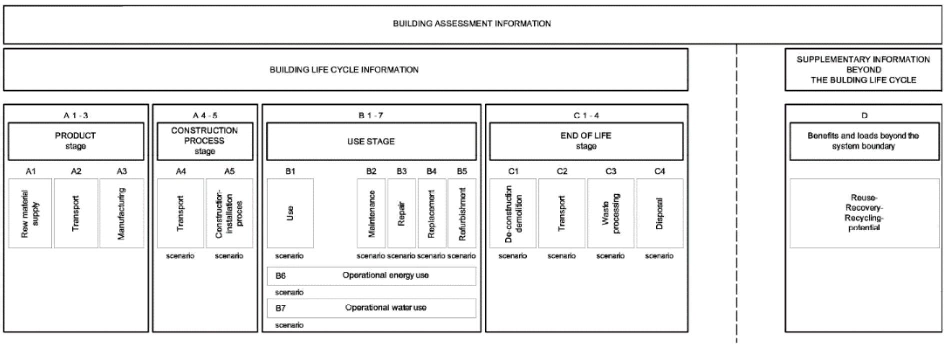

Fig. 5. Display of modular information for the different stages of the building assessment [4]

Depending on the purpose of the building LCA, some stages may be omitted or replaced due to the absence of detailed information or relevancy to the assessment. Since only structural elements are being considered in the analysis the following life-cycle stages are considered:

Product stage A1-A3

Resource extraction (A1), transport of the resourced (A2) the manufacturing process, and completion of the finished products at the factory gate (A3). Material and product quantities were extracted from construction drawings, bills of quantities, and BIM models as delivered by designers. Net quantities were used.

Construction Process Stage (A4-A5)

Transportation of building materials and products from the factory to the construction site (A4), and the actual construction/assembly on-site (A5). Regionally applicable transportation scenarios from One Click LCA were used. Those represent regionally typical transportation distances and methods for product/material types (Table 4). Wastage impacts were considered and accounted for since net quantities were used in the LCA model. Wastage quantities were estimated by default values of One Click LCA based on different materials and accounted for in module A5 (Table 5). The excavation of the underground levels and foundations was the only construction process/assembly included in the building LCA.

Table 4. Transport type and distances

Material	Transport type	Distance [km]
Structural steel	Trailer combination, 40-ton capacity, 100% fill rate	370
Steel reinforcement bars	Trailer combination, 40-ton capacity, 100% fill rate	370
Reinforced concrete	Concrete mixer truck, appr. 8 m3, 100% fill rate	60
Timber	Trailer combination, 40-ton capacity, 100% fill rate	220

Table 5. Wastage

Material	Percentage %
Structural steel	3,3
Steel reinforcement bars	4,85
Reinforced concrete	4
Timber	16,7

Use stage – Replacement (B4)

Due to the purpose of the building LCA, the only relevant life-cycle stage during the use of the building was module B4. Service life determines how long the product is used before being replaced. Values for the different products and materials were taken from the respective EPDs.

End of life stage (C3-C4)

Waste processing (C3) relates to structural elements and building materials that can be reused, recycled, or used otherwise (e.g., for energy recovery) (C3), and Disposal (C4) relates to structural elements and building materials that have to be disposed/landfilled (C4) life-cycle stages were taken into account in the building LCA analysis. Table 7 presents the end-of-life (EOL) scenarios adopted for the different materials:

Table 6. EOL assumptions

Material	Landfill %	Re-use %	Recycling %	Incineration with energy recovery %	Source
Structural steel	1	11	88		EPD [5], [6]
Steel reinforcement bars	10		90		EPD [7], [8]
Reinforced concrete	25		75		BETie [9]
Timber scenario 1				100	One Click LCA
Timber scenario 2	100				EPD [10]

The EOL assumptions are taken from the considered EPDs and One Click LCA's database (see Table 6 and Table 7). They reproduce the current practices for deconstruction and treatment of the Construction Demolition Waste (CDW) of the location where the building is situated. Since the EPD used for wood elements declares several EOL scenarios, two are proposed: landfilling and incineration with energy recovery since often timber CDW is subjected to different practices.
It is assumed in the present building LCA analysis that the amount of CO_2 absorbed during the photosynthesis and stored within wood during its life cycle is equal to that released at the EOL and thus there is no net impact on emissions. This assumption is commonly adopted for wood-based products in LCA [11].

Benefits and loads beyond the system boundary (D)
Based on decisions taken at the EOL, potential benefits related to the substitution of primary resources are accounted for. Module D is considered in the building LCA analysis characterizing it as a cradle-to-cradle LCA.
For the end-of-life scenario: Timber scenario 1, where the energy recovered by incineration is substituted in the energy mix, the District Heat, Luxemburg profile IEA2019 was selected.

2.4 Life-cycle inventory

EPDs provide quantified information on environmental impacts and aspects of products and services for use in a building LCA. The main EPDs and environmental data used in the building LCA are presented in Table 7 together with their embodied carbon impacts (A1-A3) in terms of their functional unit (FU).

Table 7. EPDs and environmental data

Data source	Material	FU	GWP [kg CO_2eq./FU]
EPD XCarb™ Recycled and renewably produced Structural steel sections and merchant bars ArcelorMittal Europe [5]	Structural steel sections	kg	0,33
EPD Structural steel sections in HISTAR grades ArcelorMittal [6]	Structural steel sections	kg	0,52
EPD XCarb™ Reinforcing steel in bars ArcelorMittal Europe [7]	Steel reinforcement bars	kg	0,3
EPD Reinforcing steel in bars ArcelorMittal[8]	Steel reinforcement bars	kg	1,23
One Click LCA	Ready-mix concrete C30/37	m^3	270,88
One Click LCA	Ready-mix concrete C40/50	m^3	355,83
One Click LCA	Ready-mix concrete C50/60	m^3	429,00
EPD Cross-laminated timber (X-Lam) Studiengemeinschaft Holzleimbau e.V.[10]	CLT	m^3	187,23
EPD binderholz Glulam - binderholz Bois lamelle-colle BSH - Legno lamellare BSH binderholz - binderholz BSH glulam [12]	Glulam	m^3	205,53

All the environmental data and EPDs used are by the requirements of EN 15804 hence they meet the requirements for data quality of this standard.

2.5 Calculation of the environmental indicators

The Building LCA analysis will focus on the global warming potential (GWP) to describe the environmental impact. Other indicators that describe environmental impacts, such as depletion potential of the stratospheric ozone layer (ODP), acidification potential of land and water (AP), eutrophication potential (EP), formation potential of tropospheric ozone photochemical oxidants, (POCP), and abiotic resource depletion potential (ADP) are not present in this Building LCA evaluation. Similarly, other indicators describing resource use and indicators describing additional environmental information are not included in the present building LCA analysis.

For the office building designed in composite steel structural solution, two building LCA analyses were made. The first is referred to as “Steel Composite usual AM’s structural steel” to highlight the environmental results of ArcelorMittal’s electric arc furnace (EAF) process of structural steel making. The second is referred to as “Steel Composite XCarb® to highlight the benefits achieved by the use of 100% recycled steel (scrap) and 100% renewable energy during the process of steel making. Results are presented in terms of the total gross floor area (GFA) of the office building. Fig. 6 and Fig. 7 show the GWP results by GFA per life cycle stages for EOL being 100% wood incineration with energy recovery and 100% wood landfilling respectively.

It is observed that independently of the structural option, the product life-cycle stage (A1-A3) is the most contributing to the GWP. In terms of CO_2eq. emissions, the steel frame outperforms the reinforced concrete frame by reducing by 32% the overall GWP for the usual AM’s structural steel scenario. A greater reduction is achieved for the XCarb® steel frame scenario where the overall GWP can be reduced up to 41%.

The timber frame when compared to the steel frame scenarios: usual AM’s structural steel and the XCarb®, is outperformed by 43% for the100% landfill EOL scenario and performs equally for the 100% incineration with energy recovery, EOL scenario.

Similarly, Fig. 8 and Fig. 9 show results of the GWP by GFA highlighting the contribution of each structural building part for all the frame options and both timber’s EOL scenarios. For all the structural options, it is seen that the building part that contributes the most to the overall GWP is the floors. Steel composite floors outperform prefabricated reinforced concrete hollow core slabs by 37% and 42% for the usual AM’s structural steel and XCarb® steel frame scenarios respectively. It is seen that for the timber option, the floors are greatly impacted by the choice of EOL scenarios: 82 $kgCO_2eq/m^2$ and 45 $kgCO_2eq/m^2$ for the 100% landfill and 100% incineration with energy recovery scenarios respectively.

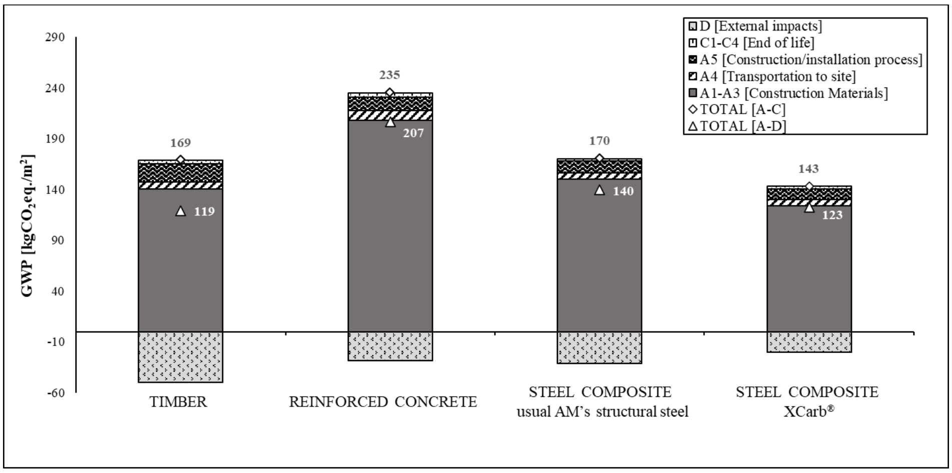

Fig. 6. GWP [$kgCO_2eq./m^2$] results by life cycle stages, 100% wood incineration with energy recovery.

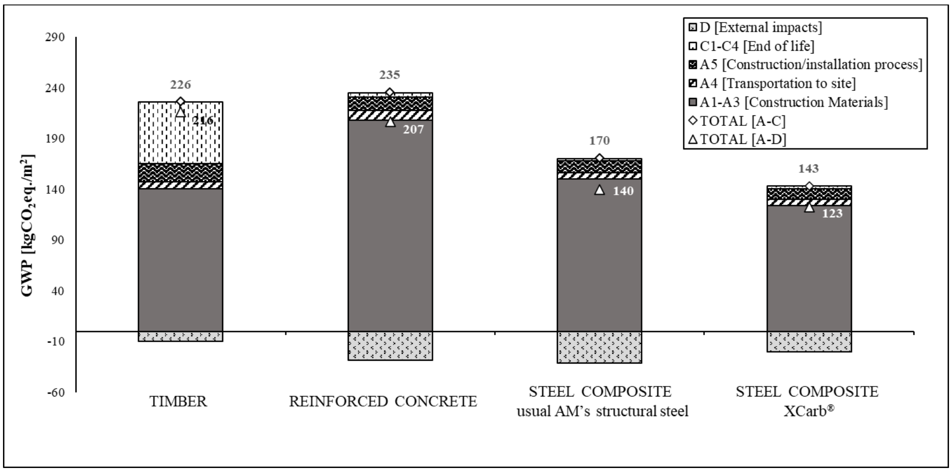

Fig. 7. GWP [kgCO$_2$eq./m^2] results by life cycle stages, 100% wood landfilling.

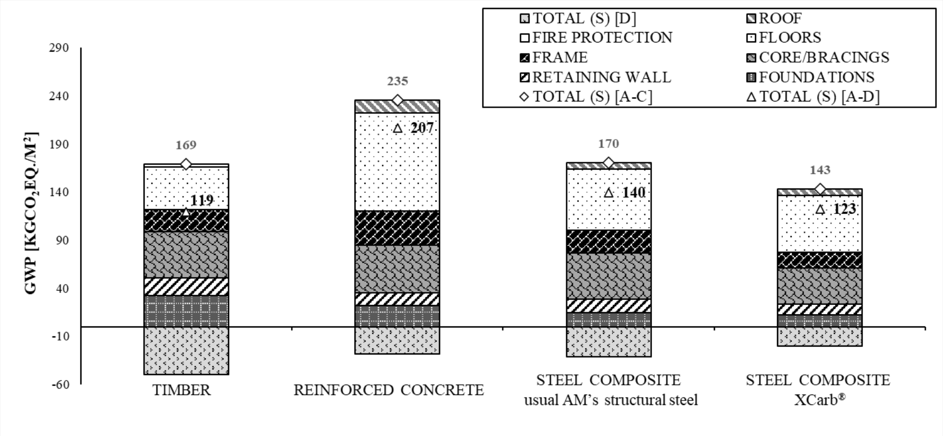

Fig. 8. GWP [kgCO$_2$eq./m^2] results by structural building parts, 100% wood incineration with energy recovery.

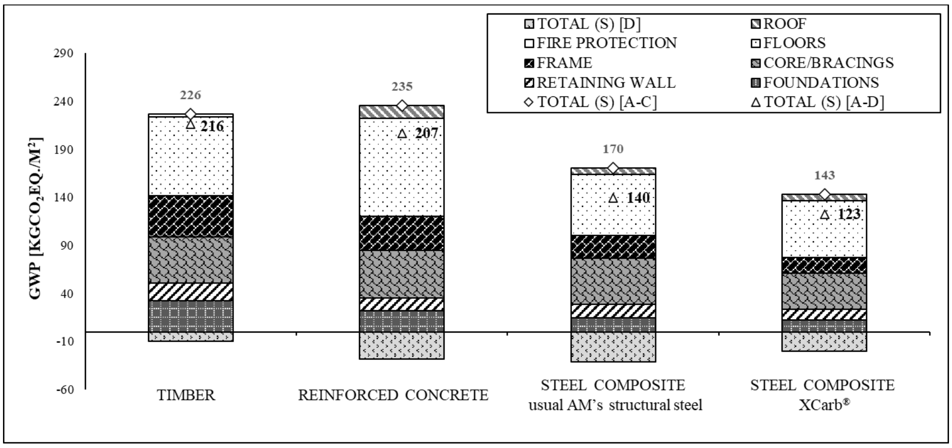

Fig. 9. GWP [kgCO$_2$eq./m^2] results by structural building parts, 100% wood landfilling.

2.6 Interpretation of results

The embodied carbon (modules A1-A3) is the major responsible for the CO$_2$eq. emissions. The reduction of raw material extraction by the use of high-recycled content materials is key to the reduction of embodied carbon. The steel frame option profits from having a high content of recycled steel (scrap), up to 100%. In addition, a greater reduction is achieved for the XCarb® steel frame option since it is produced with 100% renewable energy. The reduction of embodied carbon is paramount for the overall GWP performance of the structural options.

Timber EOL has an important influence on the overall GWP. When it is assumed the 100% incineration with energy recovery scenario, the energy created in the combustion process is harnessed for electricity generation. In consequence, the life-cycle stage module D represents the benefit of avoiding energy production and not the benefit of avoiding raw material extraction (the harvesting of virgin wood) to produce timber structural elements. According to the current practices of wood as a CDW, just the minority (6%) is being incinerated with energy recovery in its EOL [1].

The wood when landfilled, being a biodegradable material, decomposes. The decomposition results in the generation of biogenic CO$_2$, which in this analysis is assumed to be equal to the biogenic storage, and CH$_4$. Methane is a gas that contributes to the GWP, it causes 25 times more warming over 100 years compared to 1kg of CO$_2$, and so methane has a GWP of 25 [14]. In the 100% landfill scenario, it is assumed that the landfill is a large modern Type 3 facility with CH$_4$ collection. The methane uptake partially substitutes natural gas in heat production as a benefit in module D. The non-collected CH$_4$ is released and accounted for GWP in module C. This explains the variation of results of the timber frame option between both EOL scenarios. It also explains the reason why the timber frame module C, for the 100% landfill EOL assumption is the highest compared to the other structural options. According to the current practices of wood as a CDW, most of the wood (58%) is being landfilled in its EOL [1].

Floors are identified as the building part that contributes the most to the overall GWP. For this reason, it is key that floor systems are optimized. Ready-mix concrete is the main responsible for the impacts related to the floors for the steel and reinforced concrete frames. Steel composite floors are more compact and hence consume less concrete than prefabricated reinforced concrete leading to lower overall GWP. In the timber structural option, the floors are composed of CLT panels being the most timber-intensive building part. That is the reason why the floors are the building part mostly affected by different EOL assumptions (incineration with energy recovery and landfill).

CONCLUSIONS

The purpose of this building LCA application is two-fold: to quantify the environmental performance of equivalent structural options, composed of different materials and, based on the first, to aid the different construction chain players (e.g.: engineers, architects, real estate developers, etc.) in the decision-making process of different structural design options.

In this study, an R+8 multi-story office building representative of the Luxembourgish market with an RSL of 50 years is analyzed. Three structural systems are considered: a steel frame, a prefabricated reinforced concrete frame, and a timber frame. A cradle-to-cradle Building LCA considering the life-cycle stages A1-A3, A4, A5, C3, C4, and D is performed to quantify the overall GWP of each building's structural system.

The whole life cycle GWP is calculated for all structural options. The steel frame outperforms the reinforced concrete frame reducing by 32% the overall GWP for the usual AM's structural steel scenario. For the XCarb$^{®}$ steel frame scenario, the overall GWP can be further reduced by 41%.

The overall GWP of the timber frame is very sensitive to the wood EOL assumptions. When compared to the XCarb$^{®}$ steel frame scenario, the timber frame with the EOL assumption: 100% incineration with energy recovery, performs equivalently concerning the overall GWP. It is worth mentioning that according to EOL practices for wood as CDW, just as much as 6% is being currently incinerated [1]. On the other hand, when 100% landfilled, the timber frame is outperformed by the XCarb$^{®}$ steel frame scenario by 43%. Currently, most of the wood is being landfilled in its EOL [1].

To conclude, this study found that the steel frame option profits from a high-recycled material content, greatly reducing the embodied carbon from steel products. In addition, XCarb$^{®}$ environmental performance is enhanced using 100% renewable energy in steel production, lowering, even more, the embodied carbon. Finally, the study showed that the overall GWP of the timber solution is greatly impacted by the EOL assumptions: incineration with energy recovery and landfill.

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KEYWORDS

Life-cycle assessment, LCA, steel structures, reinforced concrete, timber, embodied carbon, circularity, office building, building LCA.