FACULTY OF ENGINEERING
AND ARCHITECTURE

Comparison of the environmental impact of concrete, steel, timber and masonry structural slab-support combinations in mid-rise buildings

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Preface

Due to the large impact of the load-bearing structure of buildings on the environment, life cycle assessment gains importance in the world of structural engineering. In future projects, it should serve more and more as a tool to support decision-making, besides financial and practical considerations. For that reason, I decided to devote my master's thesis to the environmental impact of a building's structural system. I hope this study can lead to new insights into this topic and provide some guidance on how structural engineering and life cycle assessment can be merged in structural designs.

With this master's dissertation, I conclude my 6-year journey at Ghent University which I spent half at the architectural department and half at the civil engineering department of the faculty of engineering and architecture, the ideal representation of my shared interests in engineering and architecture. Therefore, this study, combining structural engineering and life cycle assessment, forms the perfect closure to my journey.

For this reason, I would like to thank Koen Feyaerts of VK Architects + Engineers and my supervisor prof. Marijke Steeman for giving me the opportunity to change the topic of my master's dissertation at the last minute. This gave me the chance to broaden my knowledge in a field that had clearly grasped my interest. Moreover, I want to thank them for their advice during the feedback sessions and to share their know-how about the topic.

The realisation of this master's dissertation would also not have been possible without the guidance of my counsellors Lisa Van Gulck and Bram Derudder. Lisa was always available to help me out with my questions concerning the LCA and academic writing in general, while I could always count on Bram's knowledge in the field of structural engineering for my questions related to the structural calculations.

Furthermore, I would like to thank Eva, Sam and Lotte with whom I spent many hours at the library working on my thesis and without whom this year would not have been the same. Their company, support, second opinions, and the many coffee breaks were an essential part of the whole process.

Last but not least, I want to thank my parents, my sister and my boyfriend for their endless support during my studies, and especially this last year. This all would not have been possible without them.

Esther Claeys

May 2023

Notes from the author

This master's dissertation is part of an exam. Any comments formulated by the assessment committee during the oral presentation of the master's dissertation are not included in this text.

30 May 2023

Esther Claeys

Abstract

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Abstract

The huge environmental impact caused by the construction sector can predominantly be attributed to the load-bearing structure of buildings which necessitates the largest amount of construction materials. Moreover, the improved energy efficiency of recent buildings gradually increases the share of the environmental impact that can be allocated to building structures. As a consequence, life cycle assessment (LCA) gains importance to quantify and decrease the environmental impact of building structures and as such support decision-making in structural designs. Many different LCA studies have yet been performed focusing on the structural design of buildings. However, most studies focus on one construction material or the comparison of two materials, often with a focus on global warming potential. This creates a lack of studies comparing multiple materials and environmental impact indicators and taking into account all relevant life cycle stages. For this reason, in this master's dissertation, a comparative LCA is performed to compare the environmental impact of four commonly used construction materials (concrete, steel, timber and masonry). This LCA takes into account 24 slab-support combinations each representing an alternative structural design for the chosen functional unit, which is part of a case study building.

The results indicate that, concerning the slab types, a CLT slab leads to the lowest environmental impact. However, for larger spans, hollow core slabs are more beneficial. For the frame structures, in general, the steel frames have the largest environmental impact, while a concrete frame is the most beneficial. Glulam frames have a slightly higher impact, regardless of the choice of system boundaries, due to the contribution of the connections. Related to the wall structures, sand-lime brick walls have the lowest impact which is even lower than that of the frames in case the impact of infill walls is included. Overall, the relative differences between all slab-support combinations are smaller than expected.

The sensitivity analysis demonstrated that the results related to the supporting structures are generally valid, independent of the frame configuration. The inclusion of module D, on the contrary, goes along with a large gain in environmental impact for steel structures. Finally, when considering the CO_2-equivalent instead of the single score environmental impact indicator, the impact of the timber components decreases drastically and a much larger variability over the different combinations is obtained. These results demonstrate that the outcomes are more sensitive to changes in the LCA compared to changes in the structural calculations

Keywords

Life cycle assessment, structural design, mid-rise buildings, concrete, steel, timber, masonry.

Comparison of the environmental impact of concrete, steel, timber and masonry structural slab-support combinations in mid-rise buildings

Esther Claeys

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Abstract - **The huge environmental impact (EI) caused by the construction sector can predominantly be attributed to the load-bearing structure of buildings. As a consequence, life cycle assessment (LCA) gains importance as a means to quantify and reduce the environmental impact of building structures and as such support decision-making in structural designs. Many LCA studies have yet been performed focusing on the structural design of buildings. However, most studies mainly focus on the global warming potential of one or two construction materials. This creates a lack of studies comparing multiple materials and environmental impact indicators, and taking into account all relevant life cycle stages. In this research, a comparative LCA is performed to compare the environmental impact of four commonly used construction materials (concrete, steel, timber and masonry) in 24 different slab-support combinations. Each combination is an alternative structural design for the chosen functional unit, which is part of a case study building. It can be decided that a CLT slab leads to the lowest environmental impact for the initial plan configuration. However, for larger spans, the HCS is more beneficial. For the frame structures, the steel frame has the largest environmental impact, while a concrete frame has the lowest impact. Glulam frames have a slightly higher impact than concrete frames due to the contribution of the connection components. Related to the wall structures, sand-lime brick walls have the lowest impact. Overall, the relative differences between all slab-support combinations are smaller than expected. It is also demonstrated that the results are generally valid, independent of the column-beam configuration. However, the used impact indicators and the approach for module D has a determining influence on the final results.**

Keywords - **Life cycle assessment, structural design, mid-rise buildings, concrete, steel, timber, masonry.**

I. INTRODUCTION

The huge share of the construction sector in the global greenhouse gas emissions and its accompanying negative environmental impact, necessitate an enlarged emphasis on sustainability in the design process of buildings. This results in an increased use of life cycle assessment (LCA) to quantify the environmental impact of buildings over their entire lifetime and a shift towards more environmental motives for decision-making in the construction sector.

Although LCA is a powerful tool to examine the sustainability of different materials and structures, a perfect comparison between different LCAs is difficult to achieve due to the many influencing factors, among which the choice of the functional unit and the impact method. This can give rise to disagreeing conclusions. Moreover, due to the existence of multiple guidelines with freedom of interpretation, LCA research is still in a rather fragmented state [1].

Because most construction materials are implemented in the load-bearing structure of a building (slab and support), it is important to take into account the environmental impact of these structures during the design. For this reason, this study focuses on the environmental impact of a building's structural system. The aim is to perform a comparative cradle-to-grave LCA between different possible structural solutions for a case study building using the commonly used building materials (concrete, steel, timber and masonry), taking into account all impact indicators according to the PEF impact method and all relevant life cycle stages. As such an answer can be searched to the question: what is the structural solution with the lowest environmental impact for a multi-storey building?

The research outline is illustrated in Figure 1. First a literature study is performed, after gathering the necessary information the structural and LCA calculations will be executed and finally, a sensitivity analysis will be set up.

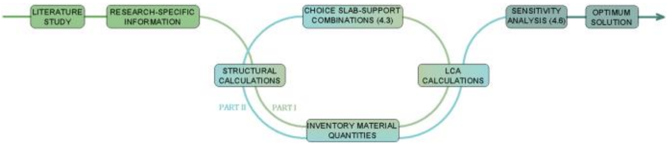


Figure 1 Summarizing figure of research outline.

II. LITERATURE STUDY

A. Life cycle assessment based on EN 15804+A2

The LCA will be performed according to the European standards EN 15804 [2] and EN 15978 [3]. Related to the building's lifecycle, four life cycle stages or modules are specified: the production (A1-A3), construction (A4-A5), use (B) and end-of-life stage (C). The LCA itself is split up in four steps as schematized in Figure 2.

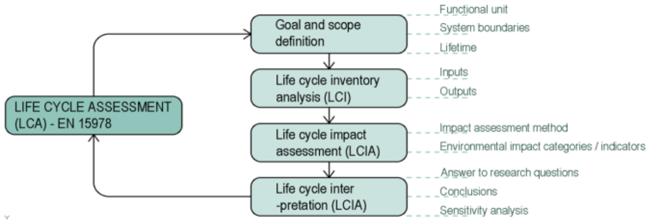


Figure 2 Scheme of steps in an LCA according to [3].

B. Application of LCA on common construction materials

The second part of the literature study is conducted to provide an overview of the existing research concerning LCAs of load-bearing structures and common structural materials. To do so, a literature matrix was set up which summarizes the main sources and their characteristics as shown in Figure 3.

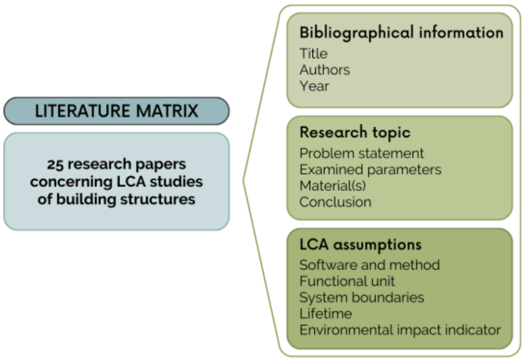


Figure 3 Concept figure of literature matrix.

The environmental impact of reinforced concrete is found to be quite high and mainly influenced by the concrete class, cement type, reinforcement ratio, construction method and the design optimization of the structure [4]. For steel, the end-of-life stage has an important influence on the environmental impact due to the high-grade recycling process. It has been demonstrated that for steel and timber structures, connection components represent an important share of the total impact [5]. A wide spread is observed in the results for timber structures, which is mainly caused by the way in which biogenic carbon is treated. In the majority of the examined cases, timber seems to be the most environmentally friendly building material, while steel has the largest environmental impact. However, the relative differences between all materials largely differ for the examined studies [6].

The overview of LCAs in the literature matrix confirms that there are lot of influencing parameters and that, as a consequence, the different conclusions are not always compatible. Hereunder, the conclusions that are most generally agreed upon in LCA studies for building structures are summarized. It can be concluded that it is recommended to define the functional unit on the building level. As such, the entire load-bearing structure, consisting of beams and columns or walls, slabs and connections can be taken into account. With respect to the LCA software, SimaPro is the most widely-used software package and it is mainly used in combination with the EcoInvent database. The majority of the studies either focus on one structural material or on the comparison between two structural designs with different materials. However, there is a lack of studies that take into account more materials and not only look at global warming potential (GWP) as an environmental impact indicator. For this reason, there is a need of additional research tackling these shortcomings and as such filling in this research gap.

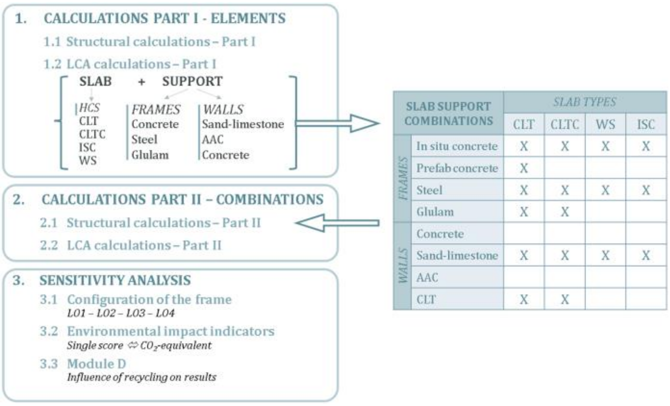
III. METHODOLOGY

A. *Research steps*

Figure 4 gives an overview of the steps that will be followed for the calculations. First, the different structural calculations will be performed to dimension the building's structural components, providing an inventory of the material quantities. Subsequently, the environmental impact of the different materials will be determined.

The complexity of the structural calculations and the LCA will be gradually increased. For the structural calculations, in part I, each slab type and each supporting structure (frame or walls), indicated in Figure 6, will be calculated separately taking into account the same loads for each calculation. The same approach will be used for the LCA calculations. Based on those intermediate results, relevant combinations of slab types and supporting structures will be composed and further investigated in part II.

Finally, a sensitivity analysis will be performed to verify the importance of some assumptions in the calculations, namely, the frame configuration, the environmental impact indicators and the approach for module D.



SLAB SUPPORT COMBINATIONS		SLAB TYPES			
		CLT	CLTC	WS	ISC
FRAMES	In situ concrete	X	X	X	X
	Prefab concrete	X			
	Steel	X	X	X	X
	Glulam	X	X		
WALLS	Concrete				
	Sand-limestone	X	X	X	X
	AAC				
	CLT	X	X		

Figure 4 Scheme of research outline.

B. *Case study building*

The case study building that will be examined is a mid-rise apartment building part of the Tondelier project, a new-build residential site in Ghent. For this study, the scope will be limited to the load-bearing structure of a generic level as shown in Figure 5.

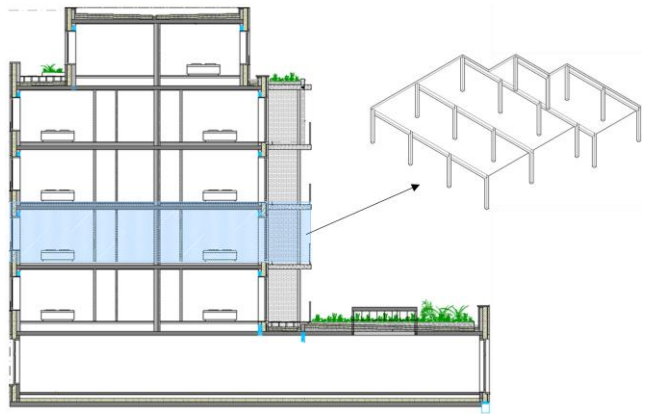


Figure 5 Case study building with indication of functional unit.

C. *LCA Calculations*

Goal and scope - The goal of this LCA is to compare the environmental impact of the building structure of a case study apartment building executed with different materials for the load-bearing structure. This makes it possible to determine the structural design with the lowest environmental impact and to make a reasonable material choice for a specific building.

The functional unit (FU) is the building's structural system, consisting of a slab and beams and columns or walls, for one typical floor with the necessary load-bearing capacity to resist all permanent and variable loads over a lifetime of 60 years. The FU was already indicated in Figure 5.

Regarding the system boundaries, a cradle-to-grave LCA will be performed including stages A, C, and later also D.

Life cycle inventory analysis (LCI) - To determine the in- and output flows of the functional unit over the entire life cycle, SimaPro 9.1.1.1 is used along with the EcoInvent 3.6 database. All processes obtained from this database are adapted to the Belgian context where possible. The basic material processes are always chosen to be unit and transformation processes which include all impacts of stages A1 up to A3 and enable adaptations. The further calculations in Excel using the output from SimaPro are mainly based on the TOTEM documentation [7]. The allocation of the impacts is done according to the principle of cut-off by classification.

Life cycle impact assessment (LCIA) - The environmental profile of the different materials will be set up using all the environmental impact indicators (EII) according to the impact method EN 15804+A2. Based on these EII a single score will be calculated, expressed in Pt, which allows an easy comparison between the different materials. For biogenic carbon, carbon neutrality over the entire lifecycle will be assumed.

D. *Structural calculations*

As each material has different mechanical and technical characteristics, it requires its own structural design consisting of a column grid or wall layout and a calculation of the necessary sections to resist the prescribed loads. On the one hand, the ultimate limit state (ULS) design requirements need to be fulfilled to ensure safety due to a sufficient load-bearing capacity. On the other hand, the serviceability limit state (SLS) requirements must be met, so that the structures perform satisfactorily during their normal use.

The loads are calculated based on EN 1991-1-1 [8] and include the self-weight of the structure, the permanent surface load (2.80 kN/m²) and the variable surface load (2 kN/m²). It is assumed that the wind load is entirely resisted by the central core and does not influence the dimensions of the load-bearing structure of the functional unit.

The general structural member for the analysis will be a continuous slab consisting of three equal spans of 5.20 m, also called a continuous one-way slab, and supported by line supports (walls or beams). Some alternative layouts, for example with larger spans, will be examined too in a later phase of the study to investigate the influence on the results.

For each structural design that will be investigated, one FU will be calculated including columns and beams or walls, a slab and connection components. To avoid the need to calculate the columns for every floor, only the columns of the second floor will be calculated.

In Figure 6 a schematic overview is given of the types of slabs and supporting structures that will be examined in the following sections. The concrete frames and slabs will be calculated using the software *ConCrete* by Buildsoft, the steel frames are designed with *12-Build* by Buildsoft and for the timber structures *Calculatis* by Stora Enso was used.

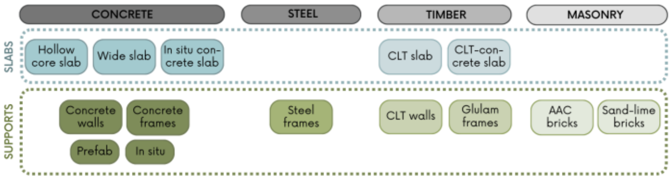


Figure 6 Overview of used structural components.

IV. RESULTS

The results of this research will be discussed according to the scheme in Figure 4, starting with the results on element level, continuing on the level of the slab-support combinations and finally, the sensitivity analysis will be discussed.

The abbreviations used in the graphs for the different slab types and support structures are clarified in Table 1.

Table 1 Abbreviations slabs and support structures

Support structures		*Slab types*	
GL	Glulam frame	*HCS*	Hollow core slab
C	Concrete frame	*CLT*	CLT slab
S	Steel frame	*ISC*	In situ concrete slab
SL	Sand-lime brick	*CLTC*	CLT-concrete slab
AAC	Aerated concrete walls	*WS*	Wide slab
CW	Concrete walls		
CLTW	CLT walls		

A. *Part I*

When looking at the slab types separately, a proportionality can be observed between the weight of the slabs and the environmental impact. The larger the weight of the slab the larger the impact, this is illustrated in Figure 7 in which the slab types are ordered from light to heavy.

It is obvious that the impact related to the production stage is dominant with a share of 81 to 87%. The other modules represent a much smaller share which is often proportional to the total impact.

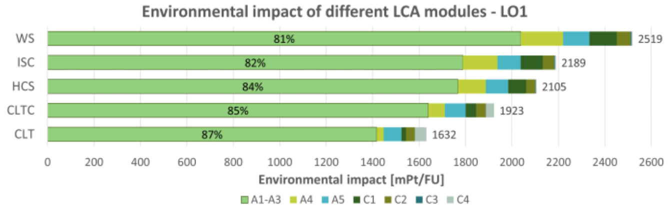


Figure 7 EI of slab types subdivided according to the LCA modules.

For the supporting structures, bearing the HCS floor, the mentioned proportionality is no longer valid. The concrete frames have a lower EI than the glulam frame as can be observed in Figure 8. The lowest impact is obtained with the sand-lime brick walls, while the highest impact is represented by the steel frame. However, in case the infill walls are omitted, the lowest EI is obtained for the concrete frame.

B. *Part II*

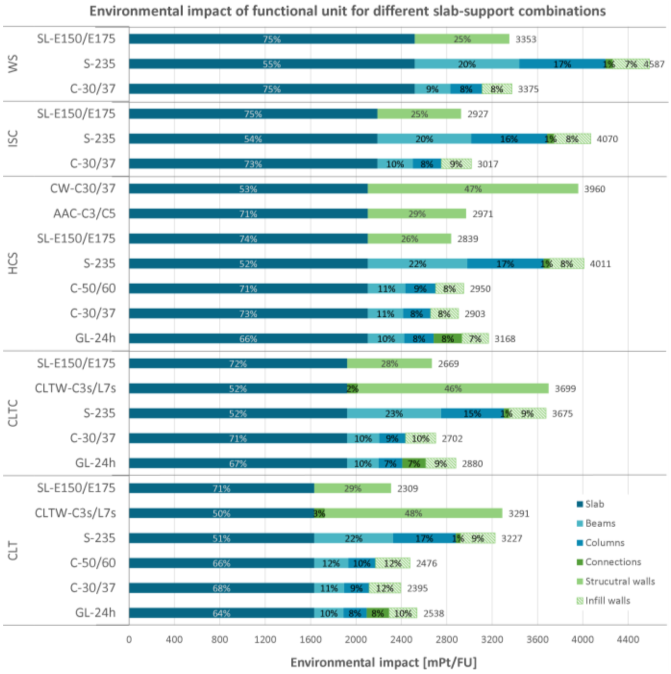


Figure 8 EI of FU for all slab-support combinations

In part II, 17 additional slab-support combinations were calculated as indicated in Figure 8. The total impact is subdivided in the share of the different structural components.

The results found for the HCS floor also hold for the supporting structures of the other slab types. In case the EI of infill walls is taken into consideration, the results of part II show that the lowest EI, for all slab types, is obtained in combination with sand-lime bricks. Subsequently, the concrete frames have the lowest impact, followed by the glulam frames which have a slightly higher impact due to the contribution of the connection components. The steel frames have the largest impact, although, for CLT and CLTC slabs, the combination with CLT walls leads to an even higher EI.

In case the impact of the infill walls is omitted, the EI of the concrete frame becomes smaller than that of the sand-lime brick walls. The further ranking remains similar. However, it can be noticed that in combination with CLT or CLT-concrete slabs the glulam frames also have a slightly smaller impact than the sand-lime brick walls.

The share of the slabs in the total impact is clearly the major contribution with 50 up to 75%.

C. *Sensitivity analysis*

After working out the main results, a sensitivity analysis was set up to verify some of the main assumptions.

Frame configuration - First, the influence of the column-beam configuration on the total environmental impact was verified. With respect to the original configuration (LO1), a configuration was calculated with a larger beam span (LO2) and one with a larger slab span (LO4). An overview of the slab-support combinations that are compared for each configuration is shown in Figure 9.

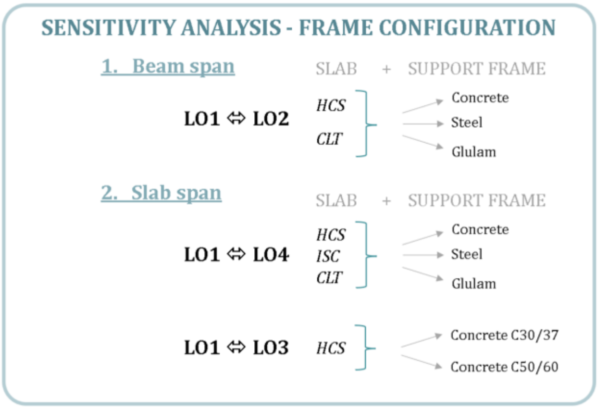


Figure 9 Overview of configurations in sensitivity analysis.

The comparison of the environmental impact for a frame in LO1 and LO2 is done for the CLT and HCS floors in combination with the steel, concrete and glulam frames.

For all combinations, the total impact increases when the beam span increases from LO1 to LO2. The increase is most significant for steel structures and least for concrete structures as shown in Table 2. As a consequence, the relative differences between the frame types remain the same, and for each configuration and slab type, the concrete frame has the lowest impact and the steel frame the highest one.

Table 2 Increase of environmental impact from LO1 to LO2

Increase total impact	*CLT*	*HCS*
Glulam	6.36%	6.78%
Concrete	1.86%	1.73%
Steel	15.40%	18.68%

Subsequently, the results for an increased slab span are compared to the results of LO1 in Figure 10 and Table 3. Apart from the FU combining HCS with a steel frame, the EI increases with increasing slab span. The increase is most remarkable for the ISC slab due to the large weight of the structure as shown in Table 3. As a result, the difference in EI between the ISC slab and the HCS is even more pronounced for LO4 than for LO1. Another remarkable finding is that for LO4 the impact of the CLT slab increased a lot, while the impact of the HCS only slightly increased. As a consequence, the total impact of the FU with a CLT slab becomes slightly higher than that for a HCS for all supporting structures. It can thus be concluded that, taking into account the environmental impact, HCS are the best option for large slab spans.

Table 3 Increase of environmental impact from LO1 to LO4

Increase total impact	*CLT*	*HCS*	*ISC*
Glulam	25.18%	3.67%	66.88%
Concrete	25.73%	4.31%	68.56%
Steel	3.92%	-6.08%	33.73%

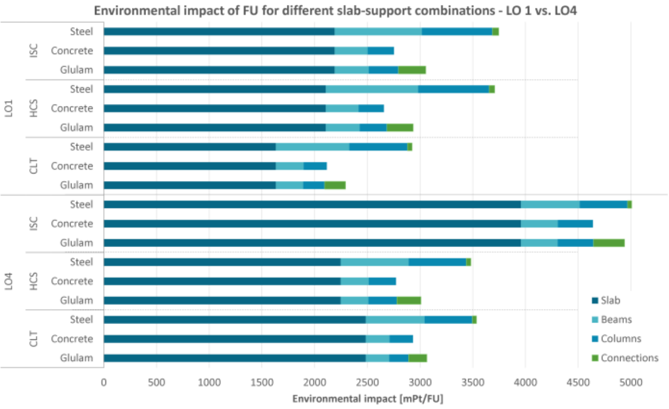


Figure 10 Comparison of the EI for LO1 and LO4.

In general, considering the comparison between LO1 and LO2 and between LO1 and LO4, it can be decided that the configuration of columns and beams has no influence on the optimal material choice for the supporting structures based on their environmental impact. For the slabs, on the other hand, it is more beneficial to use HCS for large spans.

Environmental impact indicators (EII) – The second part of the sensitivity analysis investigates the influence of the choice of EIIs on the results. Figure 11 shows the impact per kilogram of material expressed as a single score in mPt or as a climate change impact represented with a CO_2-equivalent.

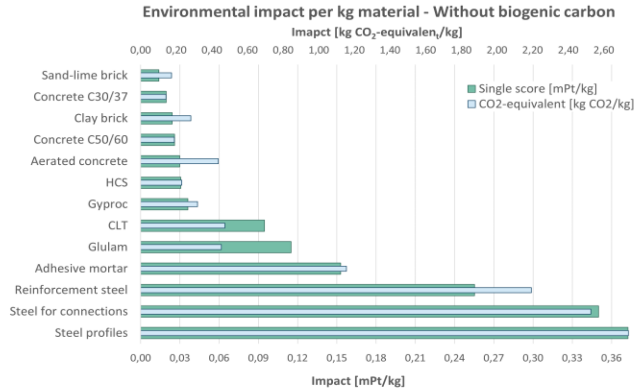


Figure 11 Comparison single score and CO_2-equivalent per kg.

Overall, the bars of both series scale quite proportional to each other. However, the materials for which climate change

(CC) represents a large share in the total impact, such as all brick types, get a much worse environmental impact when expressed as a CO_2-equivalent.On the contrary, the materials for which the CC impact only represents a minor share, especially timber products, get a much better evaluation based on their CC impact.

As a consequence, when only using the climate change impact indicator and expressing the environmental impact as a CO_2-equivalent, the timber structures seem to be more beneficial than the concrete and steel structures. This is in accordance with the results of many other studies discussed in the literature study that only take into account global warming potential as EII ([6], [9]). However, these results are not in line with the results obtained in Figure 8 where the concrete frames performed better than the glulam frames and where the CLT walls even caused the largest environmental impact.

Module D – The final part of the sensitivity analysis takes a closer look to module D which was not considered up to this point. For this part, the loads and benefits beyond the system boundaries were calculated in a simplified way. Because these calculations have a large uncertainty, the savings are not directly subtracted from the production stage (A1-A3), but represented by a separate bar with a negative value in Figure 12. As such the difference between the impacts within and beyond the system boundaries remains visible. The net impact, when all modules are summed up, is indicated with the black dots in Figure 12.

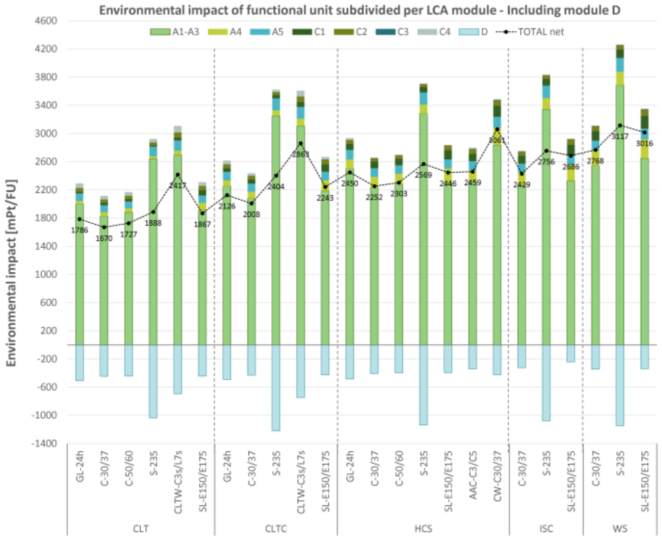


Figure 12 Environmental impact of FU including module D.

It is clear that the impact due to module D is not equally proportional to the total impact for each slab-support combination. Especially for steel structures, module D has a large impact due to the high-grade recycling process. For concrete on the other hand, module D has a lower impact. As a consequence, the FU consisting of HCS supported by concrete walls has the largest impact of all 24 cases when module D is taken into account. The impact of module D for the glulam and CLT components is in the same order of magnitude as the one for concrete. Consequently, including module D has no big influence on the relative difference in total impact between glulam and concrete frames. For masonry structures, consisting of AAC or sand-lime brick walls, the impact of module D is even more limited than for concrete structures. As a result, these designs score slightly worse relative to the other ones when taking into account module D.

It can be stated that taking into account module D averages out the total environmental impact of the functional units with a type of concrete slab. Especially for the HCS and ISC slabs this effect is clearly visible as a consequence of the large gain in module D for the steel frame. While initially the minimum and maximum case of the FU with a wide slab differed 27% (28% for the ISC slab), after including module D this difference is only 11% (12% for the ISC slab).

V. CONCLUSION

The main objective of this study was to determine which structural slab-support combination has the lowest EI for the observed case study building. Considering the five slab types in part I, it could be decided that the CLT slab has the lowest environmental impact for LO1. The results of part II pointed out that the slab-support combination with the lowest total impact consists of a CLT slab supported by sand-lime brick walls. However, in case no infill walls are taken into account, the lowest impact is achieved in combination with a concrete frame. The glulam frames always have a slightly higher EI than the concrete frames due to the contribution of the connection components. The steel frame, on the other hand, results in the largest EI. A more complete summary of all results that were previously discussed is shown in Figure 13 in which a distinction is made between concrete slabs and CLT slabs.

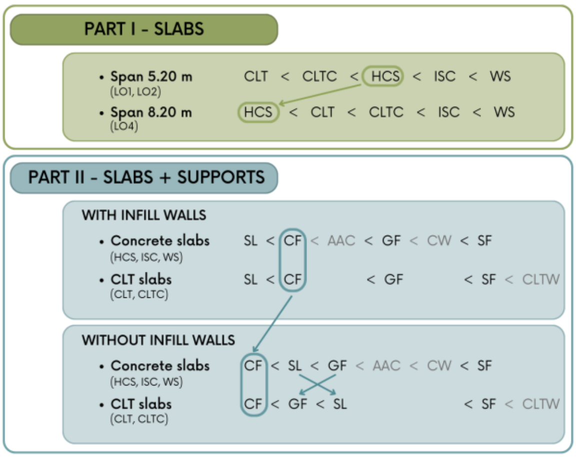


Figure 13 Summary of conclusions drawn for part I and part II.

With an average value of 65%, the slabs represent the largest share in the total impact for all slab-support combinations. Related to the LCA modules, the production stage dominates the total environmental impact in all cases and represents a share of 79 up to 90% of the total impact.

The results of the sensitivity analysis pointed out that module D has the largest impact on the steel frames. It could also be decided that smaller beam and column spans usually lead to a smaller total environmental impact. When looking at the climate change indicator only, the results seemed to be more optimistic for timber structures than when expressed as a single score. This led to a larger variability in the results over the 24 cases. However, it is suspected that the single score environmental impact gives a more realistic estimation of the total impact of the functional unit because more different aspects are considered.

It can be concluded that the results are more sensitive to changes in the LCA compared to changes in the structural calculations. Therefore, it is important to calculate the EI as precisely as possible for each case study, including all necessary EIIs and life cycle stages, to draw the right conclusions related to the material selection.

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List of abbreviations

AAC Aerated autoclaved concrete.

C Concrete frame.

CB Clay brick walls.

CC Climate change.

CFS Cold formed steel.

CLTC CLT-concrete slab.

CLTW Cross laminated timber walls.

CW Concrete walls.

EC Embodied carbon.

EF Environmental footprint.

EI Environmental impact.

EII Environmental impact indicator.

EOL End-of-life.

EOW End-of-waste.

EPD Environmental product declaration.

FU Functional unit.

GHG Greenhouse gas.

GL Glulam frame.

GWP Global warming potential.

HCS Hollow core slab.

ISC In situ concrete slab.

LCA Life cycle assessment.

LCI Life cycle inventory.

LCIA Life cycle impact assessment.
LM Literature matrix.

MPG Milieuprestatie gebouwen.

OSC Off-site construction.

PEF Product environmental footprint.
PM Particulate matter.

QP Quasi permanent.

RC Recycled content.
RR Recycling rate.
RSL Reference service life.
RSP Reference study period.

S Steel frame.
SL Sand-lime brick walls.
SLS Serviceability limit state.

TOTEM Tool to Optimise the Total Environmental impact of Materials.

ULS Ultimate limit state.

WLEC Whole-life embodied carbon.
WS Wide slab.

1

Introduction

1.1 Context and problem statement

The huge share of the construction sector in the global greenhouse gas emissions and its accompanying negative environmental impact (EI), necessitate an enlarged emphasis on sustainability in the design process of buildings. This results in an increasing use of life cycle assessment (LCA) to quantify the environmental impact of buildings over their entire lifetime. This shift towards more environmental motives for decision-making in the construction sector also finds its way through policy measures. In The Netherlands, for example, it is obliged to meet a maximum value for the 'Milieuprestatie gebouwen (MPG)' in order to get an environmental permit for offices and residential buildings [1]. Also in Belgium, environmental impact calculations are encouraged through the development of the government LCA tool TOTEM. Additionally, research has already been done to investigate the possibilities of prescribing TOTEM as a mandatory design tool in public procurement [2]. On a European level measures are also taken with the introduction of the PEF method, the EU-recommended life cycle assessment based method for the calculation of the environmental footprint (EF) of products. In general LCA studies in the European construction sector are guided by the European standard EN 15804 on the assessment of sustainability of construction works [3]. In 2019 this standard has already been adapted to EN 15804 + A2 to meet the requirements of the PEF method [4].

Although LCA clearly is a powerful tool to examine the sustainability of different materials and structures, a perfect comparison between different LCAs is difficult to achieve due to the many factors playing a role in the determination of the environmental impact of a building structure [1]. Some of the most important parameters are the system boundaries of the LCA, the functional unit, the environmental impact indicators and the type of building with its corresponding loads. EN 15804 imposes the life cycle stages that should be taken into account in an LCA as will be elaborated further on. However, there are still different possibilities for the choice of the functional unit and multiple calculation methods for the environmental impact, which can lead to disagreeing conclusions. As a consequence of the existence of multiple guidelines with freedom of interpretation, LCA research is still in a rather fragmented state [5]. Therefore, it can be stated that further standardisation is needed in LCA in order to achieve better comparability [6]. This will be further discussed and illustrated in the literature study in Chapter 2 based on some contrary conclusions of comparative LCAs throughout different studies related to building structures.

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[1] The term 'building structure' will be used in this report to refer to the load-bearing structure of a building consisting of a floor slab and the necessary walls or frames to support it.

Because most construction materials are implemented in the load-bearing structure of a building, it is important to take into account the environmental impact of these structures during the design. Moreover, the share of embodied carbon (EC) in building structures is gradually increasing due to the improved energy efficiency of recent buildings [7]. For this reason, this master's dissertation will focus on the environmental impact of a building's structural system. Many existing studies focus on the use of LCA to calculate the environmental impact of a building structure in one specific material or a comparison between two materials with a focus on global warming potential (GWP) as environmental impact indicator. This study aims to perform a comparative LCA between different possible structural solutions for a case study building using the commonly used building materials concrete, steel, timber and masonry and taking into account all impact indicators according to the PEF impact method and all relevant life cycle stages. As such, the environmental impact of different materials and structural designs can be compared one on one for the investigated typology and the most sustainable material choice can be determined.

The respective case study building is an apartment building part of the Tondelier project site in Ghent. The unit that will be investigated consists of a basement level, 5 storeys and a rooftop extension and has 3 central cores. Because the building is symmetric, only one bay will be examined as indicated in Figure 3.4 in Chapter 3. The focus will be on the structural components of one type storey of the building consisting of one floor slab and the accompanying load-bearing (wall or frame) structure to support it. This facilitates later comparison between the different structural systems.

1.2 Research questions

Performing the comparative life cycle assessment as elaborated above, an answer will be provided to the following main research question:

- What is the structural solution with the lowest environmental impact, for a multi-storey building based on a cradle-to-grave LCA of the different components and materials?

Additionally, the following sub-questions will be examined:

- Which components of the load-bearing structure represent the largest share in the total environmental impact and how much does this share differ between different slab-support combinations?
- Which are the most determining life cycle stages for the different structural materials?
- How determining are the benefits and loads beyond the system boundary (Module D) for the total environmental impact of the building structure?

1.3 Research design

To answer these research questions, first, structural calculations will be performed to dimension the building's structural components, providing an inventory of the material quantities. Subsequently, the environmental impact of the different materials will be determined using the LCA software SimaPro along with the Ecoinvent database, in combination with an Excel sheet for the post-processing of the results.

The extend of the structural calculations and the LCA will be gradually increased. Regarding the structural calculations, in part I, each slab type and each supporting structure (frame or walls) will be calculated separately taking into account the same surface loads for all slabs and the same line loads for all supports. To do so, the supporting structures will all be calculated for the HCS floor in part I. The same will be done for the LCA calculations, which will only take into account module A and module C in the first instance. Based on those intermediate results, relevant combinations of slab types and supporting structures will be composed and further investigated in part II of the calculations. The aim is to find the most optimal solution to reduce the material usage for each design while fulfilling the structural requirements.

After completing part I and part II of the calculations, a sensitivity analysis will be set up to verify the sensitivity of the obtained results to the assumptions that were made. First, the influence of the frame configuration will be further investigated. Thereafter, the choice of environmental impact indicators will be examined. And finally, module D will be added to the LCA to evaluate the effect of benefits and loads beyond the system boundaries.

1.4 Thesis outline

This thesis starts with a literature study in chapter 2, in which the general workflow of an LCA is elaborated. Furthermore, an overview of the existing literature and knowledge about the environmental impact of the different materials and structural solutions will be provided using a so-called literature matrix included in Appendix A. Thereafter, the methodology for this research will be outlined in Chapter 3. First, a description of the case study building will be given, followed by a specification of the different steps in the LCA, including some more details about the processes taken into account in SimaPro for the different materials. In the second part of the methodology, an elaboration on the structural calculations for the different structural components will be given, including the used software, the checks that will be done and the assumptions that were made in the calculations. The results of the structural and LCA calculations for the different structural designs will be compared and discussed in Chapter 4. Finally, in Chapter 5 the main conclusions will be summarized and an answer to the research questions will be formulated. The thesis outline is also summarized in Figure 1.1 which must be read from left to right, following the path of the line connecting the boxes and making one loop through the figure.

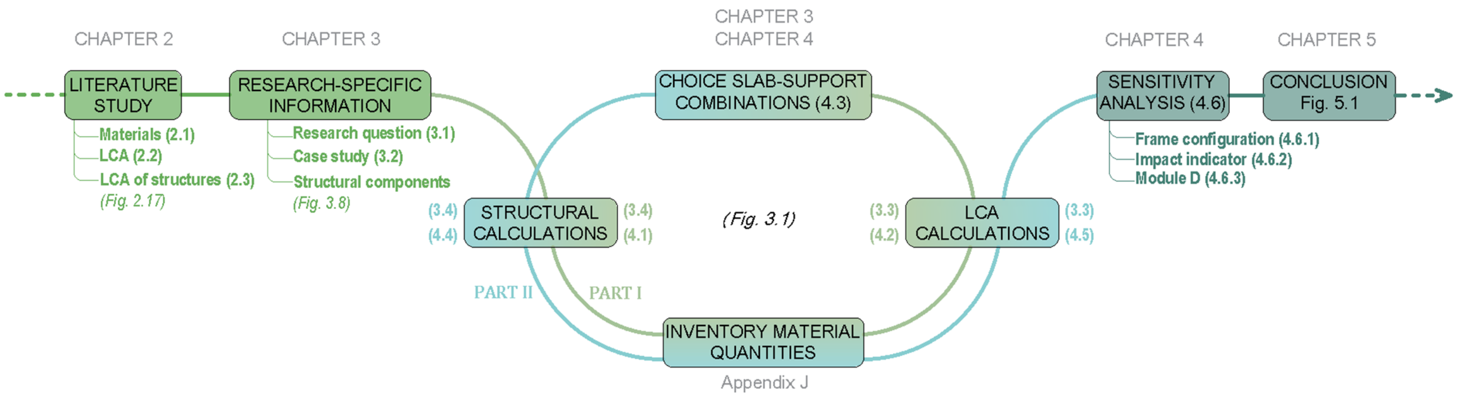


Figure 1.1: Summarizing figure of thesis outline

2

Literature study

In this chapter, first, a brief introduction to traditional construction materials will be given. Thereafter, the methodology of an LCA will be introduced, and finally, a more elaborate section will be dealing with the results of previous LCA studies providing more insight into the environmental impact of building structures and the many influencing factors.

2.1 Commonly used construction materials

As mentioned in the introduction, the focus of this study will be on the environmental impact of building structures making use of the commonly used building materials concrete, steel, timber and masonry. Hereunder, the main characteristics of each material are introduced.

2.1.1 Concrete

Concrete is one of the most widely used construction materials thanks to its high compressive strength, free form, relatively low price tag, high durability, high thermal mass, low maintenance and ease of construction [8]. Moreover, it is a locally sourced material, making it widely available and leading to the fact that there is a lot of experience in building with concrete. Unfortunately, due to its specific composition, it is the largest consumer of primary resources [9]. Together with the consumption of water during production and the carbon emissions and energy use during Portland cement production, this leads to a significant environmental footprint. Therefore, multiple solutions have been sought to reduce this environmental impact such as high-grade recycling of concrete waste, the use of high-strength concrete and off-site construction. This will be further elaborated in Section 2.3.1.

2.1.2 Steel

The second construction material that will be investigated is steel. The main advantage of steel is its high strength which leads to lightweight, but mostly more expensive, structures for high load combinations compared to concrete. An additional benefit is the construction speed of steel structures due to the large degree of prefabrication. However, in many studies steel is depicted as the material with the largest environmental footprint due to the polluting production process at very high temperatures needed to transform the raw materials, iron ore, oxygen and minerals, into steel [10]. Moreover, increasing the energy efficiency of buildings leads to a shift in emphasis on embodied carbon emissions related to material use, which can further discourage the use of steel structures. However, steel also has a unique advantageous characteristic which gets more attention recently: it can be fully recycled multiple times without a loss of quality and when designed for disassembly it can even be reused [11–13]. As such, a large amount of extraction of raw materials can be avoided.

2.1.3 Timber

In general, timber is widely presented as the optimal material to reduce the greenhouse gas (GHG) emissions of the construction industry because it is a natural and renewable resource that is so-called 'carbon neutral' because of carbon storage in biomass. Moreover, research already confirmed that the CO_2-equivalent of the building structure of multi-storey buildings can be reduced significantly by substituting reinforced concrete (RC) structures with timber structures [14]. However, because there is less experience with this construction material, there is also more uncertainty about the end-of-life (EOL) stage of timber compared to steel and concrete. The main disadvantage of timber structures, especially for more high-rise buildings, is their low mechanical resistance which can be problematic for wind loading. Some other disadvantages are the poor acoustic insulation and the risk of overheating due to the very low thermal inertia of the material [15].

2.1.4 Masonry

A final widely used construction material for load-bearing walls in mid-rise buildings is masonry. This refers to all walls composed of individual units glued together using a mortar. Different kinds and sizes of bricks are available, of which the most widely used ones are clay bricks, (aerated) concrete bricks, and sand-lime bricks [16]. Engineering bricks have higher strengths and lower porosities which make them suited to be used for load-bearing structures. This material is mainly used due to its relatively low costs, flexibility and the available experience in constructing with these elements. Sand-lime bricks, made of lime, sand and water, have some additional advantages for mid-rise residential buildings. These bricks have good acoustic properties and excellent fire safety properties. Compared to other construction materials such as concrete, approximately 60% less energy is necessary in the production process of sand-lime bricks. Moreover, when prefabricating sand-lime walls, the amount of waste on site can also be limited [17]. Comparable advantages can be attributed to aerated concrete blocks. However, these blocks are much lighter which leads to better thermal properties, but also to higher costs.

2.2 Life cycle assessment based on the standard EN 15804+A2

Life cycle assessment or LCA is a powerful tool to map the environmental impact of materials, building components or even the entire load-bearing structure of a building over the full life cycle by modelling the impact of the materials and energy use. This is realized by taking into account four different life cycle stages: the production, the construction on the building site, the use of the structure and the end-of-life stage, which are further subdivided into sub-modules as illustrated in Figure 2.1. The international standards ISO 14040 and 14044 summarize the basic principles, framework, requirements and guidelines to perform an LCA. However, a lot of parameters are still free to choose. A more specified framework applied to buildings can be found in the European standards EN 15804 [3] and EN 15978 [18] on the sustainability of construction works [19]. These standards are also further elaborated in the documentation of the Belgian LCA tool TOTEM [20] which will be an important resource to set up this study. Hereunder, the sub-processes of the LCA method, as shown in Figure 2.2, will be discussed shortly, focussing on the application to building structures according to EN 15804 [3].

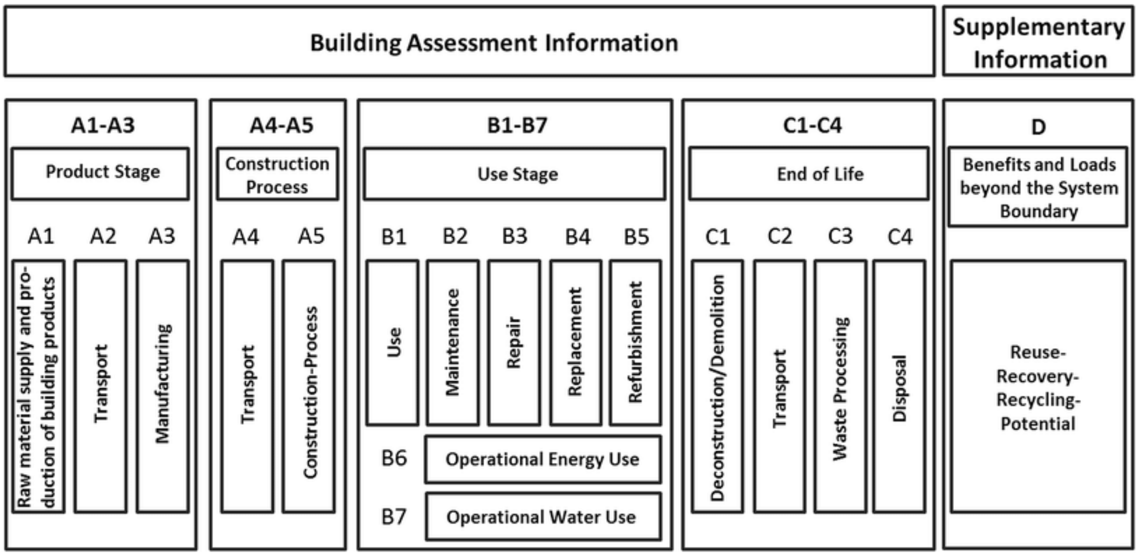


Figure 2.1: System boundaries according to EN 15978 [3]

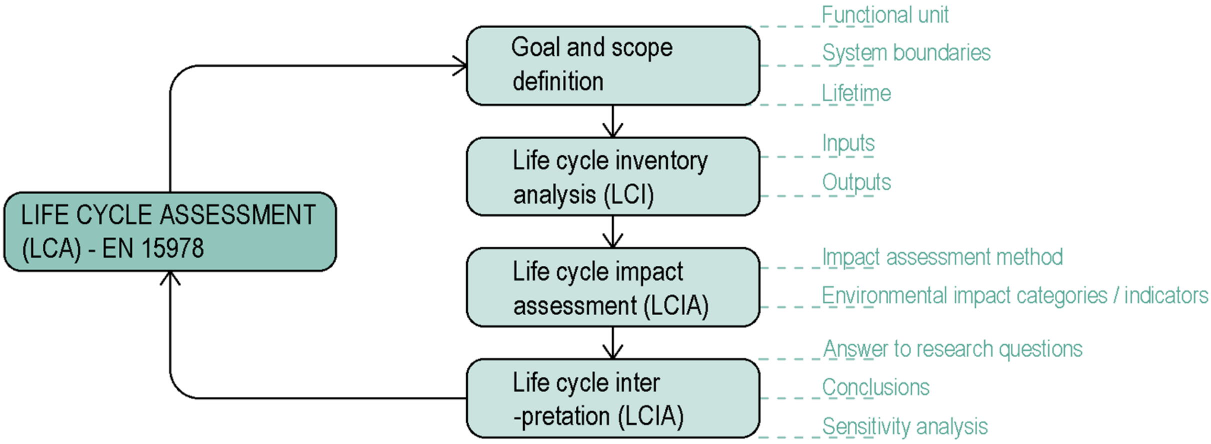


Figure 2.2: Steps in an LCA according to EN 15987 [18]

2.2.1 Goal and scope definition

In this first step, the context of the study, the objective and the use of the resulting data will be described. The context and the objective have already been summarized in the introduction. As mentioned, the objective is to evaluate the environmental impact of the load-bearing structure of a case study building executed in concrete, steel, timber or masonry. The data resulting from this investigation will then be used to formulate an answer to the research questions and as such to facilitate decision-making in structural designs based on environmental incentives.

This step also includes the specification of the functional unit (FU) and the system boundaries. The functional unit is a representation of the technical and structural requirements and functionalities of the construction that will serve as a reference for the calculations of the environmental impact and which is the basis for objective comparison in the comparative LCA. As a consequence, the different structural designs can easily be compared based on their functional equivalency. This can go from a cubic metre of concrete over a square metre of a floor element up to an entire building structure as will be the case in this study. Finally, the functional unit also has a predefined lifetime over which the environmental impact will be determined. A default value often used for residential buildings is 60 years, although the lifetime can be particularly large for structural systems as these are not replaced frequently. In literature, lifetimes of 80 to 100 years are also frequently applied. This will be further illustrated in Section 2.3.

The European standard EN 15978 [18] describes four different life cycle stages A up to D that can be taken into account in an LCA of a construction. These stages are further subdivided into different sub-modules as shown in Figure 2.1. Each impact will be assigned to the stage or module in which it occurs. Module A concerns the production of a construction material and its construction on site. Module B covers the use stage including, among other things, maintenance and operational use of resources. Module C takes into account the end-of-life, and finally, additional loads and benefits of avoided environmental impacts due to flows exiting the system (e.g. recycling or reuse of building components) can be taken into account through the inclusion of module D. However, there is not yet a generally accepted method in the standards to calculate module D. The system boundaries define the choice of which stages will be taken into account in the LCA. Most studies focussing on the environmental impact of building structures leave out the use phase B as this is less relevant [21]. However, for wooden structures, it can be chosen to take into account the maintenance related to fire safety and other maintenance programs through the inclusion of module B2 as elaborated in [22].

2.2.2 Life cycle inventory analysis (LCI)

In the life cycle inventory, also referred to as resource use and emissions profile, all the necessary information is gathered such as material and energy inputs and outputs to perform the assessment. Inputs concern the use of renewable and non-renewable raw materials and energy, but also the use of additional resources and land. Outputs include all the emissions in the different stages, the production of waste and by-products, and the impact on the landscape. To specify for example the transport of prefabricated concrete hollow core slabs from the concrete plant to the construction site, one needs to determine the vehicle, the distance and the load rating according to the quantities of the different input and output flows determined for the considered functional unit [19]. In this stage, one can make a difference between primary and secondary environmental data to determine the footprint. Primary data concerns the input data directly measured from a specific facility, for example, electricity use or water consumption. Secondary data on the other hand comes from other people and is used to fill the gaps where there is a lack of primary data. This is for example the data collected from the databases set up by researchers and universities such as Ecoinvent [4]. This study will rely on secondary data.

2.2.3 Life cycle impact assessment (LCIA)

In this stage, the environmental performance of a certain product or material is determined based on the resource use and emissions profile. The environmental impact of building components can be expressed using a range of environmental impact categories containing one or more environmental impact indicators related to different environmental problems. The in- and outputs that were collected in the previous stage are allocated to a certain impact indicator in this stage and as such the values for these indicators can be calculated. The environmental profile of the product is then the combination of the results for all different indicators. This profile makes it possible to compare different materials throughout the different life cycle stages and for different impact indicators. In the updated standard EN 15804+A2 [3], 19 impact indicators, subdivided into 12 impact categories, are included as shown in Table 2.1. The impact assessment method used in this study is the EN 15804+A2 method [23]. Besides the scores of the individual environmental impact indicators, it is beneficial to communicate the results also in the form of one aggregated environmental impact score expressed in Pt to facilitate comparison. Although weighing and normalisation are optional steps in the LCIA, they can be useful in a comparative LCA. These steps make it possible to aggregate the results of multiple impact indicators up to a single score in which each indicator has a certain weight according to its relevance in the respective LCIA.

Table 2.1: Impact indicators according to EN15804+A2 [3]

Environmental impact category	**Environmental impact indicator**	**Unit**
Climate change	Climate change - total	kg CO_2-equivalent
	Climate change - fossil	kg CO_2-equivalent
	Climate change - biogenic	kg CO_2-equivalent
	Climate change - land use and land use change	kg CO_2-equivalent
Ozone depletion	Ozone depletion	kg CFC 11 equivalent
Acidification	Acidification	mol H+ equivalent
Eutrophication	Eutrophication - aquatic freshwater	kg P equivalent
	Eutrophication - aquatic marine	kg N equivalent
	Eutrophication - terrestrial	mol N equivalent
Photochemical ozone formation	Photochemical ozone formation	kg NMVOC equivalent
Depletion of abiotic resources	Depletion of abiotic resources - minerals and metals	kg Sb equivalent
	Depletion of abiotic resources - fossil fuels	MJ net calorific value
Water use	Water use	m3 world eq. deprived
Particulate matter	Particulate matter emissions	Disease incidence
Ionizing radiation	Ionizing radiation - human health	kBq U235 equivalent
Eco-toxicity	Eco-toxicity - freshwater	CTUe
Human toxicity	Human toxicity - cancer effect	CTUh
	Human toxicity - cancer effects	CTUh
Land use	Land use related impacts/soil quality	dimensionless

2.2.4 Life cycle interpretation

The last step in the LCA concerns the interpretation of the results and the formulation of an answer to the research questions. In this step, the results of the LCAs for the concrete, steel, timber and masonry structures will be compared based on their aggregated score and based on their climate change impact separately. Additionally, a sensitivity analysis will be performed to verify the influence of specific changes in the LCA on the initial results. This will for example be done by comparing two LCA's for each design, with and without the inclusion of module D. Finally, the conclusions, recommendations and limitations will be discussed.

2.3 Application of LCA on common construction materials

As a consequence of the increasing importance of quantifying and subsequently decreasing the environmental footprint of buildings and building components, a lot of LCA studies have been carried out in recent literature related to the impact of different types of building structures. These studies provide insight into the environmental impact of building structures for a broad range of typologies, system boundaries and scopes. It is important to mention that the conclusions drawn in the different studies are not always compatible due to the different assumptions on which all LCA studies rely. This further emphasizes the need for a more specified LCA method that creates a clear basis for comparison, avoids irrelevant comparisons between different materials over different studies and which can serve as an aid in decision-making for the construction sector.

In the following sections, this will be further illustrated by summarizing the main results and conclusions of existing LCA studies for concrete, steel, timber and masonry structures. These conclusions can then be taken into account when making choices for the different structural designs of the case study building in this study. The main research papers concerning LCA studies, that were consulted to write this literature study are provided, in the same order as they are referred to in the sections hereunder, in the table in Appendix A. In this table, further referred to as the literature matrix (LM), the problem statement and conclusion of every paper are summarized and the main parameters influencing the performed LCA study are listed. Figure 2.3 summarizes the concept of the literature matrix and the information that is collected in it. To clarify to the reader which sources have been summarized in the literature matrix, the code (LM) will be added to these references in the text the first time they are referred to in each chapter.

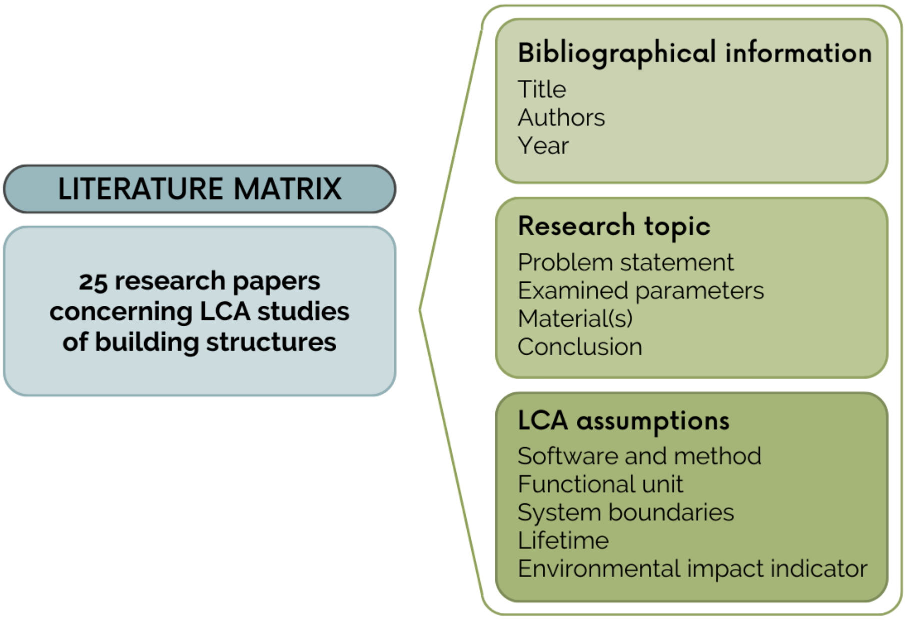


Figure 2.3: Conceptual scheme of literature matrix

2.3.1 Concrete

In this section, the existing research about the material concrete will be discussed. First, the possible methods to reduce the environmental impact are elaborated, followed by the types of concrete components and finally, the main conclusions of previous LCA studies will be summarized.

2.3.1.1 Possible methods to reduce environmental impact

High-grade recycling - Some efforts have been done to reduce the large environmental footprint related to concrete production. Mostly, at the end-of-life concrete is recycled by crushing it into recycled aggregates that serve low-quality purposes such as drainage material or road construction [15] (LM). Research has shown that some gain can be acquired in module D by changing the end-of-life treatment of concrete waste [24] (LM). This study decides that high-grade recycling of concrete structures is the best end-of-life treatment to reduce the environmental impact, although, when taking into account all life-cycle stages low-grade recycling can be more beneficial. The impact of Module A on the overall footprint of concrete structures remains the most significant, therefore, Module D has minimal relative influence. Another study [25] also stated that the carbon emissions avoided by recycling the aggregates are outbalanced by the additional amount of cement needed in combination with recycled aggregates.

Reduction of the amount of clinker - The share of cement in the environmental footprint of concrete is approximately 95%. This explains why the change in aggregates only has a small influence on the total environmental footprint [7]. To reduce the impact in module A, a possibility is reducing the amount of clinker in the cement. Calcination of limestone for the production of clinker is responsible for the largest share in the carbon emissions of concrete manufacturing, but these emissions cannot be avoided and thus the amount of clinker in the cement needs to be lowered. This can be realized by replacing limestone with pozzolans such as fly ash or blast furnace slag, which do not have any influence on the cement quality [26]. Moreover, clinker production is also responsible for 90% of the total energy consumption and thus reducing the amount of clinker will also positively affect the energy consumption [27].

High-strength concrete - In recent years the development of concrete technology has led to new types of cement-based concrete. Some examples are high-strength concrete and self-compacting concrete, which are characterised by higher strength, durability and viscosity. Unfortunately, this goes along with a larger cement content and consequently larger emissions and energy consumption during the production phase. However, this can be counteracted by a reduction in material use and, eventually, a reduction in environmental impact might be obtained. Especially in columns subjected to large compressive forces, this effect is perceived [28] (LM). According to [7, 29] the optimum concrete class to minimize environmental impact is C50/60 in which 40% of cement is substituted by pulverized fuel ash. This can give rise to a reduction in EC of about 40%. This study also showed that the use of a superplasticiser can reduce the overall EC by approximately 26%, due to a reduced water and binder content while the water-binder ratio is kept constant.

Off-site construction - Another solution that shows some environmental advantages is off-site construction (OSC) of concrete products. Besides the cost and time savings and better material quality, OSC reduces environmental impacts such as dust emissions and waste disposal. For residential buildings, the environmental impact of building structures with precast concrete floors can be 12.2% lower than with in situ cast floors. Due to the larger strength of the precast slabs, higher spans are possible which results in fewer columns needed, less material use and lower environmental impact. This conclusion was drawn for a 5-storey building with a surface area of 833 m² and a rectangular shape [30] (LM). According to [31] based on 27 cases of prefabricated buildings, the embodied carbon of off-site constructed structures can be reduced by approximately 15.6% and the operational carbon by 3.2% compared to traditional constructions. However, mostly sub-assembly components are analysed as functional unit to analyse the carbon emissions of prefab residential buildings and the main focus is on carbon emissions, neglecting other environmental impacts such as ozone depletion and consumption of water. Therefore, there is still a need for more research on the level of an entire building, taking into account a broader range of impact indicators and including end-of-life stages in the assessment [32] (LM).

Optimized design - Besides changing the end-of-life treatment and the construction process, further reduction in carbon emissions can be obtained from optimizing reinforced concrete structures as a whole instead of focussing on the main components separately. Optimized designs for flat plate buildings can achieve a 5 to 17 % reduction in carbon emissions. The column concrete strength, column size and building's height are the most significant design variables to meet the most environmentally friendly solution according to [11] (LM). The lowest environmental impact is governed by the balance between the ratio of concrete and reinforcement consumption and the ratio of steel and concrete carbon emission coefficients. Moreover, the best solution was found by decreasing the slab emissions and increasing the impact of the columns which again emphasizes the importance of examining a building as a whole. Figure 2.4 confirms this and shows that the total embodied carbon (expressed in ton CO_2) increases with increasing height of the building, but also with increasing column spacing for a fixed amount of storeys in conventional designs. The largest impact can clearly be attributed to the concrete for the slabs. Therefore, an optimisation problem and methodology are very effective to design sustainable concrete buildings [11]. It is also demonstrated in other research that structural design parameters such as dimensions and cross-sections of beams and columns are equally important as material parameters according to their effect on the embodied carbon per unit dimension and load capacity [7]. In [7] it has been decided that as load capacity (and therefore size) of structural elements increases, the EC per unit of structural performance decreases which means 'heavy' components are more efficient than 'light' components.

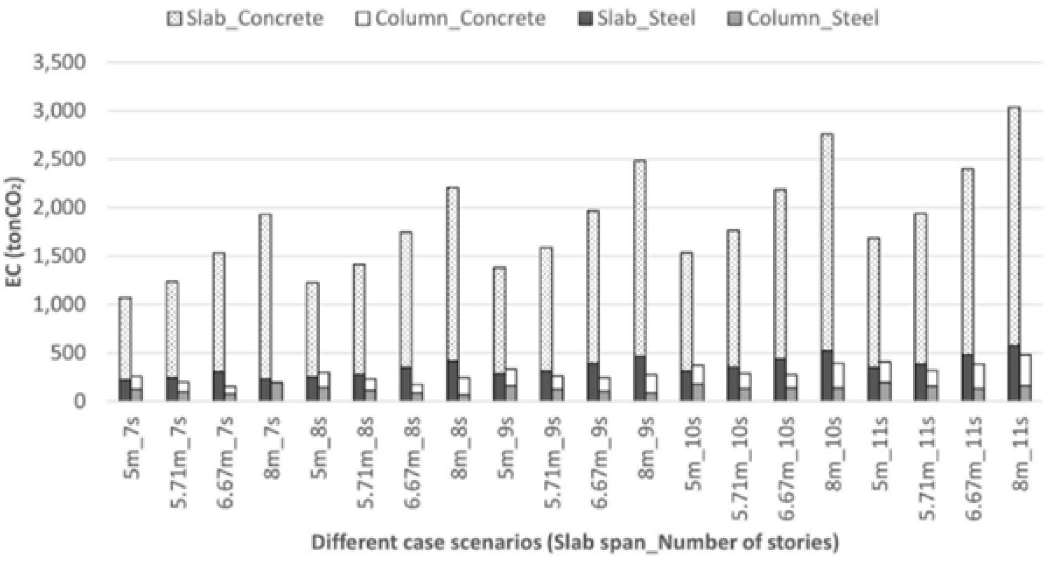
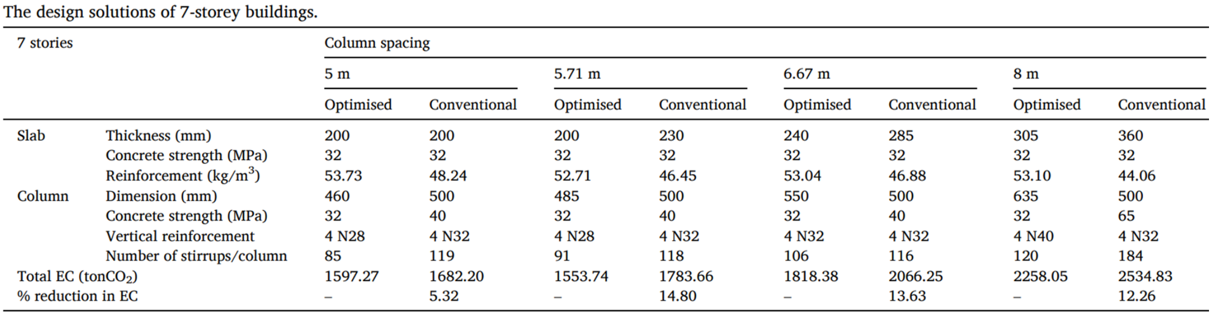


Figure 2.4: Comparison of EC (subdivided into a part related to concrete and reinforcement steel for both slab and columns) for different reinforced concrete structures as a function of slab span and number of stories [11]

The results in Figure 2.5 show some realistic designs that are set up to reduce the total EC and can be used as a guideline or reference when designing flat slab buildings in an environmentally friendly way. Unfortunately, similar studies do not always report the same design variables as being the most influential ones to optimize the structural designs. According to [33] the column grid, concrete strength and reinforcement of the slab are the main variables. This illustrates the importance of the choice of the design approach and algorithms used in the optimization study.



The design solutions of 7-storey buildings.

7 stories		Column spacing							
		5 m		5.71 m		6.67 m		8 m	
		Optimised	Conventional	Optimised	Conventional	Optimised	Conventional	Optimised	Conventional
Slab	Thickness (mm)	200	200	200	230	240	285	305	360
	Concrete strength (MPa)	32	32	32	32	32	32	32	32
	Reinforcement (kg/m^3)	53.73	48.24	52.71	46.45	53.04	46.88	53.10	44.06
Column	Dimension (mm)	460	500	485	500	550	500	635	500
	Concrete strength (MPa)	32	40	32	40	32	40	32	65
	Vertical reinforcement	4 N28	4 N32	4 N28	4 N32	4 N32	4 N32	4 N40	4 N32
	Number of stirrups/column	85	119	91	118	106	116	120	184
Total EC (tonCO$_2$)		1597.27	1682.20	1553.74	1783.66	1818.38	2066.25	2258.05	2534.83
% reduction in EC		–	5.32	–	14.80	–	13.63	–	12.26

Figure 2.5: EC of design options for a 7-storey building [11]

2.3.1.2 Types of concrete components

Slab types - In multi-storey residential buildings the most widely used concrete slab types are in situ cast concrete slabs, flat slabs, prefabricated hollow core slabs and prefab wide slabs with lattice girders and an in situ concrete layer on top (for the Dutch-speaking reader: predallen). In Belgium mostly, prefabricated slab types are used due to their low price, good performance and fast execution. Moreover, some studies also claim that prefabrication has a positive influence on the environmental impact as explained in the previous section.

According to [34] (LM) as well as [35] (LM) a beam-floor system consisting of concrete beams and prestressed hollow core slabs is the most environmentally friendly system. This provides an additional incentive to use these slab types. Wide slabs, on the other hand, have a higher environmental impact according to [32]. This is mainly the consequence of the higher steel usage in these floor systems. Some advantages of wide slabs are their lower transport weight and large width (up to 3m) which allows a fast placement [36]. Flat slabs are interesting for parking garages to avoid the use of beams that lower the free height, but they are not commonly used in residential buildings.

Supporting structure - The supporting structure can, on the one hand, consist of a frame composed of beams and columns reducing the surface loads to point loads, and on the other hand, of walls transferring line loads. For the beams and columns normally square or rectangular sections are used provided with the necessary bending reinforcement. Again these elements can be prefabricated to benefit the multiple advantages. The same holds for walls. In [37] (LM) it was found that the use of rebars is larger for a wall structure than for a rigid frame structure. For the examined apartment buildings the wall structures had a slightly higher GWP than the rigid frame structures. However, regarding some other environmental impact indicators, the wall structure scores better.

2.3.1.3 Conclusions of previous LCA studies

The preceding subsections already discussed some results of previous research related to methods to reduce the environmental impact of concrete. In this subsection, the remaining conclusions drawn from the LCA studies of concrete structures, summarized in the literature matrix in Appendix A, will be listed.

Functional unit - Regarding the functional unit in a comparative LCA study it is important to choose it as such that a relevant comparison is obtained. When comparing, for example, hollow core slabs to in situ concrete slabs as a floor solution in a residential building it is not sufficient to look at the slab only because the smallest hollow core slab has a much larger structural strength than an in situ floor. This means that the span length can be larger and fewer columns will need to be foreseen. Therefore, the functional unit must also include the columns and beams [30] (LM).

Material efficiency - A somewhat contradictory finding is that material efficiency does not always lead to a reduced environmental impact for reinforced concrete structures, although there is a correlation between the weight of the structure and the environmental performance [11]. This can be explained by the fact that an optimum must be found in the ratio of the consumption of reinforcement steel and concrete. This again illustrates the importance of the choice of the functional unit, which must include concrete as well as reinforcement steel.

Carbonation and end-of-life - During its operational phase a concrete structure reabsorbs a certain part of the carbon which was emitted during cement production due to the process of carbonation. This can decrease the GWP of concrete structures, but the amounts are still unclear. Although landfilling is not the preferred option for the end-of-life treatment of concrete, it can contribute to the CO_2-sequestrating effect because the carbonation reaction keeps going and is even increased during the end-of-life stage [15].

Governing parameters in structural design - To determine the material quantities for the LCA, structural calculations need to be done of which the governing parameters generally depend on the span length. For shorter spans, the moment capacity will determine the dimensions of the concrete slab, while for larger spans the long-term deformation will be the decisive parameter in the structural design. For concrete slabs, vibration requirements are mostly less determining [12] (LM).

2.3.1.4 Remarks and conclusion - Concrete

It can be concluded that much effort has already been done to reduce the environmental impact of concrete. The main methods to do so are high-grade recycling, reduction of the clinker concentration, new types of cement-based concrete, off-site construction and design optimization. These last two methods can lead to reductions in embodied carbon of respectively 15.6% and 5 to 17%. Because of the environmental and structural advantages of off-site construction, the most widely-used concrete components are (partially) prefabricated such as hollow core slabs and wide slabs. The structural design and choice of the functional unit determine the material quantities taken into account in the LCA calculations. For concrete structures, the necessary material quantities are mainly determined by the moment capacity and long-term deformations of the concrete slabs.

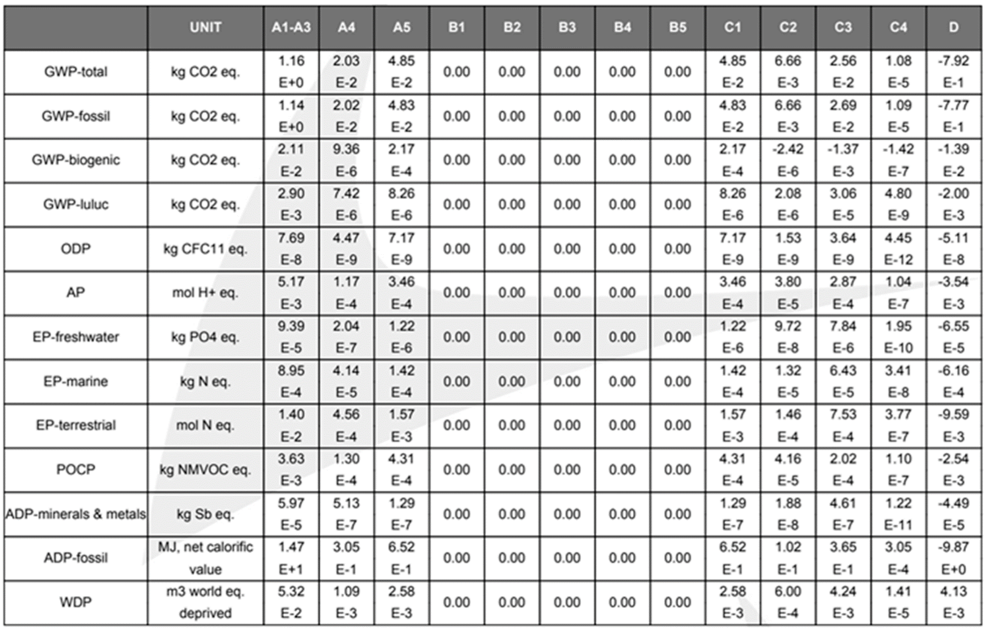
2.3.2 Steel

Similar to the previous section, in this section, the main findings about steel as a structural material will be discussed starting with possible methods to reduce the environmental impact. Next up the different types of steel components will be talked about and finally, the conclusions of previous LCA studies of steel structures will be summarized.

2.3.2.1 Possible methods to reduce environmental impact

Use of recycled steel scrap - Recycled steel scrap can help reduce the amounts of energy and raw materials needed in steel production such as coal for the reduction of iron ore, and is therefore widely used in steel production. Due to this process, most steel building components are recycled in the end-of-life stage to be used as scrap during the manufacturing of new steel products. However, due to the larger share of construction compared to demolition projects, there is a lack of steel scrap and the extraction of iron ore for the production of virgin steel still goes on. Following this reasoning, it can be argued to assign the benefit of steel recycling to the steel producer who indirectly makes scrap available [21] (LM).

Design for disassembly and reuse - Figure 2.6 shows a table from the environmental product declaration (EPD) for construction steel which is designed for reuse and can be reused for 80% at the end-of-life [38]. The LCA calculations for this EPD were executed using SimaPro 9.1.0.8 and the Ecoinvent 3.6 database. The main environmental impact indicators specified in the PEF method are represented. This EPD shows the advantages of the reuse of steel leading to a decrease of the environmental impact represented with large negative values in module D. In general it can be stated that including module D in an LCA has the largest impact on steel structures due to the high recycling or reuse rate and the high environmental impact of primary steel production that can be substituted by the recycling process [39]. Design for disassembly is an important principle to make the structure demountable and enable easy reuse and recovery of the materials and components at the end-of-life. A design for disassembly reduces waste production and sees a structure as a depository of resources [40] (LM).



	UNIT	A1-A3	A4	A5	B1	B2	B3	B4	B5	C1	C2	C3	C4	D
GWP-total	kg CO2 eq.	1.16 E+0	2.03 E-2	4.85 E-2	0.00	0.00	0.00	0.00	0.00	4.85 E-2	6.66 E-3	2.56 E-2	1.08 E-5	-7.92 E-1
GWP-fossil	kg CO2 eq.	1.14 E+0	2.02 E-2	4.83 E-2	0.00	0.00	0.00	0.00	0.00	4.83 E-2	6.66 E-3	2.69 E-2	1.09 E-5	-7.77 E-1
GWP-biogenic	kg CO2 eq.	2.11 E-2	9.36 E-6	2.17 E-4	0.00	0.00	0.00	0.00	0.00	2.17 E-4	-2.42 E-6	-1.37 E-3	-1.42 E-7	-1.39 E-2
GWP-luluc	kg CO2 eq.	2.90 E-3	7.42 E-6	8.26 E-6	0.00	0.00	0.00	0.00	0.00	8.26 E-6	2.08 E-6	3.06 E-5	4.80 E-9	-2.00 E-3
ODP	kg CFC11 eq.	7.69 E-8	4.47 E-9	7.17 E-9	0.00	0.00	0.00	0.00	0.00	7.17 E-9	1.53 E-9	3.64 E-9	4.45 E-12	-5.11 E-8
AP	mol H+ eq.	5.17 E-3	1.17 E-4	3.46 E-4	0.00	0.00	0.00	0.00	0.00	3.46 E-4	3.80 E-5	2.87 E-4	1.04 E-7	-3.54 E-3
EP-freshwater	kg PO4 eq.	9.39 E-5	2.04 E-7	1.22 E-6	0.00	0.00	0.00	0.00	0.00	1.22 E-6	9.72 E-8	7.84 E-6	1.95 E-10	-6.55 E-5
EP-marine	kg N eq.	8.95 E-4	4.14 E-5	1.42 E-4	0.00	0.00	0.00	0.00	0.00	1.42 E-4	1.32 E-5	6.43 E-5	3.41 E-8	-6.16 E-4
EP-terrestrial	mol N eq.	1.40 E-2	4.56 E-4	1.57 E-3	0.00	0.00	0.00	0.00	0.00	1.57 E-3	1.46 E-4	7.53 E-4	3.77 E-7	-9.59 E-3
POCP	kg NMVOC eq.	3.63 E-3	1.30 E-4	4.31 E-4	0.00	0.00	0.00	0.00	0.00	4.31 E-4	4.16 E-5	2.02 E-4	1.10 E-7	-2.54 E-3
ADP-minerals & metals	kg Sb eq.	5.97 E-5	5.13 E-7	1.29 E-7	0.00	0.00	0.00	0.00	0.00	1.29 E-7	1.88 E-8	4.61 E-7	1.22 E-11	-4.49 E-5
ADP-fossil	MJ, net calorific value	1.47 E+1	3.05 E-1	6.52 E-1	0.00	0.00	0.00	0.00	0.00	6.52 E-1	1.02 E-1	3.65 E-1	3.05 E-4	-9.87 E+0
WDP	m3 world eq. deprived	5.32 E-2	1.09 E-3	2.58 E-3	0.00	0.00	0.00	0.00	0.00	2.58 E-3	6.00 E-4	4.24 E-3	1.41 E-5	4.13 E-3

Figure 2.6: Overview of EI of construction steel with 80% reuse for the main indicators according to the EPD in [38]

In case the structure is accordingly designed it can be assumed that 80% of the steel is suited for reuse at the end-of-life. This requires among other things that all connections are bolted and designed for disassembly and the braces are demountable. When taking into account the easy disassembly of steel structures together with the possible reuse it has even been proven that cold-formed steel (CFS) structures can have up to 24% better global warming potential performance than a comparable reinforced concrete structure for a detached house [41] (LM). This large difference can mainly be attributed to the larger amount of recoverable materials in a CFS house compared to a reinforced concrete house. This ecological benefit was also taken into account for steel cubic modules using SHS profiles in the study of [13] (LM).

The study of Berki [21] represents the reduced release of emissions and carbon storage by the concept of carbon handprint as elaborated in the Carbon Handprint guide [42]. This concept is equivalent to taking into account module D in LCA calculations. Where the timber industry focuses on renewable materials in its handprint concept, the steel industry portrays it as the possibility of recycling and reusing the material.

2.3.2.2 Types of steel components

Steel frames - Common structural steel frames are composed of hot-rolled H- and I-profiles for beams and columns which are bolted or welded together to form a frame. These can easily be designed using a standardized profile from a catalogue for short spans. For small-scale steel structures, square hollow SHS profiles are also commonly used [13]. Johnston [43] (LM) compared hot-rolled steel frames to cold-formed steel frames in residential buildings, deciding that the difference in environmental impact is negligible in case the cladding is also taken into account. Berki [21] extended this research and compared the environmental performance of hot-rolled open profiles to that of cold-formed tubular profiles concluding that hot-rolled open profiles perform better. This is also illustrated further on in figure 2.9. No clear data is available about the environmental performance of cold-formed open profiles. For larger spans, steel trusses, composed of a top chord, a bottom chord and bracings in between, are commonly used. These elements are always joined using pinned connections [21].

Slab types - Regarding the possible slab types to combine with a steel frame, the common choices are concrete slabs as described in the previous sections or composite steel-concrete slabs. In [44] (LM), composite steel-concrete floors are used because this is a very common solution in the UK for multistorey buildings. However, in Belgian practice, this floor system is rarely used in residential buildings due to the high costs. These floors are composed of a profiled steel plate and an in situ concrete layer on top. In [44], it is stated that, on average, the structural system using a steel deck has the largest whole-life embodied carbon (WLEC) compared to concrete and timber structures, but the distribution largely overlaps with the values for reinforced concrete structures as shown in Figure 2.7.

According to [45] (LM), on the contrary, composite slabs can even be recommended for engineering applications taking into account the environmental performance. However, this study uses the cross-sectional area of a slab satisfying certain structural requirements as the functional unit. Taking into account the entire structural system might lead to other conclusions as mentioned above and as stated in [35] (LM) in which floor-beam systems were evaluated. The latter classifies steel deck floor-beam systems as average to almost not advisable. However, this is mainly a consequence of the chosen steel composition which exists for 67.6% of new steel and only 32.4% recycled steel. Moreover, modules C1 and D were not included in this study and module C3 was only partially included. Because these are mainly the stages where steel gains its benefits (as seen in Figure 2.6), it is obvious that the steel solution gets a bad score in this study.

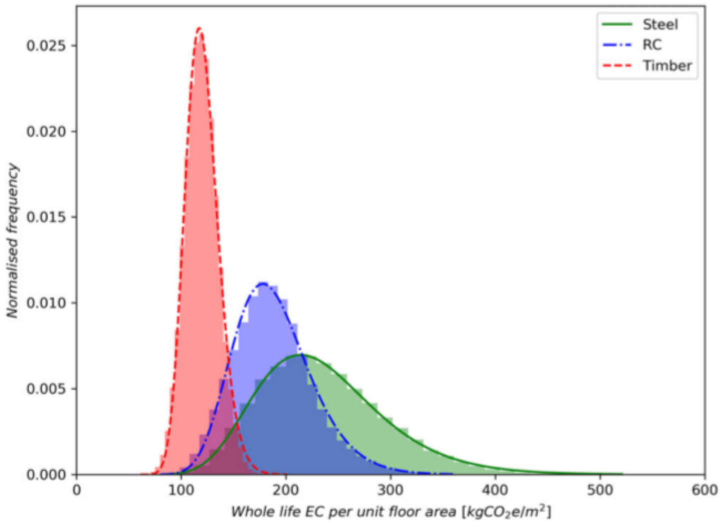
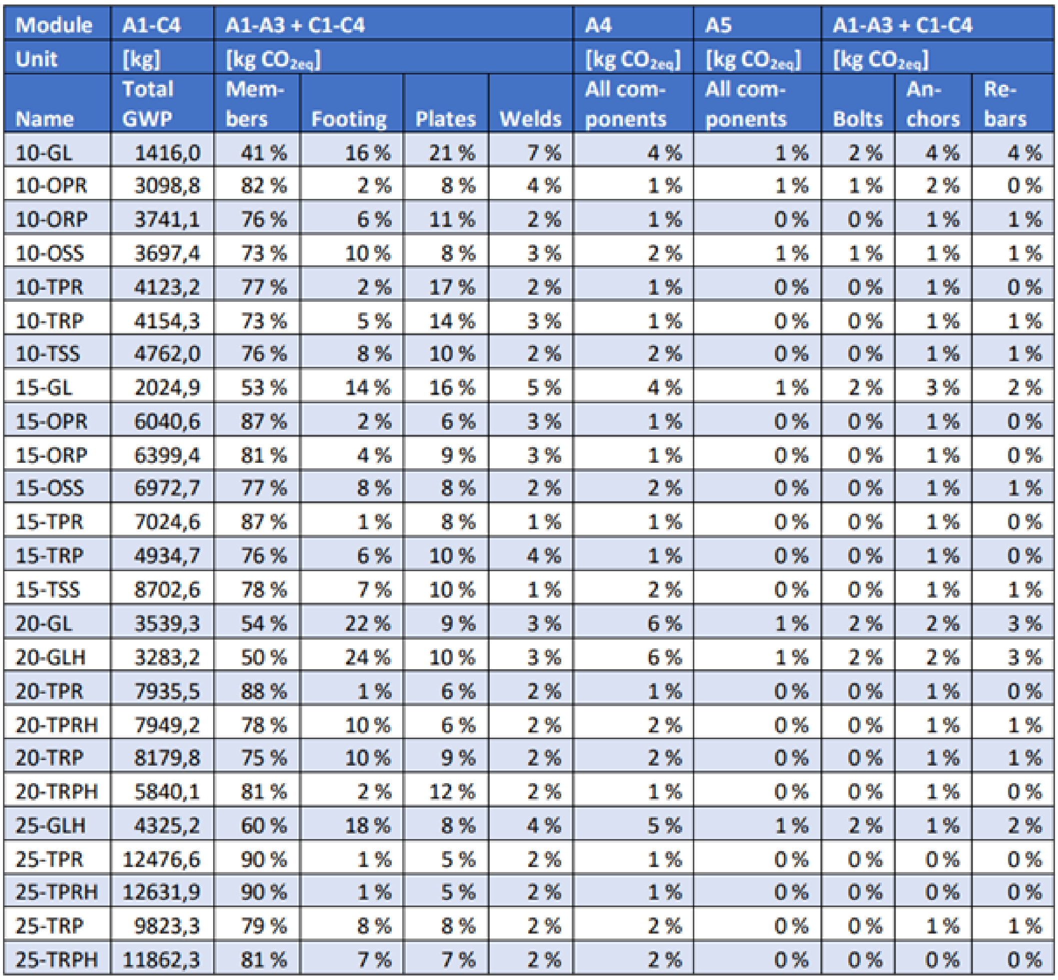


Figure 2.7: Distribution of WLEC for timber, steel and concrete structures based on 127 structural frames [44]



Module	A1-C4	A1-A3 + C1-C4				A4	A5	A1-A3 + C1-C4		
Unit	[kg]	[kg CO_{2eq}]				[kg CO_{2eq}]	[kg CO_{2eq}]	[kg CO_{2eq}]		
Name	Total GWP	Members	Footing	Plates	Welds	All components	All components	Bolts	Anchors	Rebars
10-GL	1416,0	41 %	16 %	21 %	7 %	4 %	1 %	2 %	4 %	4 %
10-OPR	3098,8	82 %	2 %	8 %	4 %	1 %	1 %	1 %	2 %	0 %
10-ORP	3741,1	76 %	6 %	11 %	2 %	1 %	0 %	0 %	1 %	1 %
10-OSS	3697,4	73 %	10 %	8 %	3 %	2 %	1 %	1 %	1 %	1 %
10-TPR	4123,2	77 %	2 %	17 %	2 %	1 %	0 %	0 %	1 %	0 %
10-TRP	4154,3	73 %	5 %	14 %	3 %	1 %	0 %	0 %	1 %	1 %
10-TSS	4762,0	76 %	8 %	10 %	2 %	2 %	0 %	0 %	1 %	1 %
15-GL	2024,9	53 %	14 %	16 %	5 %	4 %	1 %	2 %	3 %	2 %
15-OPR	6040,6	87 %	2 %	6 %	3 %	1 %	0 %	0 %	1 %	0 %
15-ORP	6399,4	81 %	4 %	9 %	3 %	1 %	0 %	0 %	1 %	0 %
15-OSS	6972,7	77 %	8 %	8 %	2 %	2 %	0 %	0 %	1 %	1 %
15-TPR	7024,6	87 %	1 %	8 %	1 %	1 %	0 %	0 %	1 %	0 %
15-TRP	4934,7	76 %	6 %	10 %	4 %	1 %	0 %	0 %	1 %	0 %
15-TSS	8702,6	78 %	7 %	10 %	1 %	2 %	0 %	0 %	1 %	1 %
20-GL	3539,3	54 %	22 %	9 %	3 %	6 %	1 %	2 %	2 %	3 %
20-GLH	3283,2	50 %	24 %	10 %	3 %	6 %	1 %	2 %	2 %	3 %
20-TPR	7935,5	88 %	1 %	6 %	2 %	1 %	0 %	0 %	1 %	0 %
20-TPRH	7949,2	78 %	10 %	6 %	2 %	2 %	0 %	0 %	1 %	1 %
20-TRP	8179,8	75 %	10 %	9 %	2 %	2 %	0 %	0 %	1 %	1 %
20-TRPH	5840,1	81 %	2 %	12 %	2 %	1 %	0 %	0 %	1 %	0 %
25-GLH	4325,2	60 %	18 %	8 %	4 %	5 %	1 %	2 %	1 %	2 %
25-TPR	12476,6	90 %	1 %	5 %	2 %	1 %	0 %	0 %	0 %	0 %
25-TPRH	12631,9	90 %	1 %	5 %	2 %	1 %	0 %	0 %	0 %	0 %
25-TRP	9823,3	79 %	8 %	8 %	2 %	2 %	0 %	0 %	1 %	1 %
25-TRPH	11862,3	81 %	7 %	7 %	2 %	2 %	0 %	0 %	0 %	0 %

Figure 2.8: Overview of total GWP [kg CO_2-equivalent] of the different frames and share of the components [21]

2.3.2.3 Conclusions of previous LCA studies

Hereunder the remaining conclusions drawn from the LCA studies in the literature matrix in Appendix A, concerning steel structures, are summarized.

System boundaries - For steel frames an adapted cradle-to-grave LCA is commonly used taking into account modules A1-A5, C1-C4 and D. The use stage is mostly not taken into account as this is less relevant for load-bearing structures, especially steel structures which have a long lifetime and mostly do not need any important maintenance operations during their lifetime.

Functional unit - In the choice of the functional unit it is important to opt for an entire structural frame consisting of columns beams, and connections because these connections can be responsible for more than 30 % of the total emissions according to [21]. For the frames investigated in the latter study, the connections were responsible for 13 up to 33 % of the GWP emissions. The main sources of these emissions are the steel consumption for bolts, connecting plates and reinforcements and the emissions related to welding such as welding fumes and wires. The relative share of the welds, bolts, anchors and rebars was calculated for all frame types and the results are shown in Figure 2.8. It could be decided that the bolts and welds have the largest impact on the glulam frame that served as a reference, being 7% and 2% respectively. Another finding was that the welds have a larger impact (1-7% and on average 2.72%) than the bolts (0-2% and on average 0.48%) for both steel and glulam frames.

Frame types - Besides showing the importance of taking into account connection components, Berki [21] investigated the influence of the frame type on the carbon footprint for load-bearing steel frames. For that purpose, a pinned, rigid and semi-rigid building frame, designed with steel members, were compared. In addition, a wooden frame was modelled as a point of reference for the total carbon footprint. This study showed that the frame type has a significant influence on the carbon emissions. In Figure 2.9, it is illustrated that a combination of mast columns with a rigid base connection and pinned beam connections led to the lowest emissions in this study.

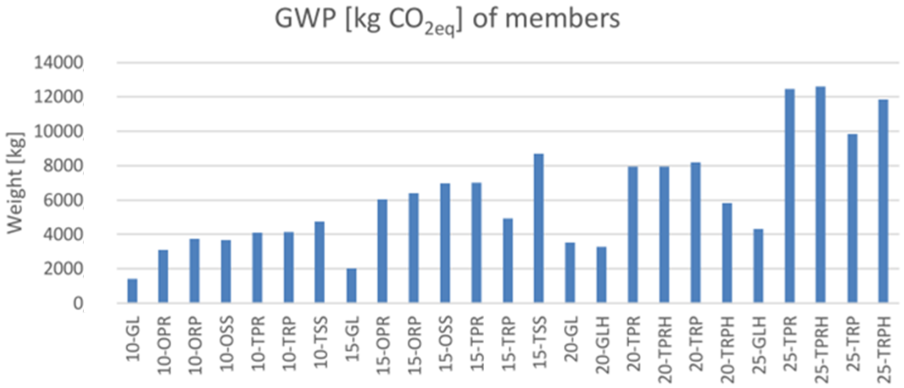


Figure 2.9: Carbon emissions of members with 10 m to 25 m span length including A1-A3 and C1-C4 in LCA - O = open, T = tube, GL = glulam, R = rigid, P = pinned, S = semi-rigid [21]

Profile types - It was also concluded that open profiles perform better than tube profiles with higher steel quality as mentioned above. This result is illustrated in Figure 2.8. However, as this study only examines frames, additional research must be conducted to determine the influence of frame type options on the total GWP of an entire building.

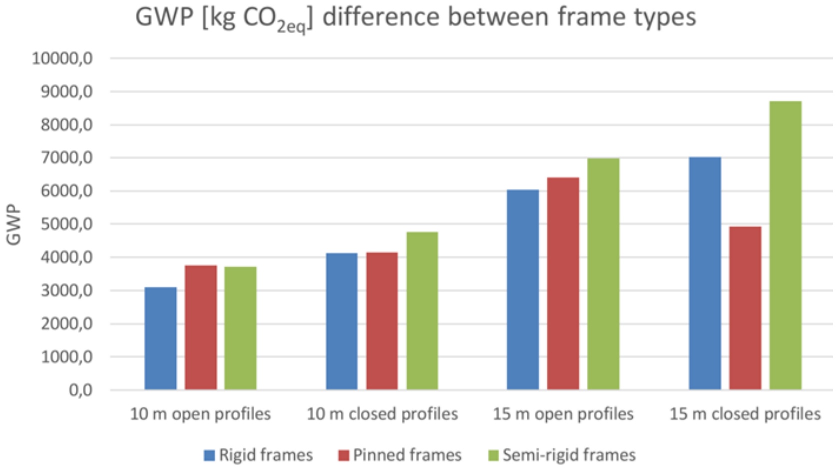


Figure 2.10: Comparison of GWP of rigid, pinned and semi-rigid steel frames for open and closed profiles of 10 m and 15 m length including A1-A3 and C1-C4 in LCA [21]

Environmental impact - Looking back at Figure 2.7 it can be seen that the structural solution using a steel deck floor has the largest embodied carbon on average according to [44]. The distributions confirm the widely spread assumption that timber structures are likely to have the lowest environmental impact. However, this figure also clearly indicates the uncertainties related to WLEC calculations due to the wide spread of the distributions.

Importance of module A - It has been stated in multiple studies that the pre-use and use phases represent the largest share of the environmental footprint of building structures [41]. According to [44] the greenhouse gas emissions for the steel and RC structures associated with module A represent at least 93% of the whole-life embodied carbon. This was also shown in [46] (LM) where the embodied carbon for single-family dwellings with a structural frame in reinforced concrete was compared to that of buildings with a structural steel frame. It was decided that RC frames approximately have a 5% less detrimental impact on the environment when focusing on embodied carbon. Nevertheless, this can differ regarding the type of structure and loading considered. According to [34], IPE beams have approximately twice the environmental impact of concrete beams for corresponding floor spans. This confirms once again the importance of an adequate choice of the functional unit and system boundaries when comparing LCAs.

Calculation methods - For the calculation of the steel frame connections the software Ideastatica can be used [21]. This software makes it possible to easily design and verify connections with different stiffnesses. The values for the stiffness can then be used in FEM software such as SCIA Engineer to calculate for example the buckling requirements which must be thoroughly examined for steel structures as these are possibly the critical requirements.

2.3.2.4 Conclusion - Steel

It can be concluded that, when trying to lower the environmental impact of steel structures, the main focus must be on the end-of-life stage. Due to the ability to be reused and recycled, steel structures can gain much in environmental impact through the inclusion of module D. When performing an LCA of a steel structure attention must be paid to the choice of the functional unit due to the influence of frame types and connections on the total environmental impact.

2.3.3 Timber

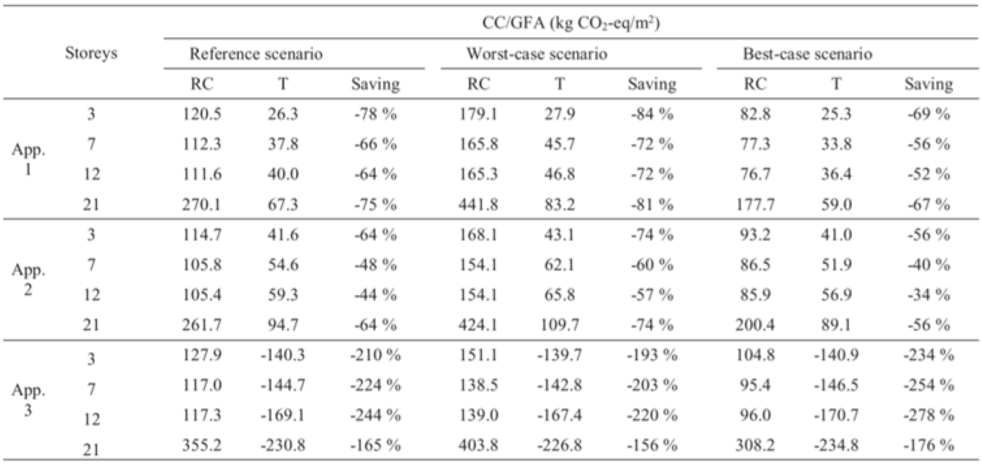
Hereunder some particularities about timber as a structural material will be discussed, as well as types of timber products and conclusions of previous LCA studies. First, some more information will be given about biogenic carbon emissions and their influence on the environmental impact of timber.

2.3.3.1 Biogenic carbon emissions

An important factor in the quantification of the environmental footprint of timber structures is the concept of biogenic carbon emissions. These are the carbon emissions which are released from biomass due to combustion or natural decay and which were initially captured out of the atmosphere in the material through photosynthesis during the growth of trees [14] (LM). To ensure climate-friendly timber production, it is important to maintain the biospheric carbon pool stable at the production site. As such, the biogenic carbon fluxes into and out of the atmosphere related to timber production are in balance. However, besides biogenic emissions, there are also emissions produced while felling trees and further manufacturing timber products.

An additional difficulty is the difference between carbon flux neutral and climate change neutral products. This difference must be made due to the time difference between sequestration and release of carbon which causes a net effect of the radiative forcing. This feature can be used as an additional advantage of timber structures. Because the sequestration during timber production precedes the release of carbon after the lifetime of the structure, there can be a temporary decrease in radiative forcing. This can be achieved in building structures which have a long lifetime if the life cycle of the trees used for the timber production is short compared to the building's lifetime.

However, in many LCA studies ([14,47]), this feature is neglected and it is assumed that biogenic emissions are climate change (CC) neutral when taking into account the entire life cycle of a product. This assumption of biogenic carbon neutrality is also provided by the standard EN 16485 [48] in case of sustainable forest management. Although the way in which biogenic carbon emissions are treated influences the environmental impact, irrespective of the assumptions made, timber structures can cause lower climate change impact than reinforced concrete structures according to [14] as shown in Figure 2.11.



		CC/GFA (kg CO_2-eq/m^2)								
	Storeys	Reference scenario			Worst-case scenario			Best-case scenario		
		RC	T	Saving	RC	T	Saving	RC	T	Saving
App. 1	3	120.5	26.3	-78 %	179.1	27.9	-84 %	82.8	25.3	-69 %
	7	112.3	37.8	-66 %	165.8	45.7	-72 %	77.3	33.8	-56 %
	12	111.6	40.0	-64 %	165.3	46.8	-72 %	76.7	36.4	-52 %
	21	270.1	67.3	-75 %	441.8	83.2	-81 %	177.7	59.0	-67 %
App. 2	3	114.7	41.6	-64 %	168.1	43.1	-74 %	93.2	41.0	-56 %
	7	105.8	54.6	-48 %	154.1	62.1	-60 %	86.5	51.9	-40 %
	12	105.4	59.3	-44 %	154.1	65.8	-57 %	85.9	56.9	-34 %
	21	261.7	94.7	-64 %	424.1	109.7	-74 %	200.4	89.1	-56 %
App. 3	3	127.9	-140.3	-210 %	151.1	-139.7	-193 %	104.8	-140.9	-234 %
	7	117.0	-144.7	-224 %	138.5	-142.8	-203 %	95.4	-146.5	-254 %
	12	117.3	-169.1	-244 %	139.0	-167.4	-220 %	96.0	-170.7	-278 %
	21	355.2	-230.8	-165 %	403.8	-226.8	-156 %	308.2	-234.8	-176 %

Figure 2.11: CC impact per m² for structures in reinforced concrete (RC) and timber (T) with 3 to 21 storeys for different scenarios related to biogenic carbon [14]

2.3.3.2 Types of timber components

Mostly, high-rise timber structures consist of a beam and column frame composed of glued laminated or shortly glulam timber elements, filled in with cross-laminated timber (CLT) slabs [14,15,49,50] (LM). However, some other structural solutions making use of timber components are also possible.

CLT - Due to the multiple layers of manufactured wood panels that are assembled in alternating right angles and glued together with a structural adhesive, solid CLT plates have more isotropic characteristics compared to other wood products. Moreover, these slabs have a large load-bearing capacity, high in-plane stiffness and outstanding dimensional stability. By adding some additional layers to the panel, also excellent fire protection can be obtained [51]. These CLT slabs can then also be used as shear walls around stairs and elevator shafts [52].

Glulam - Glulam components are manufactured by placing finger-jointing board lamellas in the longitudinal direction and subsequently glueing them together with parallel fibres. As such, elongated beams are created comparable to solid wood beams but with the same advantages as mentioned for CLT slabs and larger possible dimensions. Compared to steel, glulam even has a better strength/weight ratio [53]. This makes it possible to use lighter foundations, necessitates less energy for transport and is advantageous for earthquake resistance. According to [34] glulam structures lead to the lowest carbon equivalent for light-duty columns and long, light-duty beams.

For higher buildings additionally, glulam trusses can be used in the facade structure. Laminated veneer lumber (LVL) is another engineered wood product that can be used. It is comparable to glulam but with a higher allowable stress and can be combined with glulam to give the glulam beams a higher strength [15]. It is also possible to use hardwood beam sections [54] (LM), although these are less strong for the same dimensions due to possible weaknesses in the beams.

Besides the many advantages, these manufactured wood products also have a few disadvantages. The first disadvantages are that they consume much more wood than light wood framing, need additional processing and use adhesives to create a solid panel which increases their environmental impact compared to natural timber [15]. However, overall the production of engineered wood components is not a highly energy-consuming process. The production costs associated with glulam also make it more expensive than other timber products. Moreover, the lower moisture resistance compared to steel and concrete can necessitate larger dimensions to reduce the moisture impact, which again adds to the costs and material use, and thus also to the environmental impact [55]. Another downside of glulam beams is the important impact on agricultural land occupation followed by a large impact on ecosystems [34]. This also stresses the importance of taking into account all the relevant impact categories to determine the environmental impact of a material, because, for all other categories, glulam beams have the lowest impact.

Figure 2.12: Example of a composite concrete-timber floor system [56]

Composite timber-concrete system - Another possibility is the use of hybrid timber-concrete floor systems to combine the compressive concrete strength with the tensile strength and light weight of timber [56]. An example of a timber-concrete composite system is shown in Figure 2.12 which exists of a CLT slab with a concrete layer on top. The shear connection at the interface guarantees the combined action of both materials and is realised by notches in the timber and screws which are anchored in the concrete and CLT. The main advantage of this system compared to CLT-only floors is the increased stiffness which helps to fulfil the deflection and vibration considerations. Additionally, better basic sound insulation is achieved and better fire resistance [57]. A similar slab was investigated in [50] (LM) and showed an average reduction of 26.5% in GWP compared to a reinforced concrete structure when assuming carbon neutrality for the timber.

2.3.3.3 Conclusions of previous LCA studies

System boundaries - Mostly the use phase is not taken into account in LCA's for timber structural systems. However, in [22] it is stated that glulam structures need additional maintenance and this can negatively influence the environmental impact. As these needs depend on the characteristics of the glulam, the used timber species and treatment, the design details and the exposure of the beams it is difficult to quantify this and to determine a generic maintenance regime. That is why, mostly, impacts due to maintenance are left out of scope [34].

Environmental impact of timber - Multiple studies for different types of buildings and functional units agree on the savings in environmental impact by replacing steel and concrete structures with timber structures [14, 21, 44, 58]. However, the amount in which timber structures perform better than their concrete or steel counterparts varies widely over different studies and different building configurations. According to [44], for example, the advantage of timber structures is much smaller than stated in [14], among other reasons because the end-of-life treatment is taken into account. The savings in environmental impact are mainly attributed to the production process which is much less polluting than is the case for concrete and steel [15]. The drying process represents the largest share of emissions in the construction of engineered wood products, followed by the type of pressing used to combine the layers [59].

Timber versus steel and concrete - When comparing CLT flooring systems to concrete slab flooring, the latter shows significantly higher emissions according to [12]. Moreover, studies indicated that CLT slabs can compete with concrete slabs for spans up to 7m while fulfilling the structural requirements. For increasing spans the vibration requirements and resonance frequency become governing for the CLT slabs due to their lighter weight which can lead to a large required thickness of the slabs. At shorter spans, on the contrary, the necessary thickness of the CLT slabs is mostly determined by the deformation [12].

In [60] a comparison was made between load-bearing columns made of glulam and made of reinforced concrete. This showed that for small axial loads, the necessary cross-section is smaller for the glulam columns than for the concrete columns, while for larger loads the contrary holds.

In [15] a state-of-the-art review was made, based on 36 comparative LCA's, in which the GWP of wooden multi-storey structures was compared to that of steel and concrete structures. A trend that was noticed is that the reductions in GWP are bigger when replacing concrete with timber than when replacing steel with timber as shown in Figure 2.13. This boils down to the fact that steel structures have a lower GWP than concrete structures according to this research and contrasts the conclusions of many other studies ([34,46]). In [49] (LM) it is even stated literally that steel substitution by timber is more advantageous than concrete substitution. This, once more, emphasises the importance of taking into account the assumptions in every LCA.

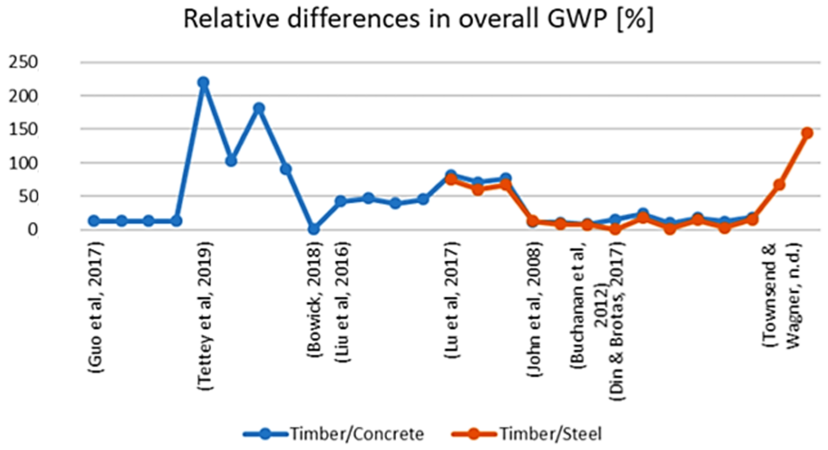


Figure 2.13: Relative difference in total GWP between timber multi-storey buildings and its steel or reinforced concrete equivalent according to different studies [15]

Influence of building height - Another conclusion drawn from previous research is that the savings in environmental impact per m² floor area by using a timber structure slightly decrease with building heights up to 12 storeys, while it increases for buildings with 12 up to 21 storeys [14] as illustrated in Figure 2.11. This confirms that timber structures are also interesting for high-rise buildings up to at least 21 storeys. For these high-rise buildings, it is very important to take into account the resistance against wind forces because it is more difficult for lighter timber structures to resist these compared to concrete structures [14]. In that case, it can be recommended to supplement the timber structure with a reinforced concrete basement and foundation to be able to resist wind loading. Due to the lower Young's modulus of glulam (3 to 15 times smaller), it can also be necessary to add a concrete level from a certain building height [15]. Therefore, when comparing multiple structural systems it is a common choice for the functional unit to consist of the entire building structure and foundation with a predefined load-bearing capacity, number of storeys and lifetime to include all impacts [14].

Influence of connections - The study of Berki [21] mentioned above concluded that including connection components is important, especially in wooden frames. This importance is mainly a consequence of the large difference in environmental impact between glulam components and steel components. Therefore these connections must be included in the definition of the functional unit when comparing different structural solutions.

End-of-life treatment - When looking at the end-of-life there are different options to cope with timber structures. The most advantageous one, taking into account the carbon footprint, is to use wood as an energy source. In that case, the carbon that was sequestered in the production phase is emitted back into the atmosphere. However, there is also a gain due to the exported energy which can be taken into account in module D [15].

Timber structural components can also be recycled into less high-quality products, also called down-cycling, such as non-structural materials (flooring or moulding) or particle boards [53], but these products again require a production process which has a certain environmental impact. However, an important advantage is the reduced need to dry these products. A study has been done to see the effect on GWP when the wood is first recycled to particleboard and subsequently used for incineration in a power plant. This can lead to a reduction in GWP up to 10% compared to the use of primary wood [15].

Reuse without loss of quality as possible for steel structures is rarely feasible for timber structures. This is among other things a consequence of their shorter lifespan. Moreover, in case a shorter life span is taken into account for timber structures, their relative benefits compared to steel structures for example become smaller because the embodied carbon needs to be divided over fewer operational years or a replacement needs to be considered.

2.3.3.4 Conclusion - Timber

It can be concluded that most studies depict timber as the structural material with the lowest environmental impact. However, there is a large spread in the relative difference between the impact of steel, concrete and timber structures. This was illustrated in Figure 2.7. One of the factors causing this spread is the way in which biogenic carbon emissions are treated. In many LCA studies, this issue is simplified by assuming that timber is a carbon-neutral building material if carbon is again released into the atmosphere by incineration at the end-of-life stage. For multi-storey buildings, CLT and glulam are widely used manufactured wood products. It has been proven that a 10% gain in environmental impact can be achieved when recycling these products after their first life cycle and subsequently burning them to produce energy [15].

2.3.4 Masonry walls

As the initial structural design of the case study building consists of concrete wide slabs supported by sand-lime masonry walls, this last material is also added to the scope of the study. This makes it possible to use the initial design as a reference point for the alternative structural solutions to be compared to. Some other commonly used masonry blocks will be discussed too. The main advantages of sand-lime walls were already mentioned in the introductory section. Hereunder, the environmental impact and the production process of this material will be further elaborated on.

2.3.4.1 Production process

Sand-lime brick - During the production process of sand-lime bricks, the green units composed of lime, sand and water, are subjected to steam under high pressure in an autoclave to initiate a reaction between silica and lime to create calcium silicate hydrates. This reaction is comparable to the one between water and Portland cement in concrete production [16]. This process needs a lot of energy which represents an important share of the environmental impact of bricks. Moreover, the production of lime goes along with some atmospheric emissions due to the generation of lime fines [61].

Aerated autoclaved concrete - A comparable reaction between silica and lime occurs in the production process of AAC. During the production process, a mixture of sand, water, cement and lime is put to rest in a mould. This triggers a reaction which leads to the hardening of the mixture. The addition of a small amount of aluminium powder starts the formation of hydrogen bubbles which make the mixture rise and finally result in a material with many air cells at the end of the hardening process. To finish the process the blocks are subjected to high pressure in an autoclave. [62]

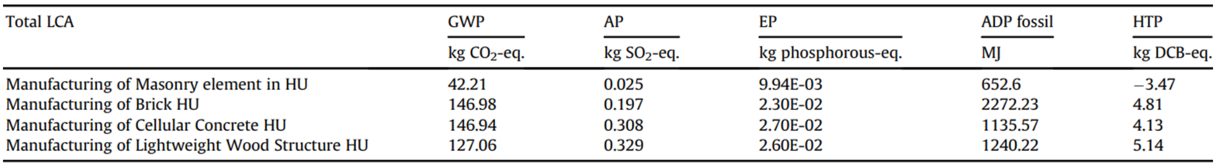
2.3.4.2 Possible methods to reduce environmental impact

Recycling construction waste - Recycling construction waste is an important method to reduce the need for raw materials and thus the environmental impact. The main manufacturer of AAC in Belgium, according to OVAM [63], is Xella. This company has an agreement with OVAM to retake the AAC waste material collected at the recycle parks in Flanders. Subsequently, approximately 25% of the necessary sand during production can be replaced by recycled AAC [17]. The remaining waste is landfilled at the foreseen locations. A possible problem with this waste treatment is the potential sulfate leaching [63], although When using the AAC sand in screed or stabilized sand this problem is limited.

Cutting waste - During the production process itself, the cutting waste of AAC can immediately be returned to the production process. The recycled AAC granulates then become a substitute for the raw materials. The materials that cannot be returned to the production process can be used for other construction materials. An example is the use of AAC powder for cement [17]. Similarly, the lime fines generated during the production of lime, as mentioned above, can be reused in the paper industry as well as in the chemical and mining industry.

Fly-ash - Another method to reduce the environmental impact of AAC is by replacing 5 to 10% of the cement with fly-ash, a by-product of the steel industry. As such, not only the amount of cement is reduced, but a waste product is reused as well.

Alternative masonry element - In [64] (LM), it was shown that the use of an alternative masonry element can reduce the environmental impact of masonry walls. This alternative masonry element is composed of natural cellulose and glue and was compared to conventional bricks, and porous concrete bricks (Ytong). The impact during the production stage could be lowered due to the new material composition, while the structural and thermal capacities remained constant. This led to a GWP which is about one-third of clay bricks and concrete bricks. Also, other impact indicators such as acid potential and eutrophication potential could be lowered a lot as shown in Figure 2.14. This figure also shows that the GWP impact of traditional bricks and cellular concrete bricks is approximately the same. This study thus concludes that the use of new combinations of raw materials can improve the environmental performance of masonry walls. However, this study also emphasizes the influence of the location of production on the environmental impact due to, for example, the difference in transport and energy mix.



Total LCA	GWP	AP	EP	ADP fossil	HTP
	kg CO_2-eq.	kg SO_2-eq.	kg phosphorous-eq.	MJ	kg DCB-eq.
Manufacturing of Masonry element in HU	42.21	0.025	9.94E-03	652.6	−3.47
Manufacturing of Brick HU	146.98	0.197	2.30E-02	2272.23	4.81
Manufacturing of Cellular Concrete HU	146.94	0.308	2.70E-02	1135.57	4.13
Manufacturing of Lightweight Wood Structure HU	127.06	0.329	2.60E-02	1240.22	5.14

Figure 2.14: Comparison of the emissions of different masonry elements over their entire life cycle [64]

2.3.4.3 Types of masonry components

Blocks - For mid-rise residential buildings, the most used types of masonry are autoclaved aerated concrete (AAC) blocks and sand-lime blocks. Both types of blocks are made of sand, lime and water, but for AAC blocks additionally, cement and aluminium powder is added. Although both types of blocks almost have the same composition, they have some different characteristics as listed in Table 2.2.

These elements are available in standard sizes of which the thickness varies according to the necessary structural wall thickness. Besides the standard brick formats, also larger prefabricated wall elements are available. The advantage of these larger elements is the fast construction on site and the reduction of construction waste if all elements are tailored in the factory. This of course lowers the environmental impact. According to [17] only 1.4% of the used materials end up as waste discarded from the sites due to this efficient material use. This is lower than the standard 5% adopted by OVAM.

Table 2.2: Comparison between aerated concrete and sand-lime brick [65]

Aerated concrete	**Sand-lime brick**
Good thermal insulation	Lower thermal insulation
Blocks are glued together	Blocks connected with glue or mortar
Light weight	Heavy weight
Easy processable	Difficult to process
Frost resistant	Not frost resistant
Application inside and outside	Application inside and foundations
More expensive	Less expensive

2.3.4.4 Conclusions of previous LCA studies

Environmental impact - The environmental profile of calcium silicate or sand-lime brick [66] clearly shows that the production process represents the largest share of the GWP. This is mainly due to the need for lime which requires an energy-consuming production process. When looking at an EPD of aerated autoclaved concrete [67] it can also be decided that the largest share of the environmental impact can be attributed to the raw material supply and the energy necessary for the production of cement and lime (A1). This is also indicated in Figure 2.15 which shows the relative share of the GWP of the modules A1 to A5 in the production process. Due to the use of energy-efficient autoclaves, the impact related to the hardening process can be limited.

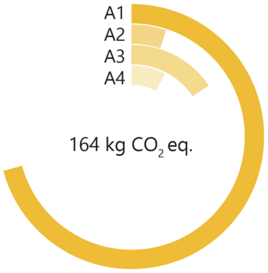
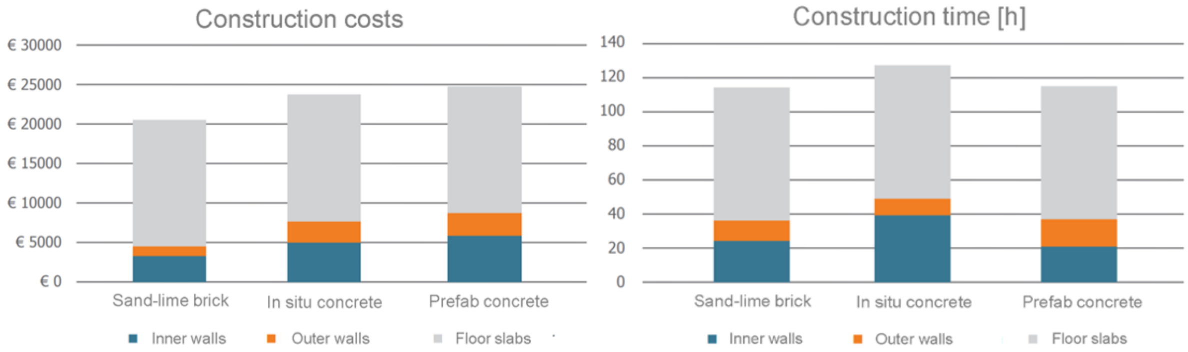


Figure 2.15: Relative share of modules A1 to A5 in GWP of AAC [67]

Comparison of bricks - A comparative analysis between AAC blocks and burnt bricks [68] decided that AAC blocks have a lower environmental impact due to their large recyclability. On the other hand, according to a report from the Dutch Institute for Building Biology and Ecology [69], sand-lime brick is the building material with the lowest environmental impact for residential buildings. In the respective study, sand-lime brick was used for separating walls between houses and the load-bearing outer walls. The MPG method, mentioned in the introduction, was used to determine the environmental impact and compare it to that of (prefab) concrete, timber frame construction and clay bricks. The results, given in Table 2.3, show that sand-lime bricks have the lowest environmental impact for every type of residential building. Moreover, in this research report, it is also decided that sand-lime bricks are the most economical choice for all three mentioned types of residential buildings and have the shortest construction time. Compared to a prefab concrete structure, the sand-lime solution is more than € 4000 cheaper for a single-storey apartment of 80 m² as illustrated in Figure 2.16.

Table 2.3: Comparison of MPG-score for different building materials and types of residential buildings according to [69]

Type of residential building	Material	MPG-score [€]
Single-family house	Wood frame	0.018
	Sand-lime brick	0.018
	Clay brick	0.035
	Prefab concrete	0.036
Terraced house	Sand-lime brick	0.036
	In situ concrete and wood frame	0.054
	Prefab concrete	0.082
Apartment	Sand-lime brick	0.04
	In situ concrete and wood frame	0.047
	Prefab concrete	0.085



(a) Construction cost

(b) Construction time

Figure 2.16: Comparison between sand-lime brick, in situ concrete and prefab concrete, based on [69]

2.3.4.5 Conclusion - Masonry

For mid-rise residential buildings AAC and sand-lime blocks are a common choice of masonry elements. It can be concluded that an important share of the environmental impact is caused by the energy consumed during production. To reduce the environmental impact construction waste can be recycled or alternative masonry elements composed of natural cellulose can be used. Previous research showed that AAC blocks have a lower environmental impact than burnt bricks due to their recyclability. Another research stated that sand-lime brick is the material with the lowest environmental impact for residential buildings.

2.3.5 General remarks

An important side note to keep in mind is that the geographical location of a structure also influences the environmental impact due to the difference in loading, geotechnical characteristics, production, availability of materials and transport distances [14,41]. Finally, it must be mentioned that hybrid structures, being a combination of some of the above-mentioned slab types and supporting structures are also commonly used in building practice [35]. An example can be a timber floor system supported by a concrete frame or hollow core slabs supported by a steel frame. Table 2.4 gives an overview of the slab types and supporting structures that were used in the papers summarized in Appendix A. In this study, first, a selection of slab types and supporting structures will be investigated separately, and subsequently, based on those intermediate results, some specific combinations of slab types and supporting systems will be investigated as elaborated in Chapter 3.

Table 2.4: Overview of slab types and supporting structures discussed in research papers used in the literature study

Slab types	**Supporting structure**
Concrete	
Hollow core slab	Prefabricated concrete frame
Wide slabs	In situ concrete frame
In situ concrete slab	Prefabricated concrete walls
Beam and block floor system	In situ concrete walls
Steel	
Composite concrete - steel slab	Cold-formed steel frame
Light steel floor joist + dovetailed sheet	Hot rolled steel frame
Timber	
CLT slab	Glulam frame
Composite CLT-concrete slab	Light wood frame
I-joist beams with OSB slab	CLT walls
Light steel floor joist + OSB	
Ceramics	
Aerated autoclaved concrete slab	Sand lime brick
Pots and beams floor	Aerated autoclaved concrete blocks

2.3.6 Conclusion

The discussion above related to the different materials confirmed the statement made at the beginning of Section 2.3, namely that a lot of parameters influence the LCA studies and that as a consequence the different conclusions are not always compatible. Hereunder, the conclusions that are most generally agreed upon and some general insights in LCA studies for building structures that could be derived from the literature matrix are summarized.

The first conclusion can be drawn concerning the choice of functional unit which has a large influence on the environmental impact. In most studies, the functional unit is defined on the building level. As such, the entire load-bearing structure can be taken into account consisting of beams and columns or walls, slabs and the connections between these elements. Regarding the structural lifetime of the functional unit, the results are more spread. Taking the weighted average of the common lifetimes and the number of studies found that implemented these lifetimes gives approximately 60 years, which is a commonly used value for residential buildings [19]. However, when only structural components are taken into account sometimes this value can be increased up to 100 years. In [21] for example, the structural lifetime of the wood frames, as well as the steel frames, is set to 100 years taking into account the promises of the wood industry for a 100-year life-expectancy of their products.

When looking at the system boundaries applied in the different LCAs, the use stage B is rarely taken into account for the investigation of building structures. Mostly a cradle-to-grave LCA is applied, omitting the use phase, but taking into account production and construction (module A), end-of-life (module C) and the additional benefits and loads from recycling, reusing and energy recovery (module D). This is a logical decision because the operational energy use is hard to link to the building's structure and is more related to the facades for example which are not part of the functional unit in most studies. Moreover, when taking into account a lifetime of 60 years, maintenance and repair of the load-carrying system will not yet be necessary. In [15] it was also found that only small differences occur in operational energy consumption for different structural materials, which justifies this choice. Another common choice is a cradle-to-gate LCA when focussing on the embodied carbon emissions of construction materials.

Concerning the LCA software, it is clear that SimaPro is the most widely-used software package and it is mainly used in combination with the Ecoinvent database. GaBi is another LCA software package that is used in many studies. For the impact assessment of the LCA's on the one hand, many studies only focus on GWP as environmental impact indicator, sometimes supplemented with a few other indicators. On the other hand, the ReCiPe method is widely used to translate the use of resources and emissions in a score for several environmental impact indicators and additionally in a single score.

The majority of the studies either focus on one structural material or the comparison between two structural designs with different materials. However, there is a lack of studies that take into account more different materials and not only look at global warming potential as an environmental impact indicator in the comparison of the environmental impact of building structures. This is also illustrated in Figure 2.17. The most extensive research paper that was discussed is [44], in which a comparison of identical building frames in concrete, steel and engineered timber is performed regarding their mass and whole-life embodied carbon. This study involves 127 frame configurations ranging from 2 to 19 stories. However, again only WLEC is discussed as an environmental impact indicator, disregarding for example the impact of land use for timber.

Finally, related to the environmental impact the following conclusions could be drawn: off-site constructed concrete members have lower environmental impacts than in situ concrete, design-optimization can reduce the environmental impact up to 17%, for steel and timber structures the connection components have an important influence and in the majority of the examined cases, timber seems to be the most environmentally friendly building material.

To summarize this literature study, Figure 2.17 on the next page shows an overview of the different studies from the literature matrix that were discussed and the links between them. Only slabs and frame structures were considered for this figure. Each paper is represented by the number it has in the literature matrix in Appendix A. As such, an image is created of where these studies are situated in the research field and where there are still gaps in the field. It can be decided that concrete is the most widely studied material, according to this set of research papers. The central circle depicts the research papers comparing all three materials and indicates the need for additional research in this area as only a handful of studies focusing on all three materials have been conducted.

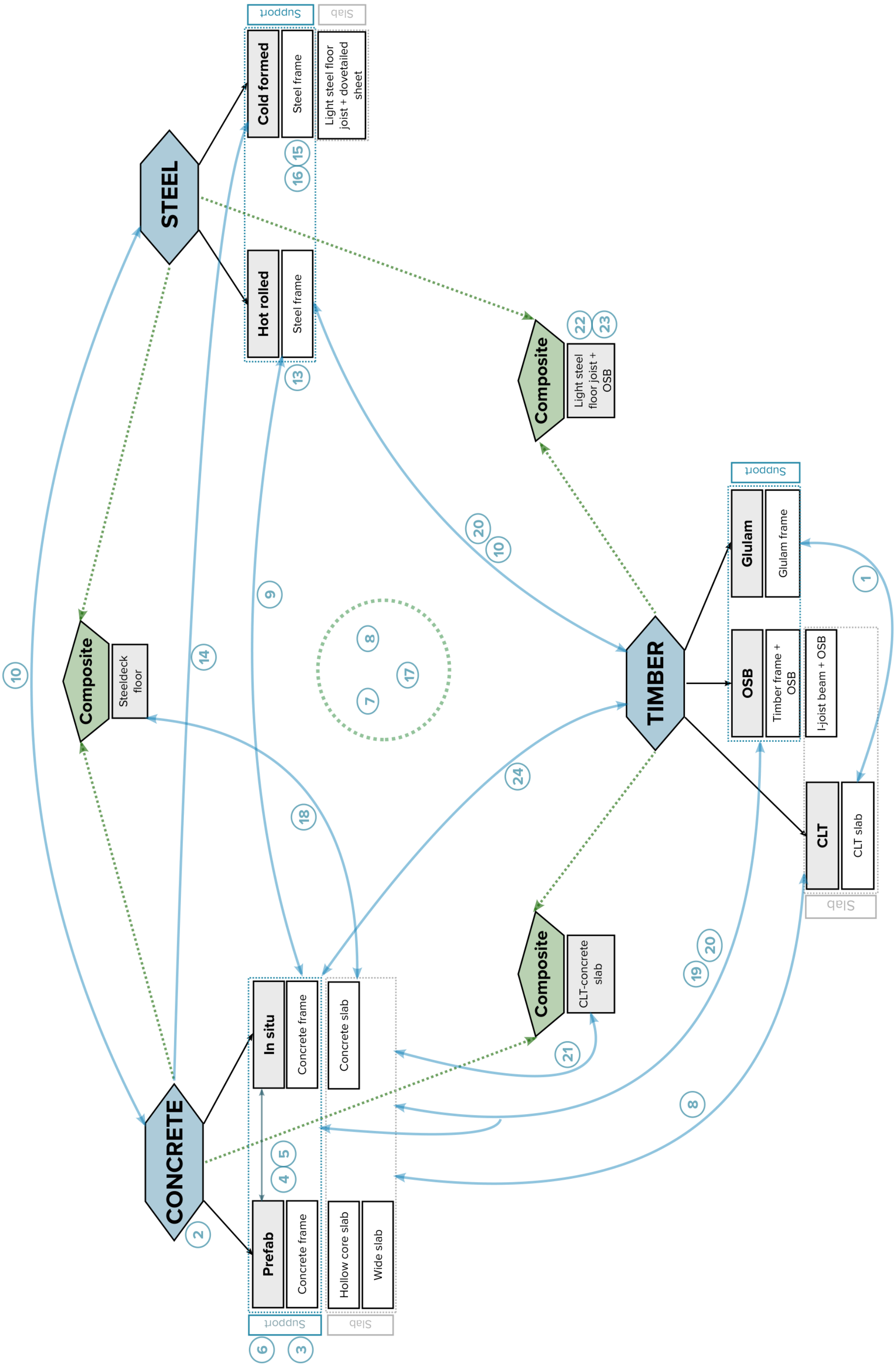


Figure 2.17: Summarizing figure of literature study showing the position of the used resources concerning concrete, steel and timber structural components (numbers as in Appendix A)

3

Methodology

3.1 Research questions

3.1.1 What is the structural solution with the lowest environmental impact, for a multi-storey building based on a cradle-to-grave LCA for the different components and materials?

Throughout the literature study in Chapter 2, it became clear that the type of material that is used, the type of structural components and their different combinations, have an important influence on the environmental impact of a building structure. The objective of this research is to quantify the difference in environmental impact between different structural solutions for a given case study building, and as such, to target the structural design and material with the lowest environmental impact for the given building typology. The respective case study building is described in the next section. Additionally, some sub-questions will be examined to provide a more detailed answer to the main research question.

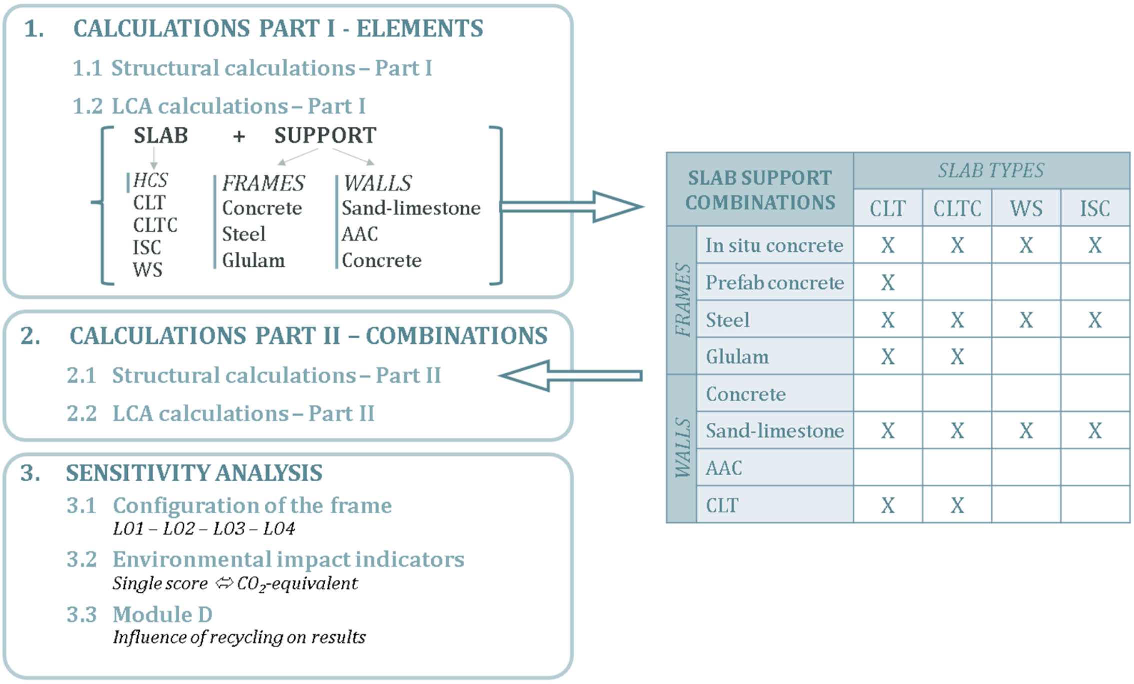
- **Which components of the load-bearing structure represent the largest share in the total environmental impact and how much does this share differ between different slab-support combinations?** It is interesting to know which of the structural components (beams, walls, floors ...) contributes the most to the environmental impact.

- **Which are the most determining life cycle stages for the different structural materials?** Similarly, the governing life cycle stage can be determined. This gives an idea of where one should interact in the life cycle to lower the environmental impact.

- **How determining are the benefits and loads beyond the system boundary (Module D) for the total environmental impact of the building structure?** The influence of including module D in the LCA calculations will be investigated to quantify the importance of the end-of-life treatment for different materials.

3.1.2 Research steps

The different research steps that will be executed to answer the research questions were discussed in Chapter 1 and are repeated here in a schematic overview in Figure 3.1. Part I of the calculations focuses on the slab and support elements separately. Based on the intermediate results of this part, slab-support combinations will be put together, which will be further investigated in part II. Finally, the sensitivity analysis will examine the sensitivity of the results to changes in the frame configuration, environmental impact indicators and the inclusion of module D. The further structure of this study follows this scheme of which the different steps will be further clarified in the corresponding sections.



SLAB SUPPORT COMBINATIONS		SLAB TYPES			
		CLT	CLTC	WS	ISC
FRAMES	In situ concrete	X	X	X	X
	Prefab concrete	X			
	Steel	X	X	X	X
	Glulam	X	X		
WALLS	Concrete				
	Sand-limestone	X	X	X	X
	AAC				
	CLT	X	X		

Figure 3.1: Schematic overview of research steps

3.2 Case study building

To be able to compare the environmental impact of different structural designs, a case study building will be used. The case study building that will be examined is part of the Tondelier project which is a new-build residential site on an old factory terrain in the city of Ghent which combines contemporary apartments, city houses and commercial space around an enclosed park area.

Figure 3.2: Aerial view of Tondelier project

The structural design and the techniques of the building were executed by VK Architects + Engineers while Blaf and Bureau Bouwtechniek are responsible for the architectural design and execution. An overview of the entire project located between the Gasmeterlaan and the Tondelierlaan is shown in Figure 3.2.

The focus on sustainability in this new-build project makes it the ideal case study to examine the environmental impact of building materials. The entire project is composed of different buildings ranging from mid-rise apartment buildings to single-family houses. For this study, more specifically a generic part of the mid-rise apartment building indicated in Figure 3.3b will be examined. This concerns building block 2 of the project, lot 2 up to 6.

The considered building combines different functions over the levels. It has a classical structural scheme with moderate spans which is typically used for structures of buildings with offices or a residential function. The building exists of two basement levels, a ground floor with an open layout realised with a frame structure for a commercial function, four upper levels with a residential function expressed by a wall structure and a receding top level. This can also be seen in the sectional views in Appendix B. The locations of these sections are indicated in figure 3.4.

(a) Location on the site

(b) Close up

Figure 3.3: Building block 2 - Lot 2 to 6

For this study, the scope will be limited to the load-bearing structure of a generic level. As the plan of the four generic levels is symmetric, only the part indicated in green at the bottom of the plan in Figure 3.4 will be investigated which is representative for the entire structure. The load-bearing structure of one of these levels, namely the second floor, consisting of a floor slab and the necessary supporting structure to transfer the loads, will serve as the functional unit for the LCA. This is further elaborated in Section 3.3 and shown in Figure 3.5.

In the initial structural design, the floor slabs, consisting of wide slabs, are supported by walls of sand-lime brick and the central cores are composed of concrete walls. However, for the sake of this study, this structural scheme will be adapted for different construction materials. Some cases that keep the wall structure will be worked out, while other designs will make use of a frame structure. To clarify each structural design, a conceptual plan will be included in the respective sections.

Figure 3.4: Plan of floor 1 to 4 of the case study building with indication of the functional unit (green) and sections (blue)

3.3 LCA calculations

To determine the environmental impact of the different materials and processes corresponding to each structural design, an LCA will be performed as described in the literature study. The mentioned stages in the LCA are elaborated hereunder for the chosen case study building. The choice of the functional unit and system boundaries is important to enable appropriate comparison between the different design alternatives. First, the impact of the different slab types will be calculated separately. Then the supporting structures will be calculated and finally, the most relevant combinations of both will be further investigated as was shown in Figure 3.1.

3.3.1 LCA software

To perform the LCA the life cycle software SimaPro will be used in combination with the Ecoinvent database, included in the software. As mentioned in the introduction, the Belgian government promotes the use of the software tool TOTEM. However, for this study, the more widespread software SimaPro will be used, which was also used in many other comparable studies as illustrated in Section 2.3. This software can determine the environmental impact of products across every life cycle stage and makes it possible to adapt the selected processes to the Belgian context where necessary. Hereunder, the different steps as described in Section 2.2 are elaborated for the LCA study performed in this master's dissertation.

3.3.2 Goal and scope definition

For this study, a comparative LCA will be performed. The goal of this LCA is to compare the environmental impact of the building structure of a case study apartment building executed with different materials for the load-bearing structure and thus accompanying different structural designs. This makes it possible to determine the structural design with the lowest environmental impact and make a reasonable material choice for a specific building. Additionally, the most impacting life cycle stages and the most crucial structural elements will be determined.

Because this study focuses on the structural system of a building, the functional unit is defined on the building level. The functional unit will be the building structural system, consisting of a slab and walls or beams and columns, for one typical floor with the necessary load-bearing capacity to resist all permanent and variable loads over a lifetime of 60 years. To simplify matters the impact will be calculated only for one floor level, namely the second floor as illustrated in Figure 3.6, which represents an acceptable average of all floors. This result can, later on, be multiplied by the number of floors to quantify the environmental impact of all floors which is representative for the entire building. In plan view, the functional unit exists of three spans of 5.20 m over a width of 16 m for the original structural design, as shown in Figure 3.5. The foundations will not be taken into account because these are highly dependent on the local soil characteristics of the project under consideration. The reference study period and service life are both taken equal to 60 years for all materials.

Regarding the system boundaries, for each structural design, a cradle-to-grave LCA will be performed including stages A, C (and D) and leaving out the use stage B because this stage is less relevant regarding the choice of the functional unit. However, first, the calculations will be done only including modules A and C. Later on, in the sensitivity analysis, module D will be included in the LCA calculations to verify the effect of reuse and recycling on the initial results. Figure 3.7 shows the system boundaries that will be considered in the different steps of the LCA calculations.

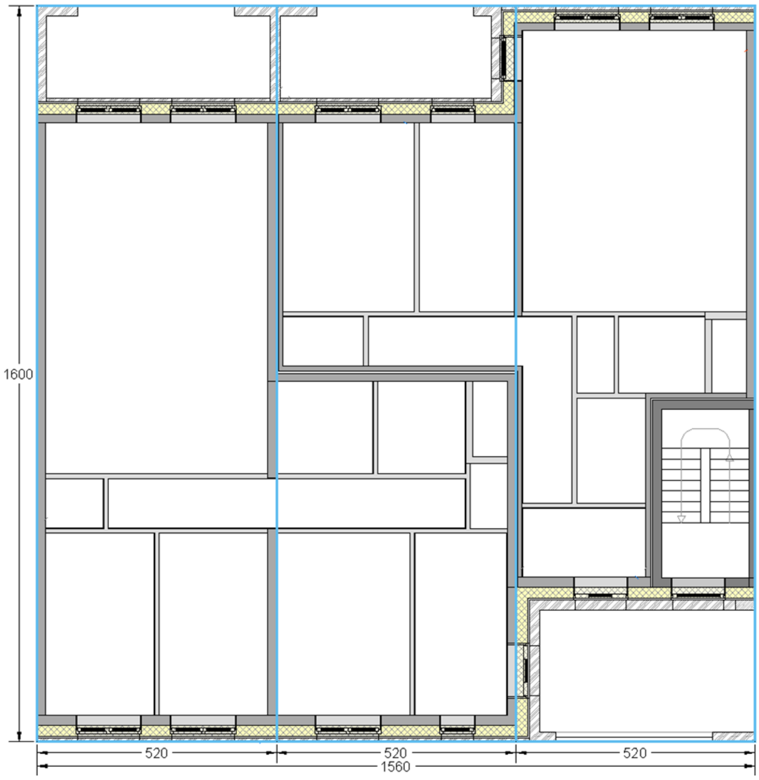


Figure 3.5: Plan view of the functional unit - Original structural design

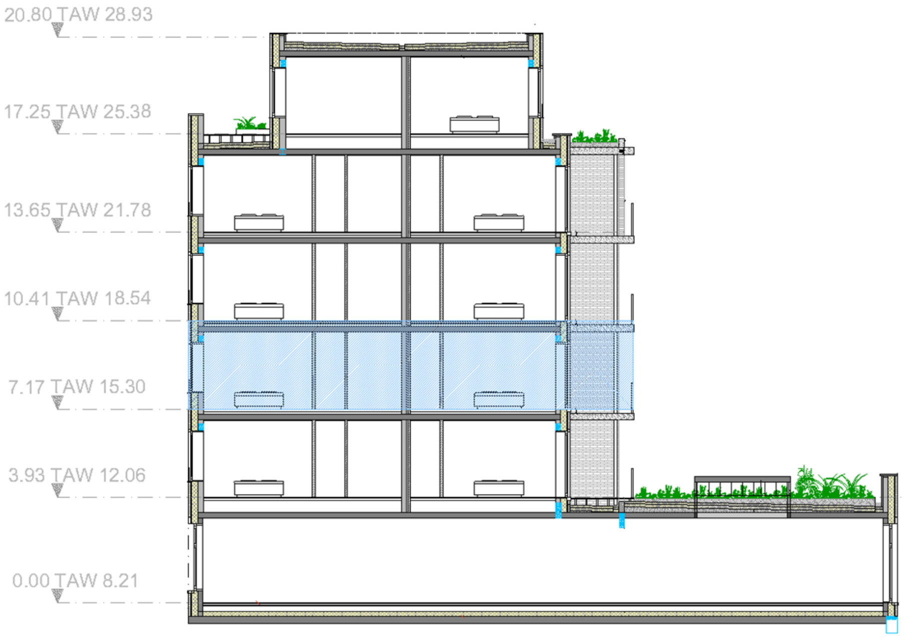


Figure 3.6: Section over the functional unit (hatched in blue) - Original structural design

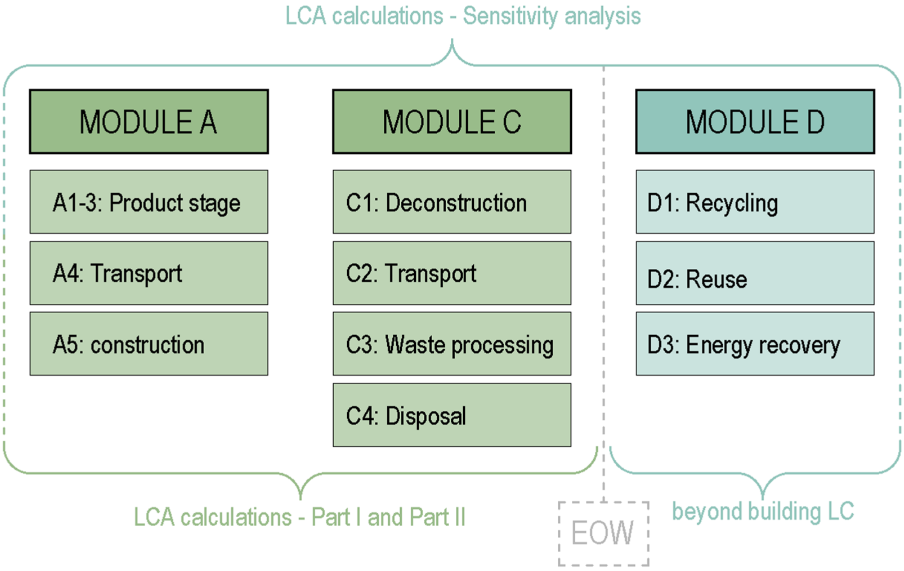


Figure 3.7: System boundaries considered for the LCA calculations

3.3.3 Life cycle inventory analysis (LCI)

To determine the in- and output flows of the functional unit over the entire life cycle, SimaPro 9.1.1.1 will be used along with the Ecoinvent 3.6 database. As mentioned in [70], this is one of the most widely used LCA software-database combinations. All processes taken into account are obtained from this database and where possible adapted to the Belgian context. The elaborate road map which was used to choose and adjust the processes to the Belgian context can be found in Appendix C. The total amounts of each in- and output flow will be determined based on the dimensions of the structural components, calculated in Section 3.4. The further calculations in Excel using the output from SimaPro were mainly based on the TOTEM documentation Environmental profile of buildings [20]. The allocation of the impacts is done according to the principle of cut-off by classification. This entails that all burdens and benefits related to reuse and recycling are allocated to the next life cycle or thus to module D. Assumptions and specific processes in the LCI for each module are discussed hereunder.

3.3.3.1 Module A

The production stage (A1-A3) includes the environmental impact of the raw materials and the energy to collect them, the transport to the production site and the production process. In tables A.1 and A.2 in Appendix D a detailed overview is given of the processes used to calculate the impact of the different materials for stages A1 up to A3.

As mentioned in Section 2.3.3 the assumptions made regarding biogenic carbon emissions have an important influence on the outcomes of module A for wood products. The Ecoinvent database only covers the static contribution of the biogenic carbon cycle and neglects the forest dynamics [71]. For end-products, the biogenic CO_2-content is not included in the calculation of the CO_2-impact in the database due to the assumption of carbon-neutrality when taking into account the entire life cycle of these products [72]. In this study too, carbon neutrality for biogenic carbon is assumed and therefore, no biogenic carbon will be taken into account when calculating the environmental impacts.

Modules A4 and A5 represent the transport and construction process. Regarding the transport means and distances from the production plant to the construction site, the default scenarios defined for the main product or material categories in EN 15804 [3] were used. Concerning the transport means, four different types of lorries are distinguished as indicated in Appendix E. The standard transport scenarios and distances for each material category are elaborated in Table 3 of the TOTEM document Environmental profile of buildings [20].

The impact of the construction process itself is represented by the material losses. According to OVAM, 5% losses of material during construction should be taken into account [20] independent of the type of material. However, as stated in [73], a larger fraction of losses is expected for hardening materials such as concrete and mortar than for prefabricated components such as steel profiles or HCS. Therefore, based on the literature a lower percentage of losses can be accounted for, for prefabricated products. According to [73], the material losses can be within a range of 1% for prefabricated products, up to 10% for in situ fabricated components. Table 3.1 gives an overview of reasonable values for the material losses for the respective materials and the sources from which these values are derived. The latter concludes that taking into account 5% material losses leads to a 5% increase in the environmental impact. Changing this value to 1% or 10% gives rise to a decrease of 3.8% and an increase of 4.8% respectively. Because all values in table 3.1 only slightly deviate from the initial value of 5% and, as a consequence, the differences in total environmental impact are small, it is decided not to investigate the effect of a change in material losses in this study. All calculations will be done taking into account the standard value of 5%.

Table 3.1: Adopted percentages of material losses for each material with the respective source

Material	**Percentage of waste [%]**	**Source**
Prefab concrete C50/60	0.030	[74]
Prefab reinforcing steel BE500	0.050	[74]
In situ concrete C30/37	0.050	[20]
In situ reinforcing steel BE500	0.100	[74]
Steel profiles	0.010	[73]
Steel for connections	0.050	[20]
Glulam beams & columns	0.030	[74]
CLT plates	0.030	[74]
Clay brick	0.050	[20]
Aerated concrete	0.014	[17]
Sand-lime brick	0.014	[17]
Adhesive mortar	0.050	[20]

3.3.3.2 Module B

In this LCA the operational phase of the building will not be considered due to the long lifetime of the load-bearing structure and the marginal contribution of this module to the total environmental impact. Moreover, as the FU only includes the structural system, operational energy use cannot be taken into account. Further arguments were discussed in Section 2.3.

3.3.3.3 Module C

Module C includes the processes used during the end-of-life stage which starts when the building is decommissioned. This process provides a source of (waste) materials which can be reused, recycled or disposed. This module stops at the end-of-waste as described in the next subsection.

Module **C1** concerns the **deconstruction and demolition** and is restricted to the activities on-site. This includes the fuel consumption of the demolishing machines and the accompanying emissions of particulates to the air according to [20]. This module will be taken into account following the recommendations of TOTEM [20]. It is assumed that only for destructive removal operations an environmental impact must be included.

Transport from the building site to the disposal site or to the system boundaries, for materials which will be recycled or reused, is represented by module **C2**. According to the TOTEM documentation, all waste transport is done with the lorry for freight transport of 16-32 metric tons. The distance travelled is determined according to [20] and depends on the type of waste treatment. To determine this, each construction material must be allocated to a waste category. The waste categories for each material are given in Table 3.2 with the accompanying percentages for the different waste treatment scenarios.

Table 3.2: Waste categories per material and percentages of waste treatment [20]

Material	Waste category	Landfill	Incineration	Recycle	Reuse	Sorted on site
Concrete	Stony & glass: concrete	0.05	0.00	0.95	0.00	0.75
Steel	Metals: iron. steel. non-ferro	0.05	0.00	0.95	0.00	0.85
Glulam and CLT	Composite wood products	0.00	0.95	0.05	0.00	0.40
Aerated concrete	Aerated autoclaved concrete	0.70	0.00	0.30	0.00	0.30
Sand-lime brick	Stony & glass: other stone waste	0.05	0.00	0.95	0.00	0.75

Module **C3** describes the processes for **waste treatment** up to the moment when the products are no longer considered to be waste, for example, sorting materials and preparatory processes for recycling. At the end of the sorting process, it is assumed that the products reached their end-of-waste status and further impacts are allocated to the products made with the secondary materials in module D. Module C3 is also taken into account according to [20] using the fractions given in Table 3.2. For this module, an impact is only allocated to the materials that are sorted off-site and subsequently recycled. This means that no impact is allocated to on-site sorting.

Finally, module **C4** represents the actual **waste disposal**, which is subdivided into landfill and incineration. The landfill and incineration processes that were used for each material are given in Table A.4 in Appendix F.

3.3.3.4 End-of-waste (EOW)

The choice made for the end-of-waste determines the boundary between module C and module D, or also, between the current and the next life cycle. For this study, the system model 'allocation, cut-off by classification' is used. The main assumption in this model is that waste is the responsibility of the producer. The EOW status is reached at the point where the materials are considered secondary raw materials rather than waste materials. This was also indicated in Figure 3.7.

For materials that are recycled or reused, according to [20], it is assumed that this point corresponds to the end of the sorting operation or collection point and thus the burdens from disposal processes which include demolition, transport and disposal of non-recyclable materials are allocated to the primary product. However, the subsequent impacts, for example, due to the recycling process itself, are allocated to the next life cycle. The loads and benefits corresponding to these processes can still be taken into account through module D.

3.3.3.5 Module D

Module D takes into account the net additional benefits and loads due to the future substitution of resources which are not included in the system boundaries. These benefits result from reuse, recycling and energy recovery at the end-of-life of materials. Before elaborating on the method used to calculate module D for the different materials, it must be mentioned that there is not yet a generally agreed-upon calculation method related to module D. In this research, only a simplified calculation method is used to make an estimation of the impact corresponding to module D. In general, the benefits related to recycling taken into account in module D are set equal to the impact of the primary material that is substituted by the secondary material that is obtained at the end of the life cycle. However, the loads to process these materials must be taken into account too. A general formula is given in equation 3.1. Steel is the only material for which a closed-loop recycling process will be taken into account. The other materials have an open-loop recycling process which corresponds to a value of RC equal to zero in equation 3.1.

$$Impact\,module\,D = (RR - RC) * (E_{recycling} - E_{virgin} * Y * Q) \tag{3.1}$$

In which

- RR $=$ recycling rate
- RC $=$ recycled content
- $E_{recycling} =$ environmental impact of the recycling process (= loads)
- $E_{virgin} =$ environmental impact of the substituted material (= benefits)
- Q $=$ quality ratio
- Y $=$ yield of recycling process

Because this is a simplification, module D will not be taken into account in the main calculations. However, the influence of including module D on the results will be discussed in the sensitivity analysis in Section 4.6. For each of the used materials, specific waste management practices are commonly used. Hereunder, an overview is given of the corresponding processes taken into account for each material. 's **Concrete** - The loads and benefits taken into account for concrete structures will be based on the master's thesis of Suzanne Kelem [24] (LM) in which the influence of the end-of-life treatment of concrete on the environmental impact was investigated as mentioned in the literature study. Because low-grade concrete recycling is stated to be the best end-of-waste treatment, when taking into account modules A, C and D, this waste treatment will be considered in this study. According to [24] a reduction of 1.1% can be achieved by including low-grade concrete recycling of concrete elements in module D. As indicated in Table 3.2, a recycling rate (RR) of 95% is assumed for concrete. The value of E_{virgin} for concrete is equal to the impact of the production process of limestone because this material can be substituted by crushed concrete. The Ecoinvent process is given in Appendix G. $E_{recyling}$ is set equal to zero because crushing of concrete is taken into account in module C3.

Masonry - For masonry walls composed of clay bricks or sand-lime bricks, again a recycling rate of 95% is assumed. Equation 3.1 can be used in which E_{virgin} equals the impact of crushed gravel for clay bricks and the impact of crushed limestone for sand-lime bricks. $E_{recyling}$ is again equal to zero as indicated in Appendix G. For the masonry walls composed of AAC blocks, it is assumed, according to Xella [17], that 30% of the construction waste can be recycled by crushing it and reusing it as a substitute material for sand during the production of new AAC. According to [75] this crushed AAC can also serve to replace sand in screed or cement-stabilised sand. Therefore, E_{virgin} will be equal to the impact of the production process of sand. Due to a lack of adequate information concerning the values of Q and Y, both factors are set equal to 1.

Steel - Steel is the only material for which a closed-loop high-grade recycling process will be considered because this is common practice. The applied method is based on [76] and [77]. The total impact is calculated using equation 3.1 in which $E_{recycling}$ equals the impact of the electric arc furnace steel production process, while E_{virgin} equals the impact of 100% primary steel using the converter production process. The recycled content is set equal to 15%, the yield of the recycling process is 92% and the quality ratio is 1.

Another possibility is to reuse steel elements without any processing. The calculation of module D for this waste scenario will be based on the mentioned EPD [38]. In this EPD a reuse rate of 80% is assumed with a quality ratio Q of 90%. The remainder 20% will again have a recycling rate of 95%, resulting in 19% recycling and 1% landfill. For the impact related to the recycling process, the same parameters as discussed above will be used. Both parts can be calculated separately and added together afterwards. The processes used for E_{virgin} and $E_{recycling}$ are displayed in Appendix G.

Timber - As mentioned in the literature study, for timber products, which are burnable materials, incineration with energy recovery is the most advantageous end-of-life treatment based on carbon footprint. The benefits from the exported energy are calculated using the assumptions of [78]. Equation 3.2 is used to determine the benefit per kg of waste that is incinerated.

$$e = LHV * (XER, heat * ESE, heat + XER, elec * ESE, elec) \tag{3.2}$$

In which:

- LHV $=$ lower heating value of waste = 13.99 MJ/kg
- XER,heat $=$ efficiency for the energy recovery process for heat $=$ 0.2
- XER,elec $=$ efficiency for the energy recovery process for electricity $=$ 0.1
- ESE,heat $=$ emissions and resources per MJ substituted energy source for heat production
- ESE,elec $=$ emissions and resources per MJ substituted current average electricity production

The processes used in SimaPro for ESE,heat and ESE,elec can be found in Appendix G.

Besides incineration with energy recovery, it is also possible to recycle wood products into wood chips which can be used for more low-grade applications. Taking into account the waste scenario of TOTEM [20] for uncontaminated wood, a recycling rate of 75% can be assumed. Equation 3.1 can again be applied, in which E_{virgin} is the impact of the production process of wood chips for plywood production, while $E_{recycling}$ takes into account the shredding process of wood. These different end-of-life treatments will be further discussed in the sensitivity analysis in Section 4.6.

3.3.4 Life cycle impact assessment (LCIA)

In the life cycle impact assessment, the environmental profile of the different structural designs will be set up using all the environmental impact indicators (EII) shown in Table 2.1 according to the impact method EN 15804 + A2, which is included in SimaPro as 'EN 15804 + A2 Method V1.00 / EF 3.0 normalization and weighting set'. Based on all these EII, a single score, expressed in Pt, will be calculated which allows an easy comparison between the different materials.

However, when using this impact method, it is perceived that the amount of biogenic carbon sequestered during the production phase is larger than the amount released at the end-of-life for timber products. As a consequence, these products get a negative resulting impact which is not in line with the assumption of biogenic carbon neutrality over the entire life cycle. This is a consequence of the choice of production and waste processes in SimaPro which are, apparently, not perfectly compatible. Therefore, a small adaptation will be done to this impact method to fulfil the assumption of carbon neutrality related to the biogenic carbon component. The factors for 'Carbon dioxide biogenic' and 'Carbon in air' will be set equal to zero in this impact method.

In the sensitivity analysis, a closer look will be taken at the carbon dioxide equivalent separately, which represents the climate change impact, because this is a commonly used indicator in the construction sector.

3.3.5 Life cycle interpretation

The last stage of the LCA is the life cycle interpretation as was shown in Figure 2.2. In this stage, the results of the different LCAs will be interpreted and compared to each other to formulate an answer to the research questions. This will be elaborated in Chapter 4.

3.4 Structural calculations

As each material has different mechanical and technical characteristics, it requires its own structural design consisting of a slab type, a certain column grid or wall layout and a calculation of the necessary dimensions to resist the prescribed loads. On the one hand, the ultimate limit state (ULS) design requirements need to be fulfilled to ensure safety due to a sufficient load-bearing capacity. On the other hand, the serviceability limit state (SLS) requirements must be met, so that the structures perform satisfactorily during their normal use, referred to as the serviceability limit state. Depending on the type of material, specific ULS and SLS checks need to be performed according to the accompanying Eurocode. For concrete and wood for example, creep deformation must be taken into account, while steel on the other hand is more susceptible to buckling failure. The checks that need to be performed for each type of structural element will be discussed in more detail in the respective sections.

Hereunder, an overview of the loads that are taken into account in each calculation is given based on EN 1991-1-1 [79]. The case study building is a residential building and thus belongs to use class A. The self-weight of the structures is taken into account and depends on the type of slab and supporting structure chosen in each design. The densities of the used materials are given in Table A.7 in Appendix H. The permanent surface load is calculated based on the expected floor finishing on top of the structural slab elements for the case study building. An additional contribution is taken into account which represents an estimation of the weight of light separating walls in the apartments. For this contribution, the weight of the separating walls in the functional unit was calculated and spread out over the surface which leads to an additional permanent load of 0.9 kN/m². Finally, the total permanent load could be set equal to 2.80 kN/m². For the variable loads, a uniformly distributed load of 2 kN/m² is taken into account for residential buildings. In case the building would get a redesignation over its life cycle and becomes an office building, a larger variable load of 3 kN/m² should be taken into account. However, in that case, it is expected that no additional load of separating walls must be taken into account. As a consequence, the total load will only slightly change and it can be assumed that this would not influence the results of this study. Therefore, the structural elements will only be calculated for the loads corresponding to a residential building. Regarding the wind load, it will be assumed that this load is entirely resisted by the central core and does not influence the dimensions of the load-bearing structure of the functional unit. For that reason, no horizontal displacements will be considered as well. The choice of the functional unit was described in detail in Section 3.3. Due to the original layout of the floor level that serves as the functional unit, shown in Figure 3.5, the general structural member for the analysis will be a continuous slab consisting of three equal spans of 5.20 m, spanning in one direction (x-direction), also called a continuous one-way slab, and supported by line supports (walls or beams) along the y-axis. Due to this layout, the x-axis is the major strength axis, while the y-axis is the minor strength axis. Therefore, also the moment and shear capacities and the deformations will be evaluated for the x-direction. Some alternative frame layouts, for example with larger spans, will be examined too in a later phase of the study to investigate the influence on the results.

For each structural design that will be investigated, one functional unit with an area of 195 m² will be calculated existing of columns and beams or walls, slab elements and connection components. To avoid the need to calculate the columns for every floor, only the columns of the second floor, indicated in Figure 3.6, will be calculated and it will be assumed that this gives a good indication of the impact of all columns over the entire building.

In Figure 3.8 a schematic overview is given of the types of slabs and supporting structures for each material that will be examined in this study. In total five slab types and nine supporting structures can be distinguished when further subdividing the concrete support structures into prefab and in situ structures. This choice was made based on the literature study. It was decided not to take into account any steel floors because these are not commonly applied in Belgian practice for residential buildings. First, the slabs and supporting structures will be calculated separately. Later on, the most relevant slab-support combinations will be chosen for further investigation, based on the intermediate results of the LCA. This was also illustrated in Figure 3.1.

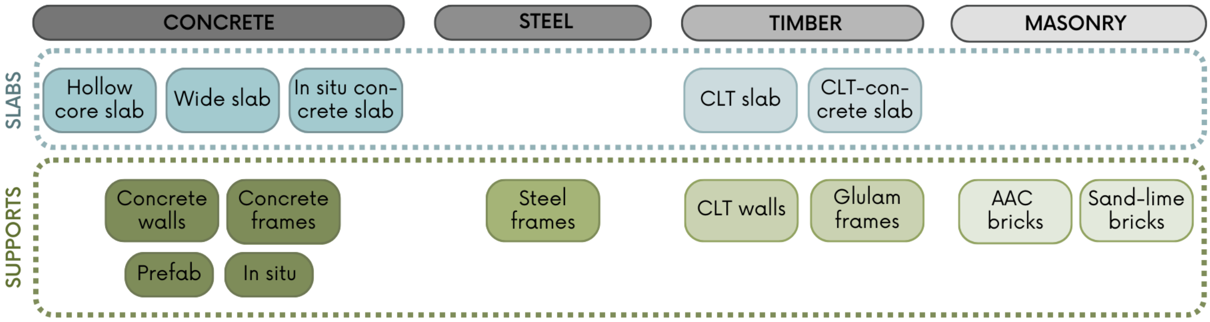


Figure 3.8: Schematic overview of slab types and supporting structures that will be investigated in this study

3.4.1 Structural calculations of slabs

In this section, the structural calculations of the different slab types will be discussed. Every slab is initially calculated assuming that it has span lengths of 5.20 m in the x-direction and carries the loads in that direction. This configuration will be further referred to as layout 1 or L01. As stated above the permanent load equals 2.80 kN/m² and the variable load 2 kN/m². Altogether, this can be schematized as shown in Figure 3.9 for a single span. However, the slab can be continuous over 2 or 3 spans depending on the location in the functional unit and the type of slab as indicated further on in Figure 3.14. Therefore, different calculations will need to be performed for every slab type as will be elaborated in the next subsections. In general, the total deformation of all slabs, taking into account long-term effects such as creep, must be limited to L/300 or 17.3 mm for a 5.20 m span. The difference between long-term and short-term deformations must be limited to L/500 or 10.4 mm for a 5.20 m span.

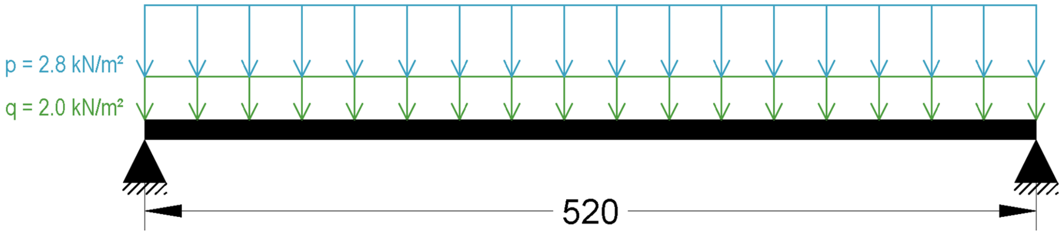


Figure 3.9: Scheme of loads on one-way slab with 5.20 m span

Besides this first layout, three other configurations will be examined with different spans of the slabs and/or beams as shown in Figure 3.10. This makes it possible to examine the sensitivity of the results to different designs and loads. In the following sections, the abbreviations L01 up to L04 will be used to refer to these layouts.

Every slab type will be calculated for configuration LO1 as well as LO4. LO3 will only be calculated for a floor consisting of HCS because this span is too large to cover with other materials which would lead to excessive slab thicknesses.

Related to the supporting structures, in part I of the calculations, each frame type will be calculated for configurations LO1 and LO2. Additionally, the concrete frames will also be calculated for LO3 and LO4. This is further discussed in Section 3.4.2. The configurations considered for part II are discussed in Section 4.3.

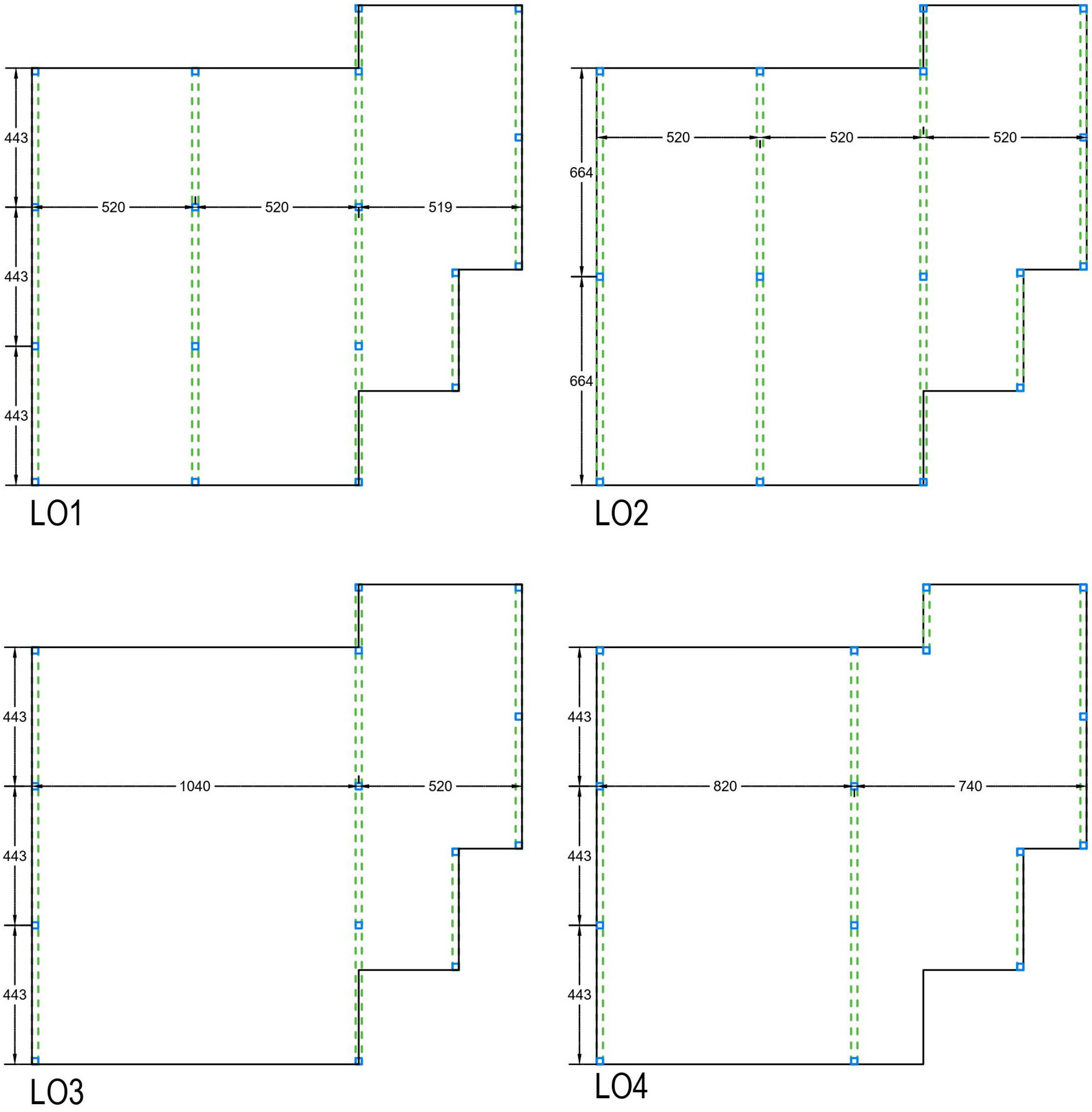


Figure 3.10: Four configurations of beams and columns, LO1 up to LO4

In the following subsections, for each type of slab, the used calculation method and main assumptions will be briefly discussed. More details and the results of the calculations can be found in Chapter 4 and in the corresponding appendices.

3.4.1.1 Hollow core slabs (HCS)

As a first step in the structural design of every slab, a conceptual structural design plan will be set up. Figure 3.11 shows the conceptual structural design plan of the functional unit with the use of hollow core slabs for configuration L01. All slabs span in one direction over a length of 5.20 m and are supported by beams, which transfer the loads towards columns. The numbers in the columns indicate the distinction between corner (1), edge (2) and central (3) columns, which will be clarified further on. However, these beams and columns could also be walls, this will not influence the design of the slabs. Alternatively, the hollow core slabs can also be designed for configurations with two spans, namely L03 as shown in Figure 3.12 and L04 which was shown in Figure 3.10. Another choice that must be made is whether the slabs are continuous over the supports and thus form one hyperstatic slab, or are conceived as three separate isostatic slabs. The first choice will limit the deflections but requires more secondary reinforcement to ensure the slab behaves hyperstatically. Therefore, the hollow core slabs will always be calculated as isostatic spans.

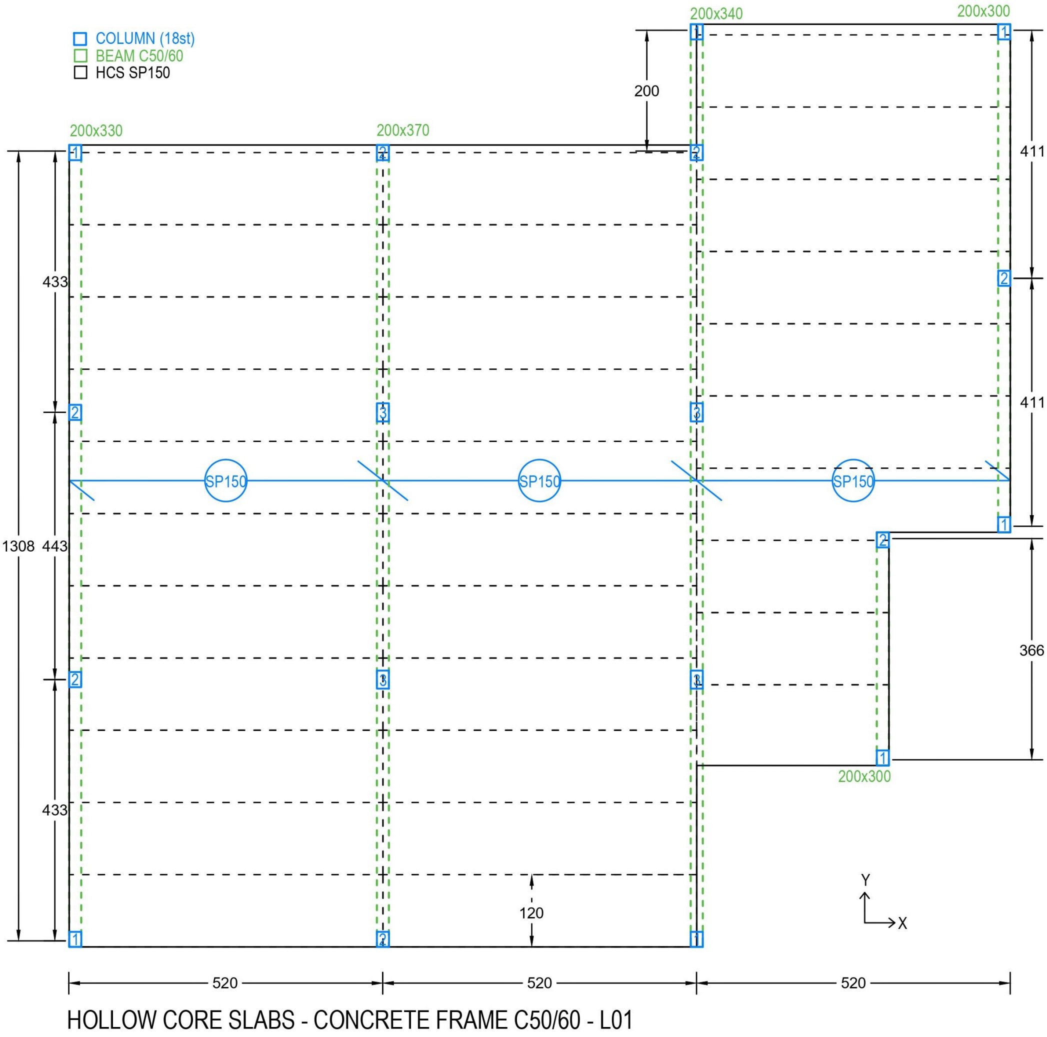


Figure 3.11: Conceptual structural design plan of the FU with HCS supported by a frame structure - L01

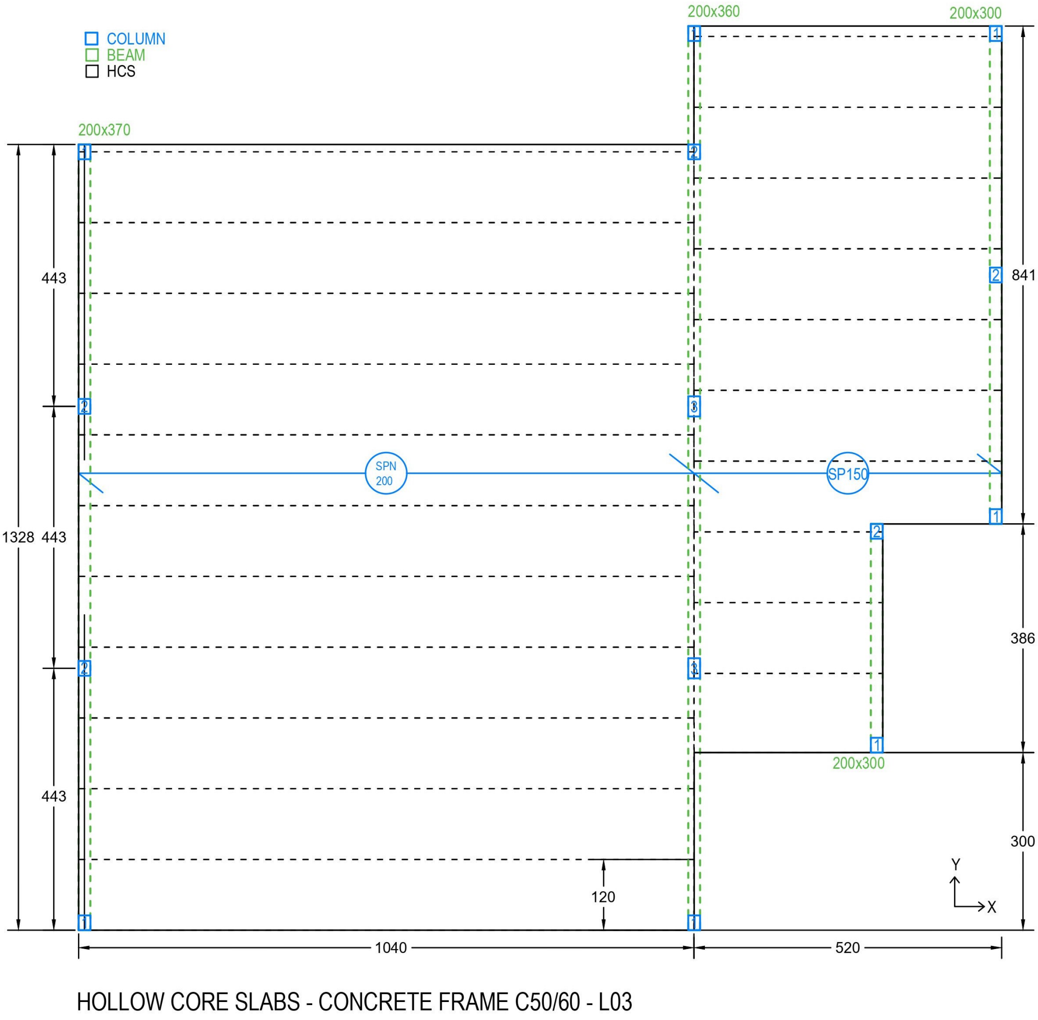


Figure 3.12: Conceptual structural design plan of the FU with HCS supported by a frame structure - L03

To calculate the necessary hollow core slabs the online tool MyFloor of Ergon, an important manufacturer of prefabricated concrete components, will be used. This tool provides a suited type of hollow core slab for different span lengths depending on a set of provided design parameters. The parameters used for the design under consideration are shown in Table A.8 in Appendix I.1. This calculation tool takes into account the ULS and the SLS, or more specifically, the limitation of crack widths, deflections and stresses to determine the suited type of HCS.

After determining the type of HCS, this HCS will be modelled using the 1D software ConCrete to determine the additional reinforcement that must be provided at the transition between two hollow core slabs. To do this, a new HCS must be created giving the dimensions and concrete class as specified by Ergon.

3.4.1.2 In situ concrete slab

The conceptual structural design plan for the in situ concrete slab can be seen in Figure 3.13. The slab can be calculated as a hyperstatic continuous slab over two or three fields. In reality, the loads on an in situ cast concrete slab will be carried in two directions, with one main direction in this case. Therefore, a 2D calculation will be done using the finite element software SCIA Engineer to determine the necessary slab thickness. After determining the slab thickness, the slab will be modelled in ConCrete to estimate the necessary reinforcement. For this slab, a concrete class C30/37 will be assumed which is a common choice for in situ poured concrete as stated above.

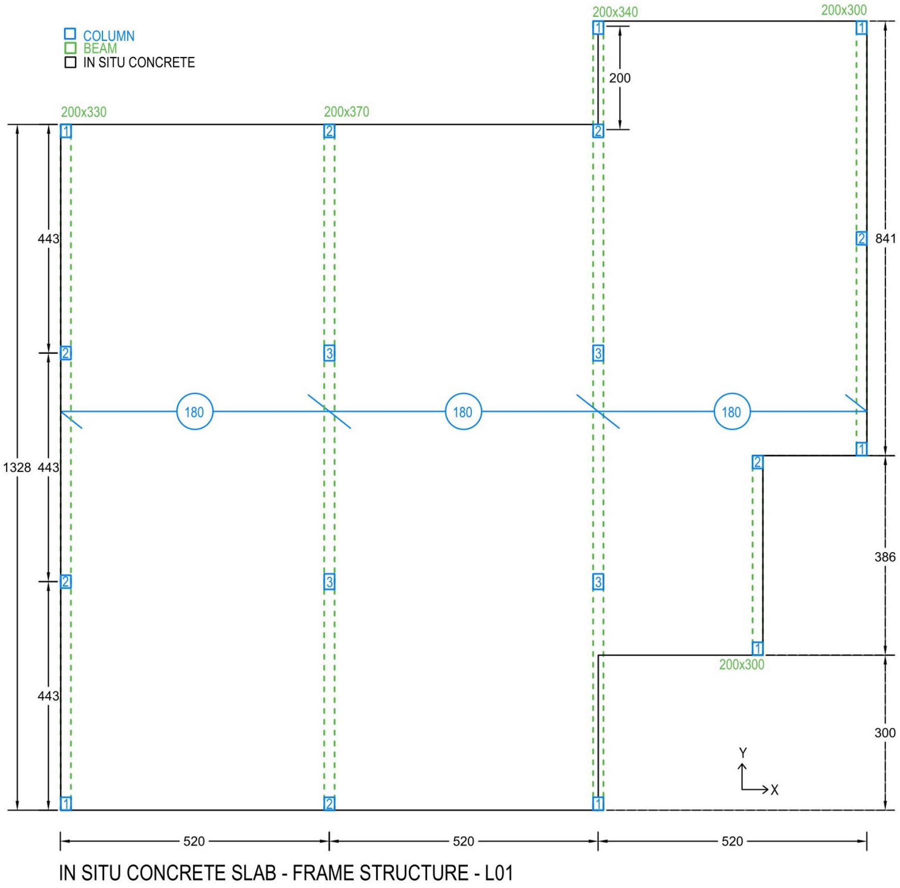


Figure 3.13: Conceptual structural design plan of the FU with an in situ concrete slab supported by a frame structure - L01

For the calculations in SCIA Engineer, the entire functional unit is modelled. The slab is a homogeneous concrete slab supported by beams to which it is virtually connected. The necessary slab thickness is calculated based on the deflection and crack width checks using the concrete tools in SCIA which consider creep and long-term effects. Furthermore, the stresses in the SLS were verified and a ULS shear and moment verification was performed.

Afterwards, the resulting slab is modelled and calculated in ConCrete to dimension the reinforcement. Due to the irregular shape of the plan of the functional unit, four different sections need to be calculated as indicated in Figure 3.14 with the numbers 1 up to 4. Each time the number or the length of the spans in the load-carrying direction (x-direction) changes, a new calculation needs to be performed. After completing the model, the necessary amount of primary reinforcement in the field and above the supports can be determined. The output ConCrete provides, can be used to determine the practical reinforcement of the slab. In general, for an in situ slab the basic reinforcement consists of an upper and a lower reinforcement net. The specific slab geometry then determines the required additional reinforcement that needs to be provided at each location. Based on the given minimum reinforcement in ConCrete, the reinforcement nets can be chosen. Using the reinforcement sketch, the theoretical amount of additional longitudinal reinforcement and the length over which it needs to be provided can be determined by subtracting the amount provided by the nets. This length takes into account the anchorage length and the shift of the moment line. Finally, this reinforcement amount is converted to a practical diameter and bar spacing which will be used to calculate the total reinforcement weights for the LCA.

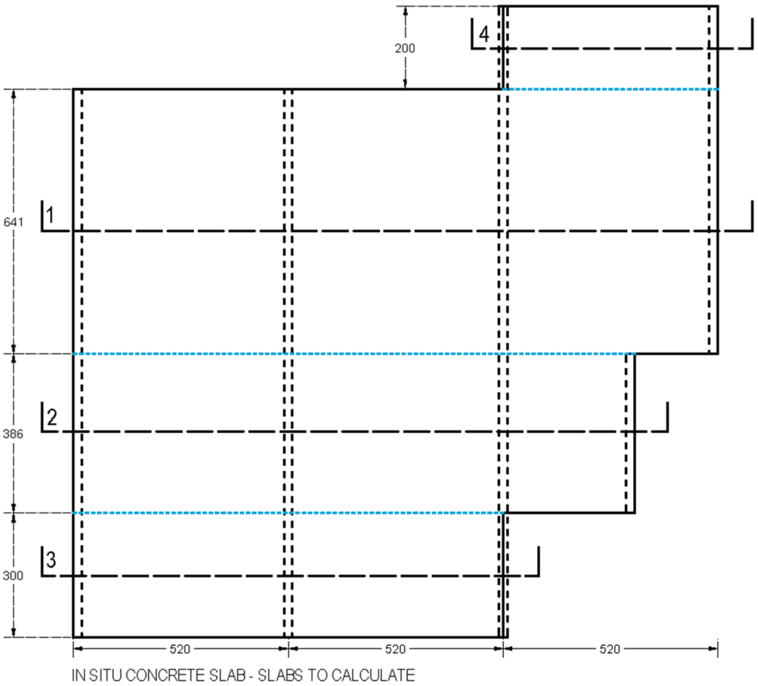


Figure 3.14: Indication of the different continuous slab types (1-4) calculated in Concrete - L01

3.4.1.3 Wide slabs

The 1D software ConCrete of Buildsoft will be used for the calculations of the wide slabs too. For wide slabs, the 1D approximation is an acceptable estimation because these slabs carry the loads mainly in one direction. In plan view, the same slab sections will be calculated as indicated in Figure 3.14 for the in situ slab. The conceptual structural design plan for L01 is shown in Figure 3.15, with wide slabs having a width of 2.40 m and a span length of 5.20 m. The main difference with an in situ concrete slab is that the slab is composed of two concrete phases: the 50 mm-thick prefabricated wide slab that forms a lost formwork and the in situ concrete layer on top of it which is the actual load-bearing floor. Moreover, the wide slabs contain lattice girders to increase their strength and stiffness.

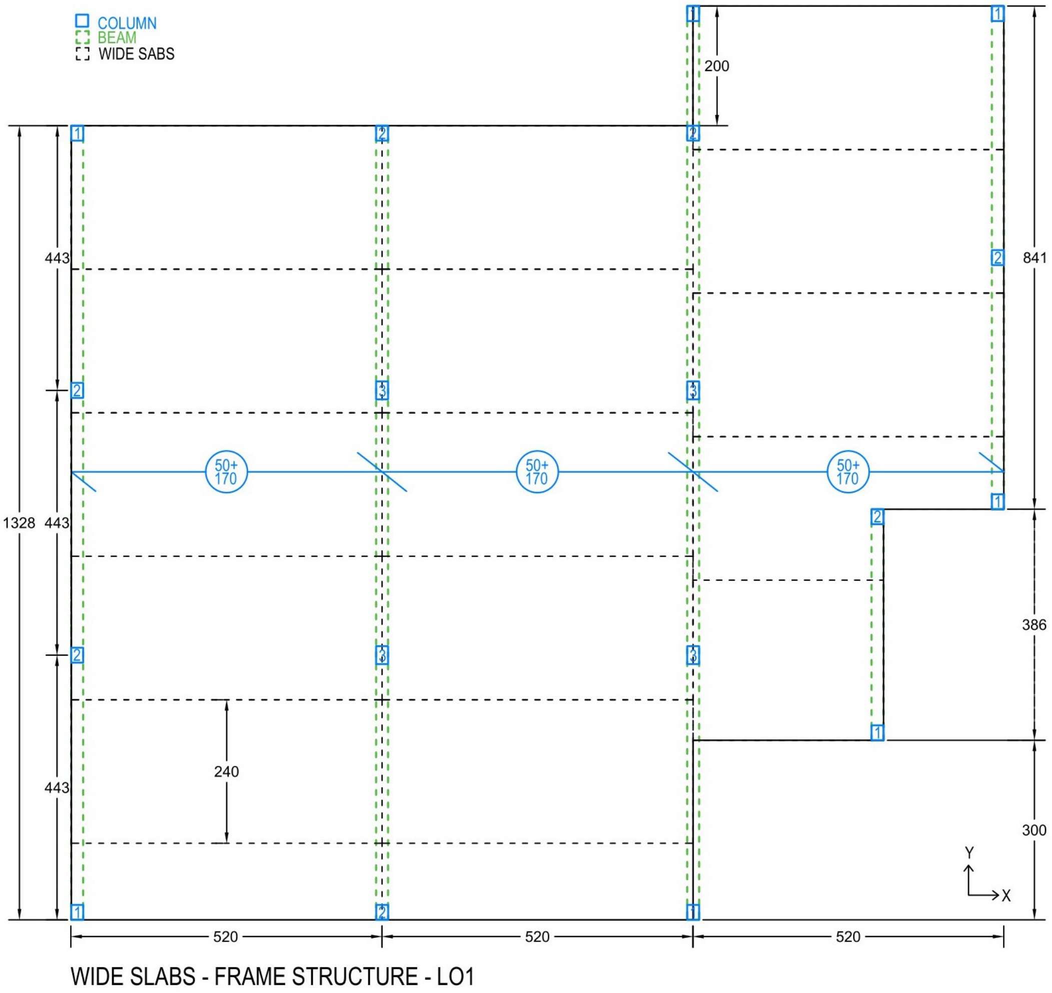


Figure 3.15: Conceptual structural design plan of the functional unit with wide slabs - LO1

In Concrete, the slab is modelled similarly to the in situ concrete slab, with both the first and the second phase having a concrete class C30/37. The design input is given in Appendix I.2. The necessary thickness of the slab can be determined taking into account the limitations for deflections and crack widths. The deformation after creep for the quasi-permanent (QP) load combination in a cracked section must be smaller than the chosen limit value of L/300 to fulfil the serviceability requirements for the deflection. ConCrete also provides an optimum slab thickness which will be used as a starting value. Furthermore, the same checks need to be performed as for the in situ concrete slabs.

The allowable crack widths are also taken into account. The calculation of crack widths in ConCrete is based on the theoretically required reinforcement. In case the limitations for the maximum concrete stress are exceeded, ConCrete increases the amount of reinforcement. Subsequently, the practical reinforcement can be determined as elaborated in the previous section for the in situ concrete slab. The resulting amount of reinforcement will be multiplied by a factor 1.05 to take into account the additional reinforcement at corners, edges and connections.

3.4.1.4 CLT slab

The structural design plan for the CLT slabs can be seen in Figure 3.16. For the design of the CLT slabs use will be made of the online software tool Calculatis of Stora Enso which makes it possible to easily calculate the necessary CLT slabs based on the Eurocode prescriptions. The detailed choices and design input for this tool are shown in Table A.10 in Appendix I.3. The geometry and supports will be adjusted according to the structural design plan, and again four different layouts will be calculated corresponding to the four sections of the floor plate.

As stated in [12] (LM) it is important for lightweight floors to check the vibration criteria. Therefore, an SLS vibration analysis will be done taking into account the stiffness in the transverse direction of the CLT panel with the screed on top of it. Besides the vibration analysis, a ULS check needs to be performed for the flexural stress, the shear stress and the rolling shear stress. The results of these are expressed as a utilization ratio of the total capacity. Next up, a ULS check is performed related to fire resistance, evaluating the same parameters. Finally, the SLS design needs to be done by checking the instantaneous and quasi-permanent deformations. Comparable to concrete structures, it is also necessary for timber structures to take into account creep deformation over time [21] (LM).

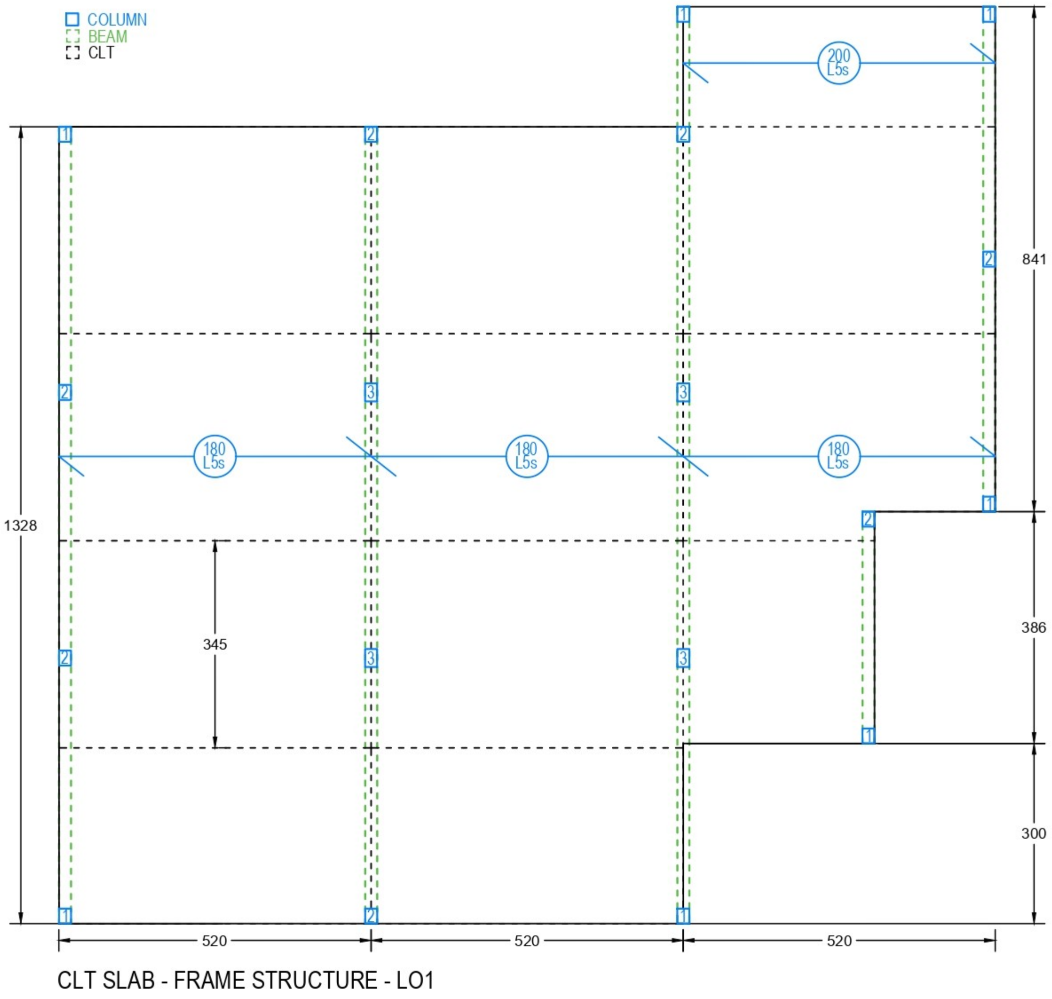


Figure 3.16: Conceptual structural design plan of the functional unit with CLT slabs - LO1

3.4.1.5 Composite CLT-concrete slab

The composite CLT-concrete slab can be calculated in a similar way with the use of the 'CLT timber-concrete composite floor' module of Calculatis. The design input is comparable to that for the CLT slab, although some additional data needs to be provided related to the concrete layer. The detailed overview of the design input can be found in Appendix I.4. The same ULS and SLS checks are executed as for the CLT slab. The reinforcement for the concrete layer also needs to be designed. This is comparable to the reinforcement foreseen in the concrete layer on top of the hollow core slabs.

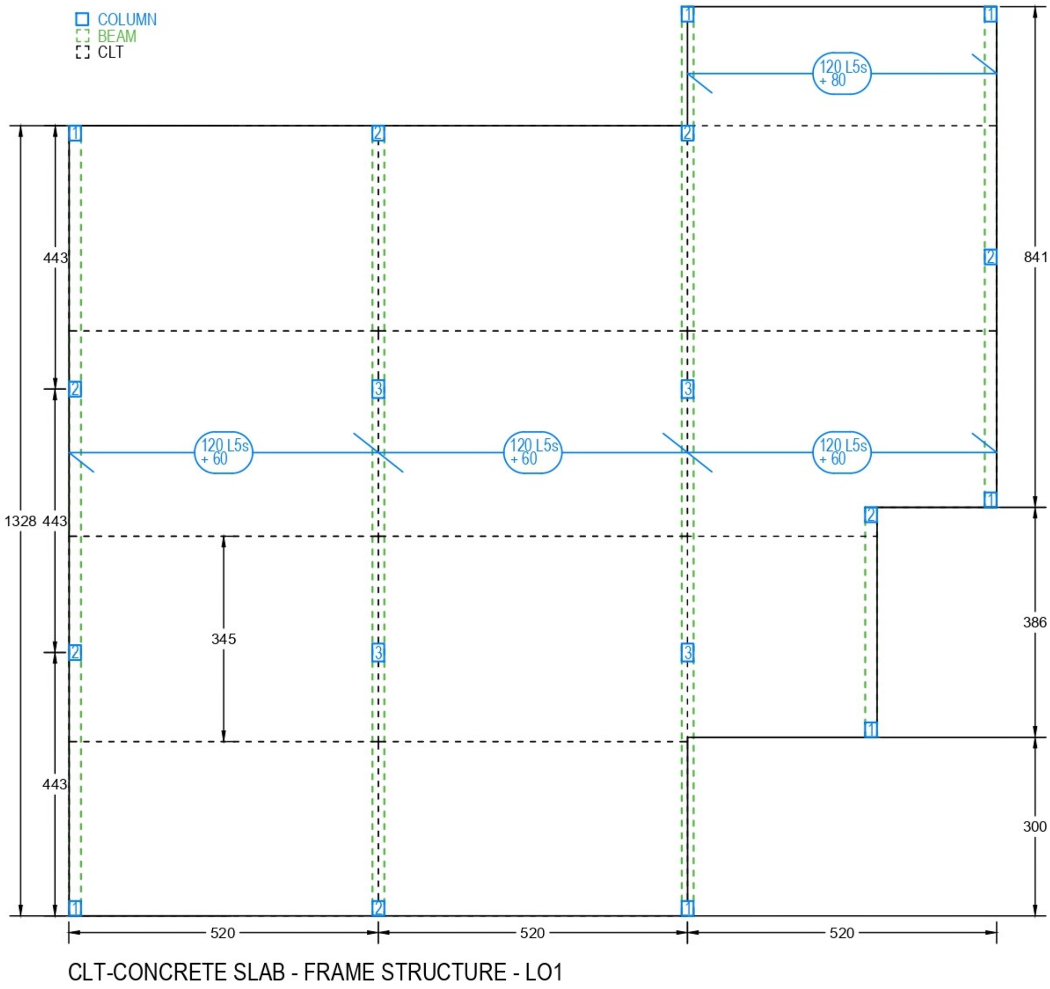


Figure 3.17: Conceptual structural design plan of the functional unit with CLT-concrete slabs - LO1

3.4.2 Structural calculations of supporting structure

Regarding the supporting structure, a distinction is made between frame structures consisting of beams and columns and wall structures. All frame structures will at least be calculated for L01 and L02. In case the slabs are supported by a frame structure, first, the beams will be calculated and subsequently, the columns which need to carry the loads from the beams and from the floors above. The main difference is that walls, apart from their load-carrying function, also have a room-separating function. When frame structures are applied in a residential building additional infill walls are needed to separate rooms and to complete the facade. Therefore, on the one hand, an additional line load must be taken into account at the location of the beams, and on the other hand, an additional component must be added to the environmental impact of these frame structures in the LCA to take into account these necessary additional infill walls. Different materials can be used for these infill walls and will also be compared related to their environmental impact. Examples are classic masonry walls and plasterboard walls. However, it must be mentioned that for buildings with an office function, the internal organization is more flexible and often no room-separating walls are necessary. Therefore, in Chapter 4, the different structural solutions will be compared with and without taking into account infill walls.

For supporting structures made of concrete, the calculations in part I are executed for concrete classes C30/37 and C50/60. This will make it possible to examine the influence of the concrete class on the environmental impact of a frame. In theory, precast or in situ cast components can be executed with concrete of the same concrete class. However, for precast elements produced in factory conditions, it is more common to adopt higher concrete classes. The hollow core slabs of Ergon, for example, are always executed using concrete of class C55/67 [80], while for precast concrete columns, concrete class C50/60 is often used [81]. Therefore, it is chosen in the following calculations to apply concrete class C30/37 for cast in situ components and class C50/60 for precast components.

In the first part, the structural calculations for the wall and frame structures will be done assuming that the wall or frame type under consideration is applied over the entire building up to the top level and that the floor slabs are HCS. As such, a first comparison between these types of wall and frame structures can be made irrespective of the weight of the slabs on top of it. Later on, these vertical supporting structures will be recalculated taking into account specific slab types which form the most relevant combinations with each supporting structure based on the intermediate LCA results. This method was already illustrated in Figure 3.1.

3.4.2.1 Concrete frame

The frame structure is composed of beams supported by columns which are both executed with concrete of concrete class C30/37 or C50/60. The beams will be calculated using the 1D software ConCrete of Buildsoft. The columns will be calculated with the software 12-Build of Buildsoft checking the compressive strength and performing a buckling check. Based on the type of HCS that is necessary according to the calculations above, the permanent load transferred to each beam can be calculated. The total load is composed of the self-weight of the beams, permanent loads and variable loads. As mentioned at the beginning of this chapter, the concrete frame will be calculated for configurations L01, L02, L03 and L04 shown in Figure 3.10, for both concrete class C30/37 and C50/60.

For configuration L01, it was chosen to subdivide the longest span into three parts creating a continuous beam over three spans of 4.43 m for the two most left beams. However, due to the irregular plan shape and the difference in loading, in total four different hyperstatic beams and one isostatic beam need to be calculated as shown in Figure 3.18 with the corresponding loads.

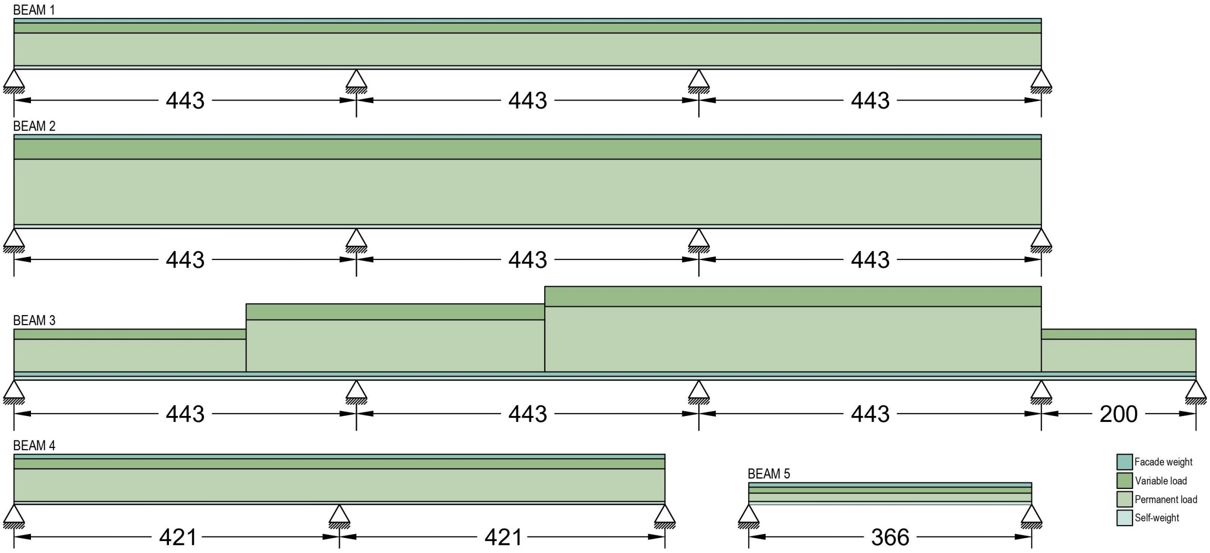


Figure 3.18: Sketch of concrete beams with indication of the corresponding loads - L01

To verify whether this is the best column layout, a second layout will be calculated. In this second column layout (L02), the longest span is subdivided only into two spans of each 6.64 m as shown in Figure 3.19. Beams 4 and 5 will remain the same due to the layout of the plan.

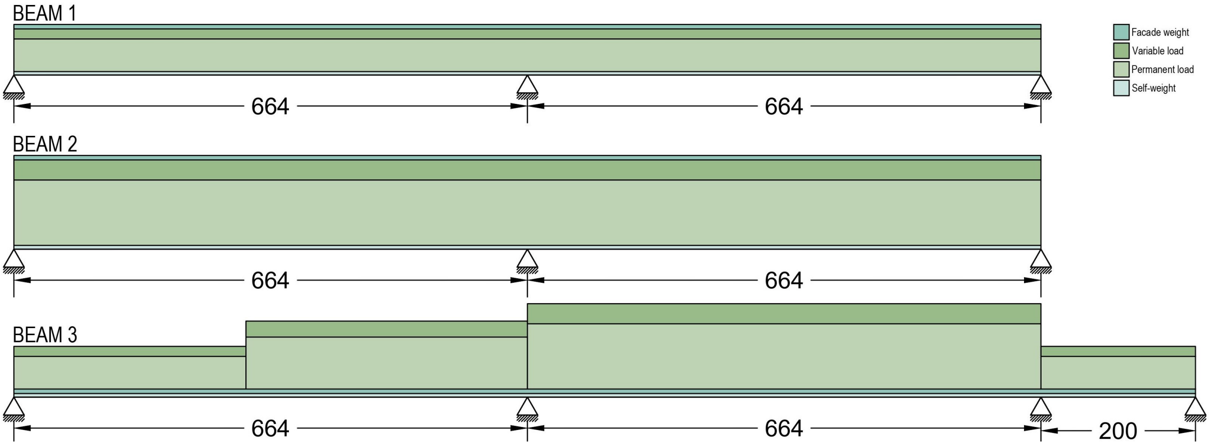


Figure 3.19: Sketch of concrete beams with indication of the corresponding loads - L02

Finally, configurations L03 and L04 will be calculated, in which the second beam and its supporting columns are not present and a larger load is transferred towards beams 1 and 3. This leads to eight concrete frames that need to be calculated, namely four configurations for two concrete classes. The results of these calculations will then be used to decide which configuration should be used for the calculations in part II.

Taking into account the total load and the layout of the beams, the necessary cross-section and theoretical reinforcement amount can be calculated using ConCrete based on the SLS requirements for deflections and crack widths. Furthermore, an SLS stress check and a ULS shear check must be done. The detailed design input can be found in Appendix I.5. Using the outcomes of ConCrete, a practical reinforcement amount consisting of longitudinal bars and transverse stirrups still needs to be calculated. This can be done using the software ConCrete Plus which can be linked to ConCrete to detail the calculated beams. An example is shown in Figure 3.20 for beam 1. It is chosen to use continuous top and bottom reinforcement and to use straight anchorages when possible. The accompanying bar bending schedule gives an overview of the number, diameter and length of bars and can be used to determine the total volume of steel.

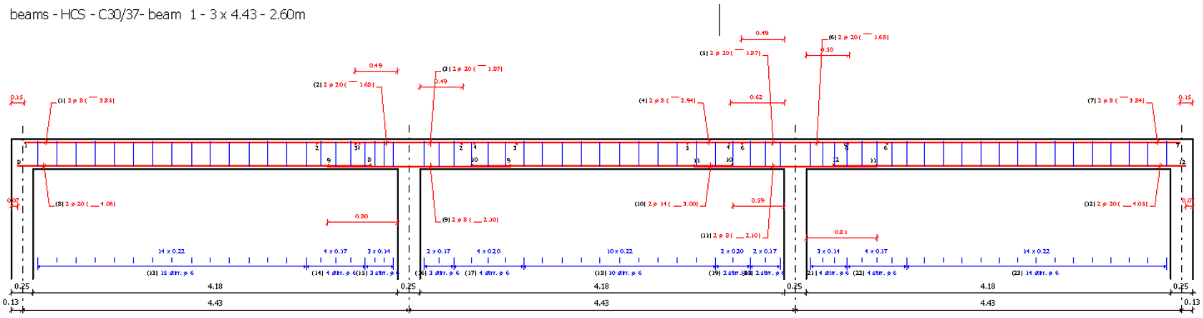


Figure 3.20: Practical reinforcement distribution concrete beam 1 - L01 - C30/37

The final part of the structural frame that needs to be designed, is the columns. The column dimensions and the necessary reinforcement will be calculated using 12-Build as mentioned at the beginning of this section. The loads on the columns of the second floor will be determined by taking into account the influence area that carries its loads towards each column and summing up the loads of all the floors above. The second floor was chosen because it represents a good average for the building.

The dimensions of the columns will be rounded up to a multiple of 10 mm. For the sake of simplicity, only three types of columns will be applied over the entire floor, namely corner columns, edge columns and central columns. The large difference in the influence area of these columns leads to a large difference in loading. Additionally, the minimum dimensions of a column must be guaranteed to make the columns practically executable. Normally, these are taken equal to 200 mm x 200 mm, but this can also be converted to 300 mm x 150 mm.

Besides longitudinal reinforcement, stirrups must be provided in the columns too to resist the shear forces, prevent buckling of the columns and complete the reinforcement cage. Due to the moderate spans and loads in the case study building it can be assumed that the minimum amount of stirrups will fulfil the requirements. The structural calculations for the frames of concrete class C30/37 and C50/60 will be exactly the same except for the difference in concrete characteristics that are provided to the software.

3.4.2.2 Steel frame

For the calculations of the steel frame, the software 12-Build of Buildsoft will again be used. This application allows dimensioning of the most common types of beams and columns with verification of the ULS and SLS according to the Eurocode. Therefore, the right standard must be selected. For steel beams, this will be EN 1993 Annex A [82]. The same beams need to be calculated as for the concrete frame. After entering the right geometry of the beams, the loads and the support conditions, the analysis of the steel structure can be performed. The detailed design input is given in Appendix I.6. In the output, 12-Build provides the most economic profile type that can be used and the maximum deflection in the QP load combination. For the beams and columns supporting the HCS in L01 or L02, profiles of the type HEA as well as HEB are chosen depending on the magnitude of the loads. An example of the output for beam 1 is shown in Figure 3.21.

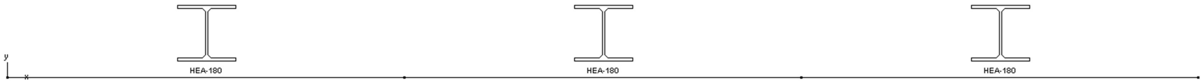


Figure 3.21: Determination of steel profile type for beam 1 in 12-Build

Subsequently, a similar calculation can be done for the steel columns supporting the beams. The loads on these columns can be derived similarly to the calculations of the loads on the concrete columns. As for the beams, 12-Build provides the most economic profile type that fulfils the necessary ULS and SLS requirements. Furthermore, a buckling check is performed for the columns which gives the ratio of the acting load to the maximum buckling capacity of the profile.

To take into account connection components between columns, beams and slabs, an additional amount of material must be calculated for timber and steel structures. For concrete, on the other hand, the connection could be realised directly without additional material. No detailed calculation of the connections will be executed, but some general assumptions are made to be able to quantify the additional amount of steel bolts and plates required for connections and to stiffen the nodes. It is assumed that for each beam, steel plates are used with a thickness of 1 cm and an area equal to twice the outer cross-section of the column and twice the outer cross-section of the beam comparable to what is indicated in Figure 3.22.

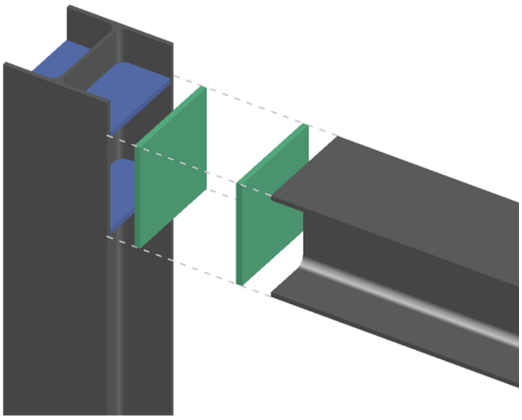


Figure 3.22: Illustration of stiffeners (blue) and connection plates (green) for connection between steel beam and column

3.4.2.3 Glulam frame

To calculate the glulam frame the online software Calculatis of Stora Enso will be used, now using elements of the types 'Sylva Beams' and 'Sylva Columns'. The same beams will be calculated as shown in figures 3.18 and 3.19, but each span will be considered an isostatic beam due to the fact that the columns extend over multiple storeys while the beams are interrupted between each pair of columns. Additionally, for glulam beams the self-weight has a less determining value as shown in Figure 3.23. The more detailed design input is comparable to that of the CLT slabs and can be found in tables A.14 and A.15 in Appendix I.7. It is chosen to work with material class GL 24h which is a commonly used quality of glulam.

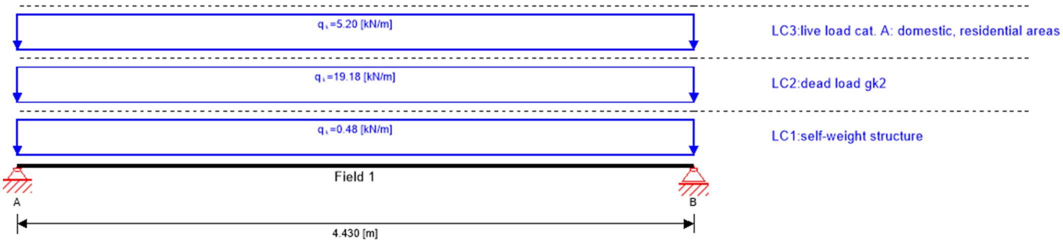


Figure 3.23: Sketch of geometry and supports of one span of glulam beam 1 with corresponding loading

For the beams, SLS and ULS checks must be performed comparably to the checks for CLT slabs. In the ULS, the flexural design must be checked and a shear stress analysis must be done to limit the shear stress at the supports. Furthermore, a buckling verification must be performed and a ULS fire check to ensure that the components fulfil the requirements for fire resistance class R60. In the SLS, a vibration analysis is done as for the CLT slabs. For the glulam columns, only ULS checks are determining. In general, the buckling check, being part of the ULS verification, will be the most decisive for the columns.

Finally, the connections between the beams and columns need to be designed. Similarly as for the steel frames, steel plates and bolts are used for the connections. For glulam frames, use will be made of four L-shaped connecting plates to connect each beam to the adjacent columns as shown in Figure 3.24. When comparing the amount of material needed for these connections to the results of [21] shown in Figure 2.9 in Chapter 2, it can be decided that this is a reasonable assumption. In both cases, a maximum of approximately 30% of the total impact of the frame can be allocated to the connection components. Therefore, the impact related to connections will be calculated as 30% of the total impact of the frame. This is a logical assumption because the heavier the frame, the more steel is needed to connect the components.

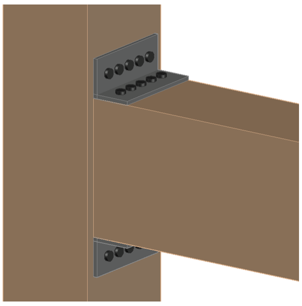


Figure 3.24: Illustration of connection plates (grey) for connection between glulam beam and column

3.4.2.4 Concrete walls

The different types of walls are only calculated for the original configuration L01, with five load-carrying walls as shown in figure3.25. The first type of wall structure that will be examined consists of massive concrete walls. This is not a very common type of supporting structure for mid-rise apartment buildings due to the large load-bearing capacity, even for the minimum thickness, which mostly largely exceeds the acting loads on the structure. The minimum thickness of a concrete wall is governed by the necessity to place longitudinal reinforcement and stirrups which have a minimum bending radius and need to be covered with a sufficient concrete cover. It must be verified whether the allowable stresses are not exceeded when applying the minimum thickness. It is also important to check the slenderness of the walls, which is determined by the ratio of the effective height to the thickness of the wall. Due to the limited line loads, it can be assumed that the basic reinforcement nets will be sufficient for these walls. However, attention must be paid to secondary reinforcement at the location of openings.

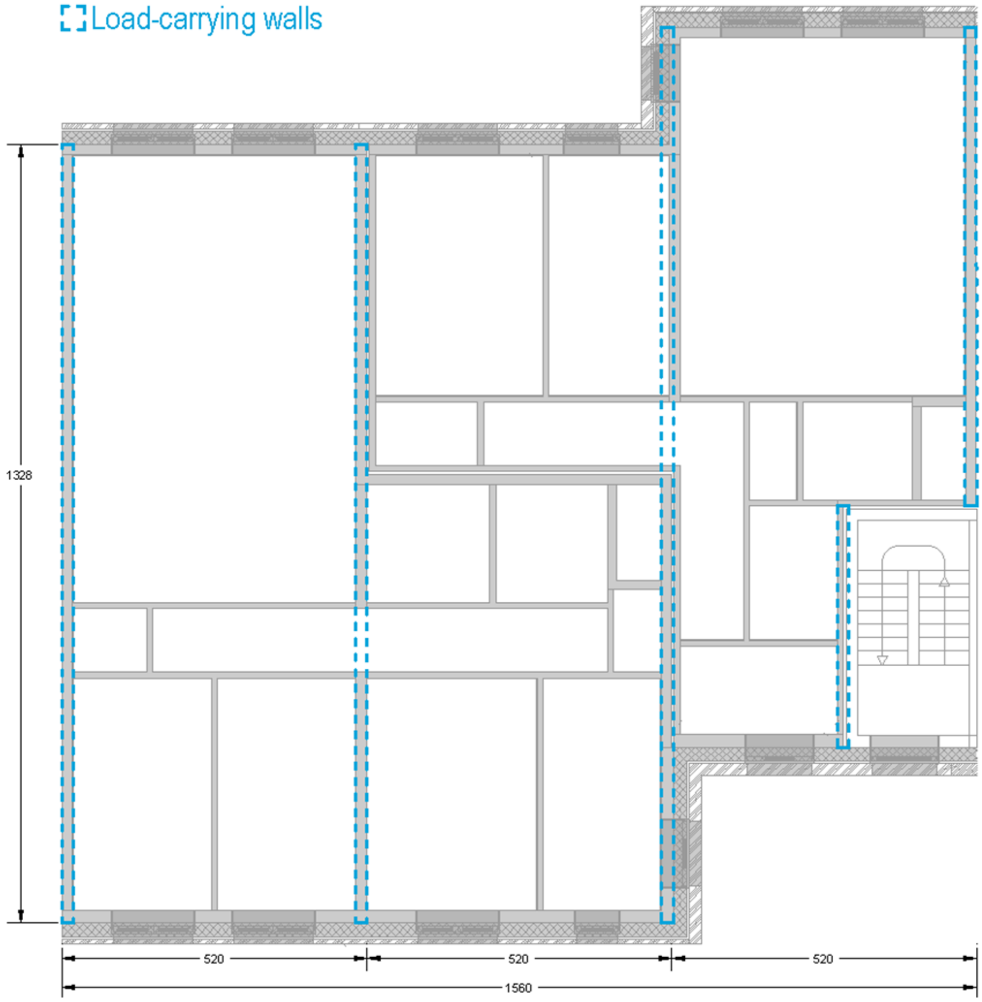
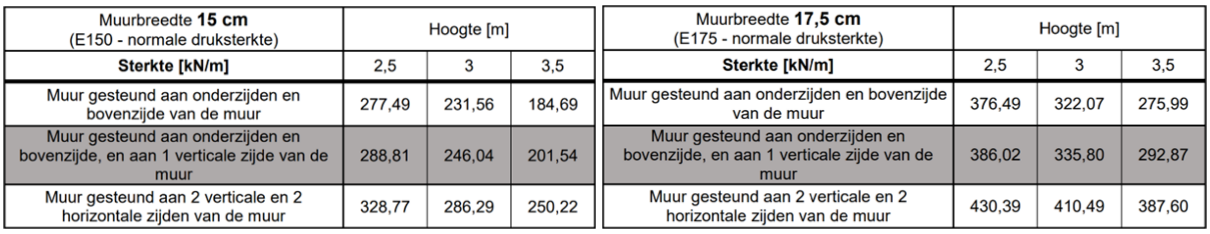


Figure 3.25: Indication of the load-carrying walls in the functional unit - L01

3.4.2.5 Sand-lime brick walls

To determine the necessary thickness and type of sand-lime brick that must be applied, a simple design table will be used which gives the strength of the blocks in kN/m for the ULS as a function of the width and height of the wall and the boundary conditions as shown in Figure 3.26. Similarly to the calculations of the concrete walls, five different walls need to be calculated depending on their loading.



Muurbreedte **15 cm** (E150 - normale druksterkte)	Hoogte [m]		
Sterkte [kN/m]	2,5	3	3,5
Muur gesteund aan onderzijden en bovenzijde van de muur	277,49	231,56	184,69
Muur gesteund aan onderzijden en bovenzijde, en aan 1 verticale zijde van de muur	288,81	246,04	201,54
Muur gesteund aan 2 verticale en 2 horizontale zijden van de muur	328,77	286,29	250,22

Muurbreedte **17,5 cm** (E175 - normale druksterkte)	Hoogte [m]		
Sterkte [kN/m]	2,5	3	3,5
Muur gesteund aan onderzijden en bovenzijde van de muur	376,49	322,07	275,99
Muur gesteund aan onderzijden en bovenzijde, en aan 1 verticale zijde van de muur	386,02	335,80	292,87
Muur gesteund aan 2 verticale en 2 horizontale zijden van de muur	430,39	410,49	387,60

Figure 3.26: Design tables for sand-lime brick, resisting vertical line load (ULS), f_k = 10.2 N/mm², f_b = 20 N/mm²

3.4.2.6 Aerated autoclaved concrete walls

The aerated autoclaved concrete walls will be calculated in the ULS using an Excel sheet based on the extensive method elaborated in Eurocode NBN EN 1996-1-1 (ANB) [83]. To calculate the strength of the wall, a reduction factor Φ is applied to take into account the slenderness and the eccentricity of the loads. Formula 3.3 expresses an upper limit for the acting line load N_{Ed} from which an acceptable thickness t and characteristic wall compressive strength f_k can be determined.

$$N_{Ed} \leq \frac{\Phi\,\dot{t}\,\dot{f}_k}{\gamma_M} = N_{Rd} \tag{3.3}$$

3.4.2.7 CLT walls

The CLT walls are calculated in a similar way as the CLT slabs using Calculatis of Stora Enso. The requirements that must be verified for these walls in the ULS are the (torsional) shear stress, axial force, buckling resistance and fire safety, and for the SLS the horizontal deformation. To fulfil the requirements for fire safety class R60, additional gypsum plasterboards need to be provided on both sides of the walls. These will also be taken into account when calculating the environmental impact of the CLT walls. In general, the ULS requirements are determining the dimensions of these walls. For the lightly loaded walls, the fire resistance requirements can be decisive, while for the more heavily loaded walls, the (torsional) shear stress in the ULS is likely to be the determining requirement.

It is clear that for all wall structures, the ULS will be decisive and it will be assumed that the SLS requirements will automatically be fulfilled.

4

Results

4.1 Structural calculations - Part I

In this section, the results of the first structural calculations will be discussed. More specifically, this involves the results of the calculations of the five slab types for configurations L01 and L04 and the results of the seven types of supporting structures for the structural design with hollow core slabs as floor elements.

Table 4.1 gives an overview of the abbreviations that are used in this chapter to refer to the different slab types and supporting structures. To refer to a specific structural design consisting of a slab-support combination, a code is used of the form ’L01-HCS-C-30/37’ of which the first part refers to the layout, the second part to the slab type and the final parts to the material of the supporting structure and its quality. For the graphs which only show results for one configuration (L01) or one slab type (e.g. HCS), the first two parts can be left out.

Table 4.1: Abbreviations for slab types and supporting structures

Support structure	**Abbreviation**
Glulam frame	GL
Concrete frame	C
Steel frame	S
Sand-lime brick walls	SL
Aerated concrete walls	AAC
Concrete walls	CW
CLT walls	CLTW

Slab type	**Abbreviation**
Hollow core slab	HCS
CLT slab	CLT
In situ concrete slab	ISC
CLT-concrete slab	CLTC
Wide slab	WS

4.1.1 Slab types

In this section, the results of the structural calculations of the different slab types are summarized. Tables 4.2 and 4.3 give a general overview of the main dimensions of the different slab types for L01 and L04 and the total amount of material needed for one functional unit. The slab types are put in order from light to heavy as can be seen in the last column.

Table 4.2: Main dimensions and total weight of different slab types for a total area of 194 m² - L01

Nr.	SLAB TYPE	Area [m²]	Thickness [m]	Volume [m³]	Weight [kg]
1	CLT 180 L5s	184	0.18	33.08	16207
	CLT 200 L5s	10	0.20	2.08	1019
2	CLT 120 L5s	194	0.12	23.30	11417
	Concrete	194	0.06	11.65	27959
	Reinforcement	-	-	0.15	1153
3	Hollow core slab SP150	194	0.20	38.81	68311
	Reinforcement	-	-	0.02	168
4	In situ Concrete slab	194	0.18	34.67	83205
	Reinforcement	-	-	0.28	2196
5	Wide slab	194	0.22	42.45	101887
	Reinforcement	-	-	0.26	2057

Table 4.3: Main dimensions and total weight of different slab types for a total area of 194 m² - L04

Nr.	SLAB TYPE	Area [m²]	Thickness [m]	Volume [m³]	Weight [kg]
1	CLT 280 L7s - 2	184	0.28	51.45	25212
	CLT 200 L5s	10	0.2	2.08	1019
2	CLT 260 L7s - 2	194	0.26	50.48	24736
	Concrete	194	0.1	19.42	46598
	Reinforcement	-	-	0.13	1055
3	Hollow core slab SP200	194	0.25	48.54	85436
	Reinforcement	-	-	0.01	88
4	In situ Concrete slab	194	0.33	63.59	152612
	Reinforcement	-	-	0.48	3798
5	Wide slab	194	0.35	67.48	161953
	Reinforcement	-	-	0.48	3729

It can be perceived that more material is needed for the designs of L04 than for L01. This is a logical result as L04 has larger spans. The results of the further structural and LCA calculations will show whether the environmental impact related to this additional amount of material can be compensated by the smaller amount of columns. The HCS is the only floor type that is also calculated for L03. For this layout, HCS of the type SP 200 can be used, which gives the same result as for L04.

It is remarkable that for the HCS in configuration L04, the amount of concrete needed is almost half as large as that for wide slabs. For L01, this difference is smaller but the weight of the necessary concrete is still 33% smaller. For the in situ concrete slab, less concrete is needed than for the wide slabs. However, the amount of reinforcement is slightly higher.

4.1.1.1 Reinforcement details

All floor types including concrete need reinforcement to resist tensile forces. For the HCS, the reinforcement amount is predefined by the producer. In the in situ concrete layer on top of the HCS and the CLT slabs for the CLT-concrete floor, a reinforcement net of diameter 6 mm and bar spacing 150 mm will be provided over the entire area and additional top reinforcement to resist the tensile stresses will be added above the supports. The resulting quantities of reinforcement steel were displayed in tables 4.2 and 4.3. For the other concrete floors, the reinforcement was calculated as explained in Chapter 3. The detailed results for L01 are shown hereunder. For L04 the reinforcement is comparable but somewhat higher due to the larger slab thickness as was demonstrated in tables 4.2 and 4.3.

Wide slabs - For the wide slabs, four slab parts are distinguished based on Figure 3.14. Each span and support section of these slab parts needs a specific amount of reinforcement at the bottom and top of the slab. The minimum reinforcement is provided by a top and bottom net which are both nets with a diameter of 6 mm and a bar spacing of 100 mm. In some areas, between the support and the midspan section, this reinforcement is sufficient. In other areas, additional bars need to be added (as indicated in tables 4.5 and 4.4). In the central zone of most spans, additional bottom reinforcement needs to be provided, while above the supports, additional top reinforcement is necessary.

Table 4.4: Practical bottom reinforcement wide slab - L01

Bottom reinforcement	**Wide slab 1**		**Wide slab 2**			**Wide slab 3**	**Wide slab 4**
Location	span 1, 3	span 2	span 1	span 2	span 3	span 1, 2	span 1
Theoretical amount [mm²/m]	435	235	416	281	125	363	610
Additional above net [mm²/m]	152	0	133	0	0	80	327
Practical diameter [mm]	6	-	6	-	-	6	8
Area [mm²/m]	170	-	141	-	-	85	335
Bar spacing [mm]	170	-	200	-	-	330	150

Table 4.5: Practical top reinforcement wide slab - L01

Top reinforcement	**Wide slab 1**	**Wide slab 2**		**Wide slab 3**
Location	support 2, 3	support 2	support 3	support 2
Theoretical amount [mm²/m]	438	469	272	628
Additional above net [mm²/m]	155	186	-11	345
Practical diameter [mm]	6	6	8	8
Area [mm²/m]	170	188	0	352
Bar spacing [mm]	170	150	170	143

In situ concrete slab - The practical reinforcement layout for the in situ concrete slab is very similar to the one for the wide slabs. The results of the necessary additional reinforcement are displayed in tables 4.6 and 4.7 for L01.

Table 4.6: Practical bottom reinforcement in situ concrete slab - L01

Bottom reinforcement	**In situ slab 1**		**In situ slab 2**			**In situ slab 3**	**In situ slab 4**
Location	span 1, 3	span 2	span 1	span 2	span 3	span 1, 2	span 1
Theoretical amount [mm²/m]	506	276	484	327	146	423	713
Additional above net [mm²/m]	223	0	201	44	0	140	430
Practical diameter [mm]	8	-	8	6	-	10	-
# bars/m	5	-	6	2	-	6	-
Area [mm²/m]	251	-	302	57	-	471	-
Practical distance [mm]	200	-	170	500	-	170	-

Table 4.7: Practical top reinforcement in situ concrete slab - L01

Top reinforcement	**In situ slab 1**	**In situ slab 2**		**In situ slab 3**
Location	support 2, 3	support 2	support 3	support 2
Theoretical amount [mm²/m]	513	550	318	740
Additional above net [mm²/m]	230	267	35	457
Practical diameter [mm]	8	8	6	10
# bars/m	5	6	2	6
Area [mm²/m]	251	302	57	471
Practical distance [mm]	200	170	500	170

4.1.2 Supporting structures

4.1.2.1 Frames

The dimensions of all frame structures supporting the HCS floor and the total weight of material needed for each type of column and beam can be found in Appendix J. An effort was made to keep the width of the beams as much as possible uniform and equal to 200 mm. The columns always have a length equal to the storey height, while the length of the beams is calculated between the columns. For the concrete frames, the reinforcement of the concrete beams and columns overlaps to ensure a good connection. Therefore the total length is considered for both dimensions.

A summary of the total material quantities for each support type is given in Table 4.8. The values for glulam and steel frames in the column 'weight of reinforcement' refer to the steel used for connections. It can be seen that the concrete frames are approximately three times heavier than the steel and glulam frames. It is also remarkable that the connections for the glulam frame need much more material than those for the steel frame. The LCA will point out which part is decisive for the total environmental impact.

Table 4.8: Summary of material quantities of frame structures for HCS in configuration L01 and L02

Characteristic	**Weight of frame [kg]**		**Weight of reinforcement [kg]**	
Configuration	**L01**	**L02**	**L01**	**L02**
Glulam	5049	6344	710	881
Concrete - C30/37	15114	17796	1004	974
Concrete - C50/60	14555	16245	1011	879
Steel	4157	5538	152	216

4.1.2.2 Concrete walls

Taking into account the parameters mentioned in Chapter 3, a minimum wall thickness of 18 cm must be implemented. For this thickness, two reinforcement nets of diameter 8 mm and bar spacing 150 mm must be provided. At the top and bottom of the walls, additional U-shaped reinforcement bars must be present to close the reinforcement cage. The same diameter and bar spacing can be used as for the nets and a minimum length of three bar spacings per element must be foreseen.

4.1.2.3 Sand-lime brick walls

The design line loads that need to be taken into account to calculate the sand-lime brick walls are shown in Table 4.9. The considered walls have a height of 3.04 m and are supported at the top and bottom. When comparing the total design loads to the resisting line loads in the design tables it can be concluded that for walls 1, 4 and 5, sand-lime bricks of the type E150 with a width of 150 mm can be used according to the ULS requirement. For walls 2 and 3, which are more heavily loaded, sand-lime bricks of type E175 with a width of 175 mm fulfil the ULS requirements. It will be assumed that this choice fulfils the SLS requirements as well. The consumption of adhesive mortar depends on the type of block and equals 2.5 kg/m² for type E150 and 3.0 kg/m² for type 175.

Table 4.9: Loading on sand-lime brick walls and corresponding brick type

Walls	**length [m]**	**perm [kN/m]**	**var [kN/m]**	**tot [kN/m]**	**t [m]**	**type type**
wall 1	13.28	110.00	15.60	171.90	0.150	E150 - normal compressive strength
wall 2	13.28	193.16	31.20	307.56	0.175	E175 - normal compressive strength
wall 3	15.28	193.16	31.20	307.56	0.175	E175 - normal compressive strength
wall 4	4.12	78.28	9.24	119.54	0.150	E150 - normal compressive strength
wall 5	8.16	110.00	15.60	171.90	0.150	E150 - normal compressive strength

4.1.2.4 AAC walls

In Table 4.10, an overview is given of the loads on the different walls and the type of AAC block that fulfils the necessary checks for each wall. It can be concluded that again two types of blocks need to be used, comparable to the case of the sand-lime brick walls. According to [84] these walls consume 17 litres of adhesive mortar per cubic metre of blocks.

Table 4.10: Loading on AAC walls and corresponding block type - L01

Sub walls	length [m]	perm [kN/m]	var [kN/m]	tot [kN/m]	t [m]	type
wall 1	13.28	91.68	15.60	147.16	0.240	C3/450
wall 2	13.28	176.52	31.20	285.10	0.300	C5/650
wall 3	15.28	176.52	31.20	285.10	0.300	C5/650
wall 4	4.12	57.65	9.24	91.68	0.200	C3/450
wall 5	8.16	91.68	15.60	147.16	0.240	C3/450

Table 4.11 gives an overview of the total material quantities for one functional unit for the different types of walls. Regarding the wall structures, again the concrete structure is much heavier than the sand-lime brick walls and AAC brick walls.

Table 4.11: Summary of material quantities of supporting walls for HCS

Wall type	Weight of walls [kg]	Weight of reinforcement [kg]
In situ concrete	70810	865
Sand-lime brick	48329	0
AAC brick	23644	0

4.2 LCA calculations - Part I

In this section, the results of the LCA calculations for the different slab types separately, and for the HCS in combination with the different supporting structures will be discussed. The first part compares the environmental impact of the different slab types based on their material and configuration and evaluates the relative share of the different modules and structural components. Similarly, in the second part, the different supporting structures will be compared. If not mentioned otherwise, the environmental impact of one entire functional unit is always expressed as a single score in mili-points (mPt) which is a weighted average of the impact related to the different environmental impact indicators. At the end of each section, a small evaluation of the results in relation to the studies discussed in the literature study is included. It is important to keep in mind that not all assumptions of these studies (e.g. FU, EIIs, system boundaries ...) are in line with the assumptions of the current study. Therefore, no absolute results can be compared and one must remain critical when evaluating this comparison.

4.2.1 Comparison of slab types

4.2.1.1 Material and configuration

Figure 4.1 gives an overview of the environmental impact of the five different slab types for configuration L01 and L04. The environmental impact is expressed in mPt and subdivided to visualize the share of each composing material. For configuration L01, according to this comparison, the CLT slabs have the lowest environmental impact, followed by the composite CLT-concrete slab, hollow core slabs, in situ concrete slab, and finally, the wide slabs have the largest environmental impact. The weight of the different floors increases in the same order. As a consequence, for this configuration, the weight of the floor slab and the environmental impact are proportional. The higher the weight of the slab, the higher the environmental impact. However, it is expected that this proportionality would no longer hold in case steel slabs would also be considered.

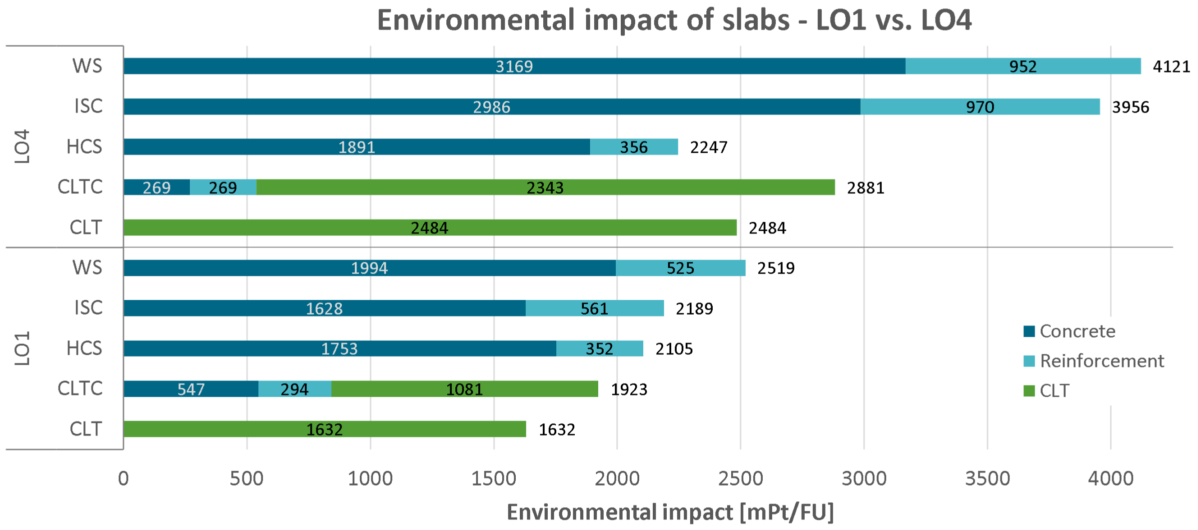


Figure 4.1: Comparison of the single score environmental impact of five slab types for LO1 and LO4

As expected, the environmental impact of the different slabs is larger for LO4 than for LO1 due to the larger spans. However, this increase in impact may be compensated by a decrease in the impact of the frame structure if the difference is not too large. This will be discussed on the level of the entire functional unit further on. The increasing trend that was seen for LO1 is still visible for LO4, except for the HCS which has a much lower impact. Due to the fact that these floors are prestressed, and have hollow cores, it is possible to cover larger spans with less material which results in a lower environmental impact. It can be perceived that the massive concrete floors (ISC and WS) are not suited for large spans (LO4). Due to their heavy weight, a very large thickness is required which comes along with an environmental impact which is almost twice as large as that of the lighter hollow core slabs. For LO1 on the other hand, there is only a difference of 20% in environmental impact between the three concrete floors. The share of the reinforcement in the total impact remains more or less the same and varies from 16% for the hollow core slabs up to 23% for the wide slabs. The environmental impact of the CLT slab and the CLT-concrete slab also increases by approximately 50% from LO1 to LO4. This also confirms that these slabs are more suited for smaller spans, which mainly is a consequence of the vibration requirements.

Verification of results - When comparing the results in Figure 4.1 with some of the studies discussed in the literature study, it seems to be a reasonable outcome. In [30] (LM), it was also found that the environmental impact of a building can be lowered by substituting in situ cast floors with precast concrete floors. In [12] (LM) on the other hand, it was also stated that CLT slabs have a lower impact compared to concrete slabs for spans smaller than 7 m.

4.2.1.2 Share of the different modules

Figure 4.2 shows again the total environmental impact for each slab type for LO1, but now subdivided according to the LCA modules. This chart clearly shows that in general the largest share in the total impact can be allocated to modules A1 up to

A3, representing the impact of the raw materials and the production of the components. This share varies from 81% up to 87% and increases with decreasing total impact. The other modules all represent a much lower share of the total impact.

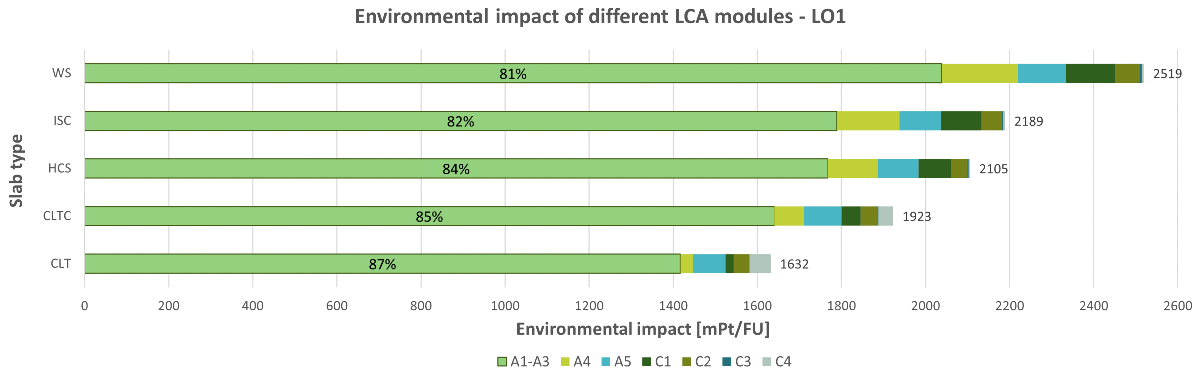


Figure 4.2: Share of module A1 up to C4 in the total environmental impact of thte five slab types

Module A5 is calculated for each slab type in the same way by taking into account 5% material losses during construction. Hence, the share of module A5 is proportional to the total impact of each slab. Modules A4, C1 and C2 are all a function of the weight of the material. As a consequence, these modules vary proportionally to each other and to the weight of the respective slab type and increase from the bottom to the top of the graph. Module C3 is always very small and not visible in this graph because it only represents the on-site sorting of waste. Module C4 only has a visible impact for the slab types containing timber, because of the assumption that wood is incinerated for 95% at the end-of-life. However, because of the assumption of carbon neutrality for biogenic carbon, the biogenic carbon that is released during incineration is not visualized and the share of module C4 is still limited. For concrete floors, one can barely see the impact of module C4. This can be attributed to the fact that 95% of the concrete is recycled at the end of life according to [2] and the impact corresponding to this recycling process is included in module D which is not shown in this chart. Moreover, the impact related to low-grade concrete recycling is always low compared to that of the incineration of timber.

Verification of results - For concrete slabs, these results are again in accordance with what was found in the literature study. In [24] (LM) for example it was shown that the end-of-life stage of concrete only slightly influences the total environmental impact. However, for timber products, the share of module A is much smaller when evaluated based on their GWP [14] (LM). This will be further discussed in Section 4.6.

4.2.2 Comparison of supporting structures

As mentioned at the beginning of this chapter, all supporting structures are primarily calculated taking into account the weight of hollow core slabs as floor elements. This enables an objective comparison between the different support structures before combining them with other slab types. In this section, the support structures will be compared based on their material, type (wall or frame) and configuration. Table 4.12 shows an overview of the configurations that were calculated for each frame type. In Appendix J, an overview is given of the main dimensions and material volumes required for the different supporting structures.

Table 4.12: Overview of calculated column-beam configurations for each frame material

Material	LO1	LO2	LO3	LO4
Concrete C30/37	X	X	X	X
Concrete C50/60	X	X	X	X
Glulam	X	X		X
Steel	X	X		X

As mentioned earlier, for frame structures a contribution is calculated for infill walls because these require additional material to separate the apartments compared to structures with load-bearing walls. If not mentioned otherwise, these walls are assumed to consist of clay bricks. For each frame structure, the area of the walls is calculated as the area between the columns and beams. The impact of the infill walls is always added at the end of each bar in the charts, as such the total impact without infill walls can also easily be compared. Additionally, the contribution of infill walls is hatched to distinguish them from load-bearing walls.

4.2.2.1 Type and material

Figure 4.3 shows the environmental impact of the different supporting structures for the hollow core slab floor in configurations LO1 and LO2 (as shown in Figure 3.10). Each impact is subdivided into the contribution of the composing elements, namely the slab, beams, columns, connection components and (infill) walls. When looking at the frame structures, it can be perceived immediately that the steel structures have the largest environmental impact. This can mainly be attributed to the contribution of the beams. The lowest environmental impact is obtained with a concrete C30/37 frame, although there is barely a difference with the concrete C50/60 frame. The impact of the glulam frame is slightly higher and is mainly influenced by the impact of the steel connections. For these connections, a quite conservative assumption was made (30% of the total impact), but even if this impact would be decreased, the concrete frame would still perform better.

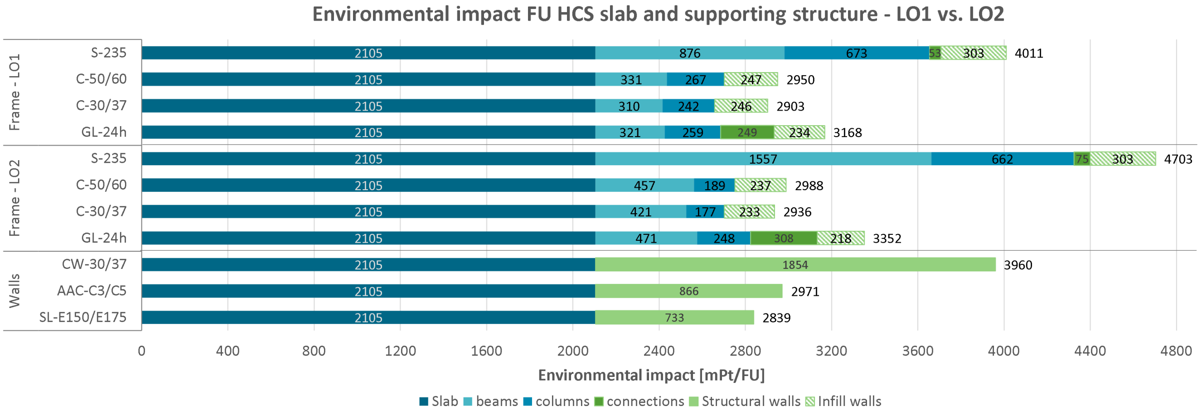


Figure 4.3: Comparison of the environmental impact of concrete, steel and glulam frames and concrete, sand-lime brick and AAC walls for LO1 and LO2

The same conclusions hold for configurations LO1 and LO2, although the total impact is always slightly higher for configuration LO2 compared to LO1. For the steel frame, the difference is quite large due to the increased impact of the beams in LO2. Furthermore, the results do not change relative to each other whether or not the infill walls are taken into account.

The chart shows four types of concrete frames depending on the configuration and concrete class of the beams and columns. For both concrete classes, the total impact is only 1% larger for configuration LO2 than LO1. When comparing the concrete classes for the same layout, class C30/37 has a slightly smaller impact, although the difference is again only 2%. This comparison will be further elaborated in Section 4.2.2.2.

When evaluating the wall structures, load-bearing concrete walls have the largest environmental impact. This can be explained by the fact that the minimum thickness of the walls needs to be respected. In this case, this leads to a wall with a larger load-bearing capacity than structurally necessary and thus also a larger impact. Due to the smaller load-bearing capacity of AAC blocks compared to sand-lime blocks, a larger material volume is required going along with a larger impact. The sand-lime brick walls have the lowest impact of all discussed support structures. Hence, it can be stated that the choice to build the apartment building with sand-lime bricks, was a good choice from an environmental point of view. However, in case infill walls are not considered, the concrete frames would still have the lowest impact.

Verification of results - According to [69], in which sand-lime bricks, a timber frame and a concrete structure were compared, sand-lime bricks are also the most environmentally friendly solution for an apartment building.

4.2.2.2 Effect of column and beam configuration

As explained in Chapter 3, eight different concrete frames are compared for part I of the calculations. The four frame layouts LO1, LO2, LO3 and LO4 shown in Figure 3.10 are each calculated for concrete of class C50/60 and for concrete of class C30/37, leading to a total of eight calculations of which the results are shown in Figure 4.4.

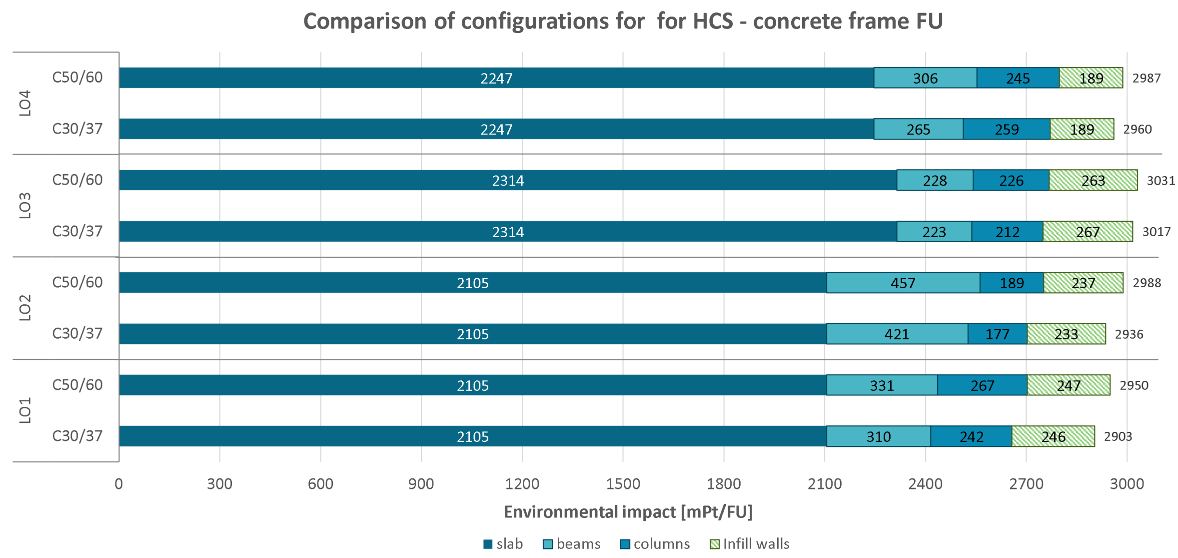


Figure 4.4: Comparison of the environmental impact of the functional unit for structural design with HCS and concrete frame, including infill walls for LO1, LO2, LO3 and LO4

It can immediately be perceived that the difference in total environmental impact between the eight cases is very small. The maximum impact obtained for L03-C50/60 is only 4.4% larger than the minimum impact obtained for L01-C30/37. It can be seen that increasing the span of the hollow core slabs, from L01 to L03 and L04, increases the environmental impact and the relative share of the slab. More specifically, this means that the additional impact due to the larger slab thickness and larger dimensions of the remaining beams and columns can not be compensated by the decrease of the impact of the frame due to omitting the central row of columns and their connecting beam. However, the increase in impact is very limited as mentioned above.

Comparably, related to the beams, it can be concluded that increasing the span slightly increases the environmental impact. In other words, the additional impact due to the increasing height of the beams is not compensated by the decreasing impact due to the smaller amount of columns. However, these are again very small increases of only 1.3% and 1.1% for C50/60 and C30/37 respectively. In Section 4.6, the effect of increasing the beam span will be further examined for other materials too.

Although the differences are small, the C50/60-frame has a larger impact than the C30/37 frame for each configuration. When neglecting the impact of the infill walls between the columns and beams, the same conclusions still hold related to the configurations and concrete classes. In this case too, for each configuration, the total impact is slightly smaller for concrete class C30/37 compared to class C50/60.

Verification of results - In Chapter 2 it was mentioned that according to [29] the optimum concrete strength to minimise the CO_2-equivalent per unit of structural performance is between 50 and 70 MPa which is not in accordance with the results found here. Nonetheless, when looking at the graphs in Figure 4.5 it can be seen that the difference in $CO2$-equivalent between C30/37 and C50/60 is very small, especially for the lower concrete mixes which contain 60% CEM I and 40% PFA binder. Additionally, this comparison does not take into account the reinforcement. It must also be mentioned that due to the relatively small loads considered for the case-study building, the smallest beams have the minimum dimensions of 200 to 300 mm for practical reasons, independent of the type of concrete that is used. Therefore, in this case, the gain of using a stronger concrete type cannot be fully exploited and C30/37 seems to be the more appropriate concrete class.

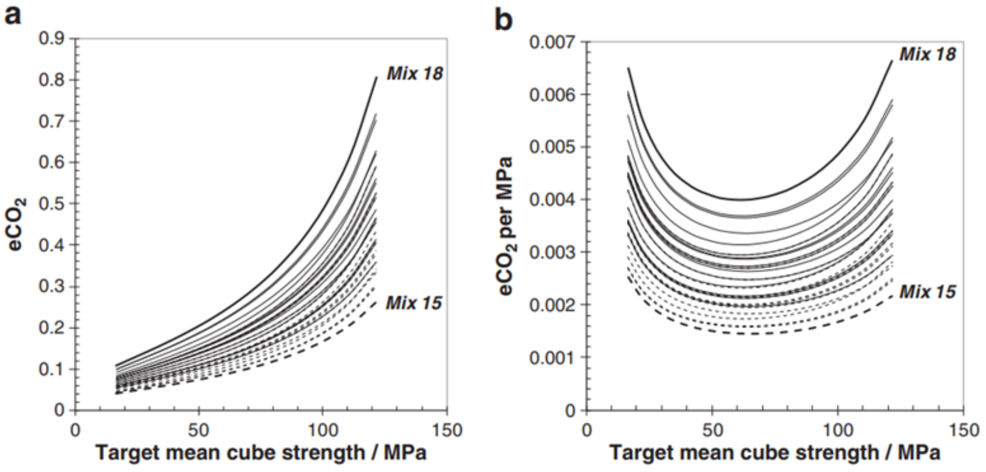
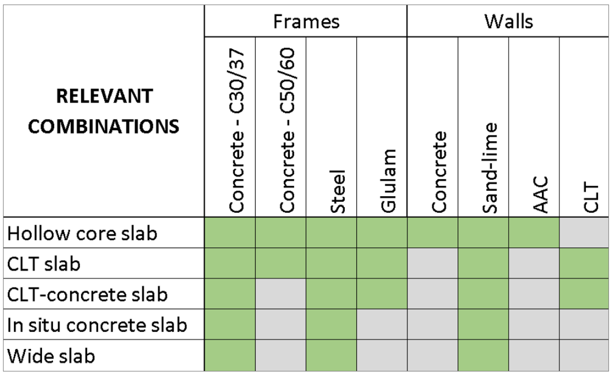


Figure 4.5: Variation of CO_2-equivalent (a) and CO_2-equivalent per unit strength (b) for 32 mix families according to [29]

Taking into account the conclusions above, it can be decided that the lowest environmental impact is obtained for the frame configuration L01 in combination with concrete class C30/37. It must be stressed that the difference in environmental impact between the different concrete frames is small compared to the difference with other materials such as steel. For now, it will be assumed that these results are generally valid, also for the other materials and slab-support combinations. However, the sensitivity analysis in Section 4.6 will further evaluate the influence of the column and beam configuration on the results and will also verify whether these conclusions are also more generally valid for the other materials.

4.3 Slab-support combinations

In the first part of the analysis, all basic types of supporting systems were calculated considering a floor of hollow core slabs. This is visualized in the first row of Figure 4.6. The second part of the analysis covers additional combinations of slab types and supporting structures. In this section, the choice of the additional slab-support combinations will be justified based on common practice and the intermediate results of the calculations of the first part of the LCA for the hollow core slabs. In general, five floor types and nine supporting structures were specified in Figure 3.8. Theoretically, this corresponds to 45 possible slab-support combinations. However, to limit the calculation time, only a set of 24 slab-support combinations will be examined. The respective slab-support combinations are also indicated in Figure 4.6 with the green cells. The red cells, on the other hand, correspond to slab-support combinations that are not calculated. Considering the intermediate results, discussed in Section 4.2, indicating a larger environmental impact for the frames of L02, L03 and L04 compared to the ones of L01, it is decided to calculate the frames in part II of the analysis only for configuration L01 for all materials.



RELEVANT COMBINATIONS	Frames				Walls			
	Concrete - C30/37	Concrete - C50/60	Steel	Glulam	Concrete	Sand-lime	AAC	CLT
Hollow core slab	🟩	🟩	🟩	🟩	🟩	🟩	🟩	⬜
CLT slab	🟩	🟩	🟩	🟩	⬜	🟩	⬜	🟩
CLT-concrete slab	🟩	⬜	🟩	🟩	⬜	🟩	⬜	🟩
In situ concrete slab	🟩	⬜	🟩	⬜	⬜	🟩	⬜	⬜
Wide slab	🟩	⬜	🟩	⬜	⬜	🟩	⬜	⬜

Figure 4.6: Overview of relevant combinations (green) of slabs and supporting structures

The left part of Figure 4.6 shows the different frame types that are considered. For each slab type, a concrete frame and a steel frame will be calculated. Related to the concrete frame, it was decided to calculate the structure of concrete class C30/37 for every slab type because this generally gave a slightly better result than the structure of concrete class C50/60. Finally, the glulam frame will not be combined with the wide slabs and the in situ concrete slab. These floor types are quite heavy and would probably give rise to unpractical dimensions of glulam beams and columns. Moreover, this combination is not used in common practice.

The right part of Figure 4.6 shows the different wall types. After the first part of the calculations, it was decided not to consider concrete walls for any other slab type because of the large impact of these walls as a consequence of the minimum dimensions that need to be met. The same holds for AAC walls, although their large impact is related to the lower bearing capacity. The sand-lime brick walls, on the contrary, will be calculated for every slab type because this is a commonly used design solution for mid-rise (residential) buildings and their environmental impact is in the same order of magnitude as the other structural solutions. Finally, CLT walls are added to the analysis for slab types containing CLT. These walls are in practice only combined with CLT floor structures, among other reasons, because of the ease of connection between walls and floors and their limited bearing capacity.

4.4 Structural calculations - Part II

After deciding on the slab-support combinations, part II of the calculations can be started as was indicated in Figure 3.1. Related to the methodology for the calculations of the second part, nothing changes. For the slab types, no additional calculations need to be performed because the loads and span lengths remain the same. Therefore, the dimensions are as given in tables 4.2 and 4.3. For the supporting structures, the only difference that must be taken into account is the weight corresponding to each slab type. The resulting dimensions and material quantities for all different supporting structures in combination with a specific slab type are given in Appendix J. A summary of these material quantities can be found in Table 4.13. The third column, 'weight of reinforcement', gives the amount of reinforcement for concrete structures and the amount of steel for connections in case of steel and glulam structures. It can be seen that for each slab type, the weights of the different supporting structures are in the same order of magnitude. The steel frame is the lightest supporting structure, while the sand-lime brick walls are the heaviest.

Table 4.13: Summary of material quantities of supporting structures for different slab types - L01

Slab	Support	Weight of frame or walls [kg]	Weight of reinforcement [kg]
CLT slab	Glulam frame	4022	567
	Concrete frame - C30/37	14409	791
	Concrete frame - C50/60	13672	762
	Steel frame	3350	124
	Sand-lime brick walls	44706	0
	CLT walls	14083	260
CLT-concrete slab	Glulam frame	4213	594
	Concrete frame - C30/37	14723	886
	Steel frame	3581	134
	Sand-lime brick walls	48638	0
	CLT walls	15325	260
ISC slab	Concrete frame - C30/37	15575	1011
	Steel frame	4253	171
	Sand-lime brick walls	48638	0
Wide slab	Concrete frame - C30/37	16364	1072
	Steel frame	4253	180
	Sand-lime brick walls	48638	0

4.5 LCA calculations - Part II

In this section, the environmental impact of the entire functional unit will be compared for the 24 design alternatives consisting of a chosen combination of a slab type and a supporting structure. These results will be compared to formulate an answer to the research questions. Based on the comparison of the frame configurations in part I, it was decided to calculate the frame structures only for configuration LO1 which showed the lowest impact. First, the results for each slab type will be discussed separately. Thereafter, the results for different slab types will be compared relative to each other.

4.5.1 CLT slab

As illustrated in Figure 4.6 the CLT floor slab will be combined with a concrete, steel and glulam frame and with sand-lime brick walls. Additionally, this type of slab will be combined with load-bearing CLT walls to get a structural design entirely composed of CLT. The results are shown in Figure 4.7. All graphs in this section show the environmental impact in mPt on the horizontal axis and the type of supporting structure on the vertical axis. The first four structures are frame structures for which masonry infill walls are taken into account between the beams and columns. However, omitting this share of the impact would still give the same ranking for the frames. Again, the steel structure has the largest environmental impact, which can be mainly attributed to the impact of the beams and columns. The concrete frames, on the contrary, have the lowest environmental impact. The glulam frame has a slightly higher impact than the concrete frame, which can again mainly be attributed to the impact of the connections. The share of the components is very much the same as that of the concrete frames.

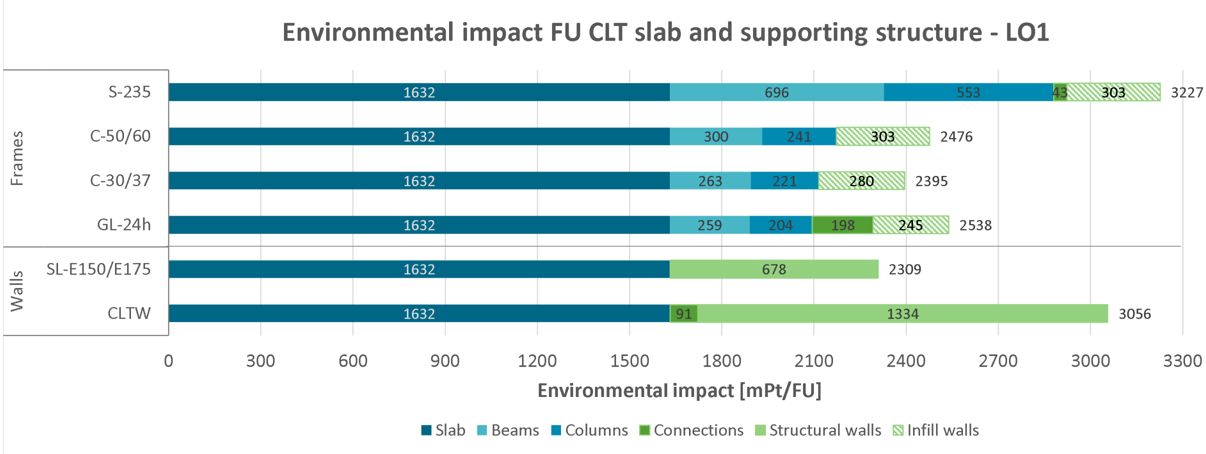


Figure 4.7: Environmental impact of FU for structural design with CLT slab combined with concrete, steel and glulam frame, and sand-lime brick and CLT walls - LO1

When looking at the results for the walls, the sand-lime brick walls have the lowest environmental impact which is even smaller than that of the concrete frame. However, when the infill walls are omitted, the concrete frame, and even the glulam frame, have a slightly lower impact than the sand-lime brick walls. The bottom case, consisting of a load-bearing CLT slab and walls, gives rise to a large environmental impact for the entire functional unit. This can be explained by the large volume of CLT that is needed for these walls and the additional impact of the plasterboards to fulfil the fire safety requirements.

Moreover, the use of CLT walls goes along with a practical drawback. These walls need to be prefabricated with the right dimensions and openings, which decreases the design's flexibility compared to masonry infill walls.

For the glulam and concrete frame structures, the infill walls represent 10 to 12% of the total impact of the functional unit and 24 to 37% of the impact of the vertical structure (columns, beams, connections and infill walls). Therefore, it was tested how much this impact can be changed by replacing the masonry infill walls in a glulam frame with CLT or plasterboard infill walls. The results in Figure 4.8 show that the share of the infill walls in a CLT-glulam structure can only be reduced up to 6% by using plasterboard walls. The use of CLT infill walls, on the contrary, increases the share of the walls up to 20%.

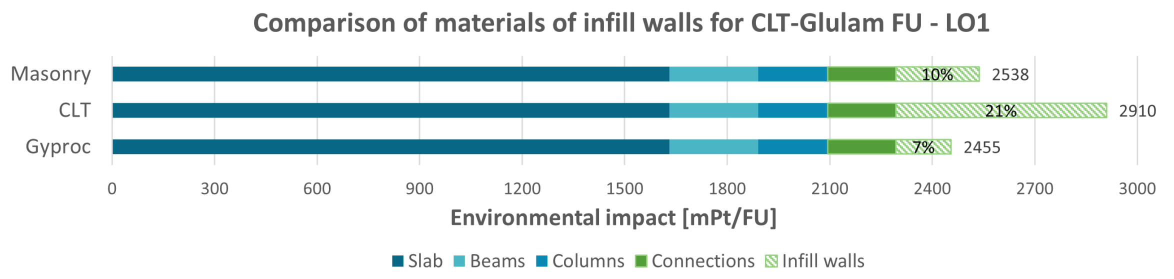


Figure 4.8: Environmental impact of FU for structural design with CLT slab and glulam frame for different types of infill walls

4.5.2 CLT-concrete slab

A very similar graph is obtained in Figure 4.7 for the CLT-concrete slab as for the CLT slab. Again, the steel structure has the largest environmental impact, followed by the CLT walls and the glulam frame. Overall, all impacts are somewhat larger than those obtained for the CLT slab due to the larger weight of the composite CLT-concrete slab.

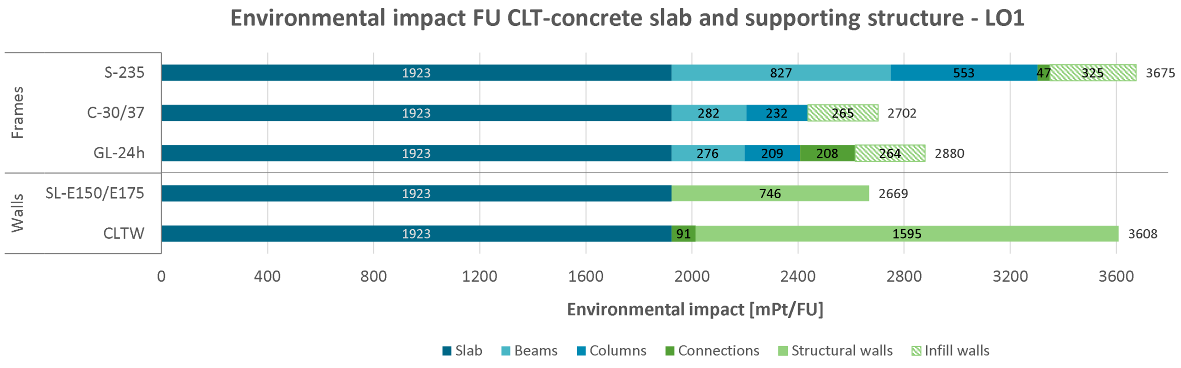


Figure 4.9: Environmental impact of FU for structural design with CLT-concrete slab combined with a concrete, steel and glulam frame, CLT and sand-lime brick walls - LO1

4.5.3 In situ concrete slab

The in situ concrete slab was only combined with a steel and concrete frame and sand-lime brick walls. For the frames and walls supporting the in situ concrete slab, the same trend is again perceived in Figure 4.10. The greatest environmental impact is obtained for the steel structure and the lowest one for the sand-lime brick walls. However, the total impact of the FU with the concrete frame is only 3% higher than the one with sand-lime brick walls and in case infill walls are not considered, the impact of the concrete frame is even 6% lower.

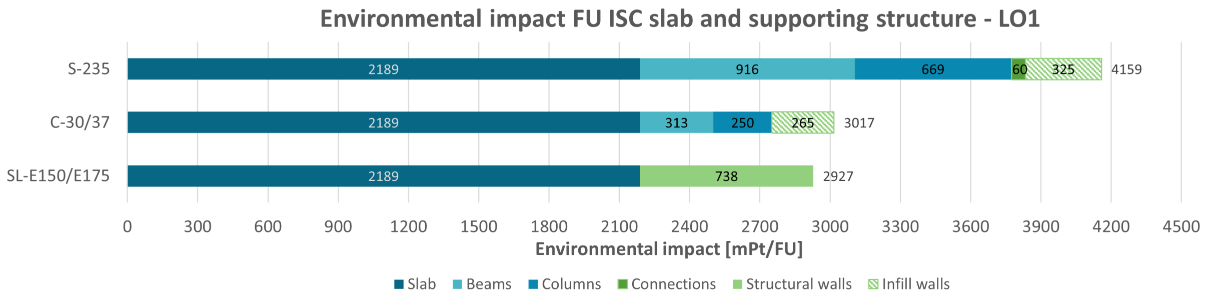


Figure 4.10: Environmental impact of FU for structural design with in situ concrete slab combined with concrete and steel frame, and sand-lime brick walls - LO1

4.5.4 Wide slab

In Figure 4.11 the results of the LCA calculations for the wide slabs in combination with a steel or concrete frame and sand-lime brick walls are shown. These results are very similar to the results above for the in situ concrete slab. The largest difference is represented by the increased impact of the slab. Because the design with wide slabs results in a one-way slab, the thickness must be somewhat larger than for the in situ concrete slab where a limited 2D load spreading was taken into account. This, of course, results in a larger environmental impact.

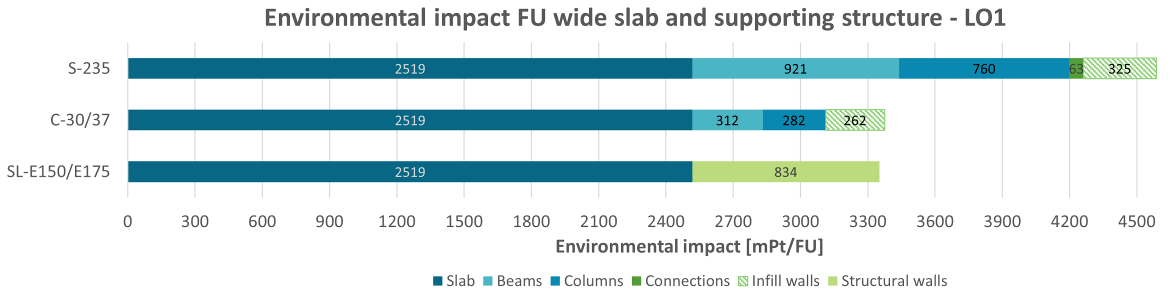


Figure 4.11: Environmental impact of FU for structural design with wide slabs combined with a concrete and steel frame, and sand-lime brick walls - LO1

4.5.5 Overall comparison

Finally, all different structural designs of the functional unit can be compared for configuration LO1 and some general conclusions can be drawn. In figures 4.12 and 4.13, the total environmental impact of the functional unit is shown for all slab-support combinations in configuration LO1, subdivided according to the structural components and according to the LCA modules respectively. The impact of infill walls is shown with a green pattern instead of a full green bar which represents the load-bearing walls. As such it is easier to neglect the impact of the infill walls and make a comparison that more generally represents the load-bearing capacity of a material in relation to its environmental impact.

In Figure 4.12 the relative share of the structural components in the total environmental impact is indicated. In general, it can be perceived that the environmental impact increases from the bottom to the top of the graph for the different supporting structures due to the increasing weight of the slabs they support. When comparing the slab types separately, it can be seen that the relative differences between the support structures are comparable for each slab type. For all slab-support combinations, the largest share is represented by the slab and takes a value between 50 and 75%. The greatest values are obtained for concrete frames and sand-lime brick walls and don't differ much for the various slab types. The same holds for the lowest values which are obtained for the CLT walls and steel frames.

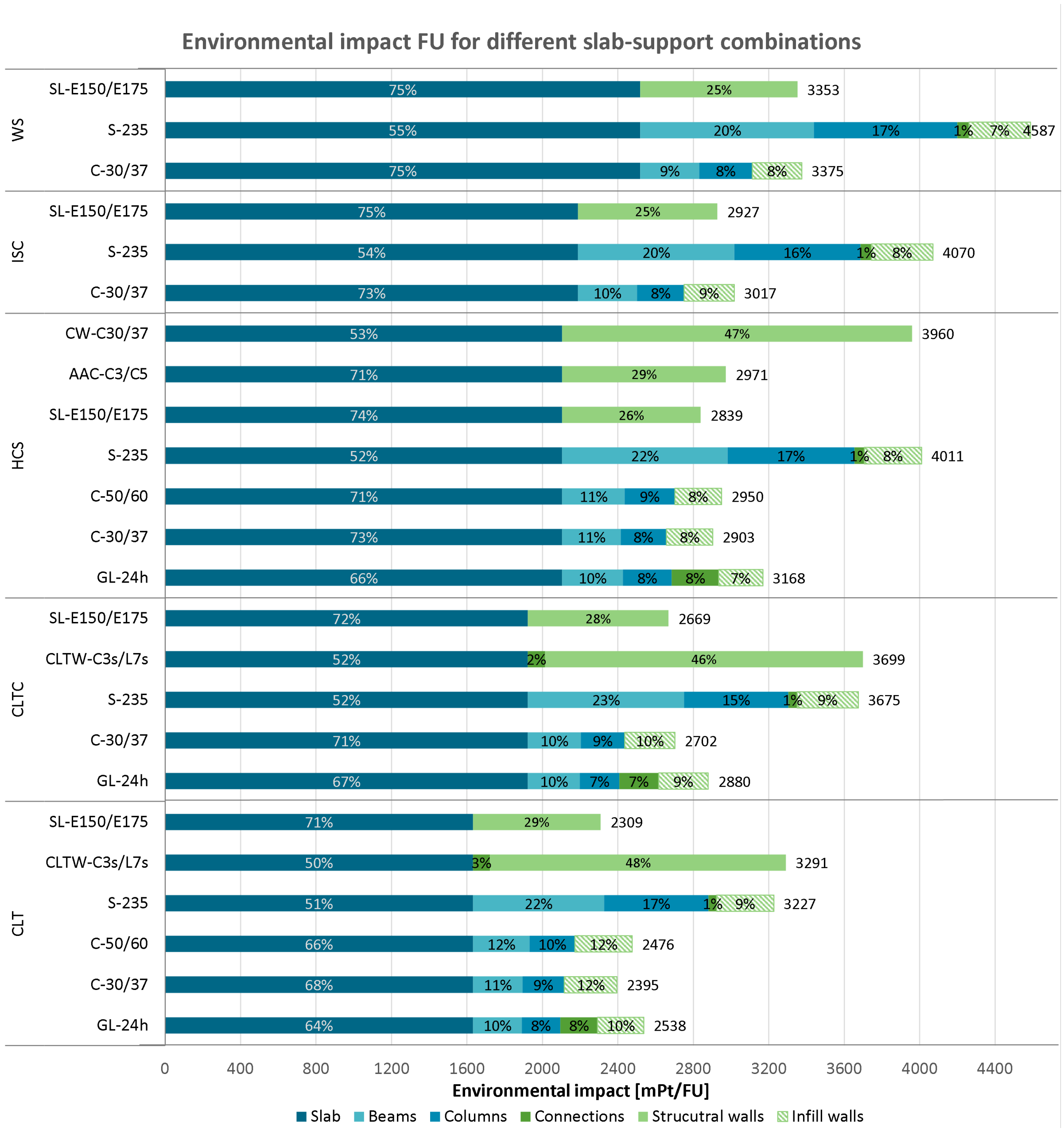


Figure 4.12: Environmental impact of the functional unit for all calculated slab-support combinations, subdivided per component (slab, beam, column, connection, wall) - L01

When looking at the glulam, concrete and steel frames it can be seen that independent of the type of slab that is supported, the relative shares of the beams, columns and connection components remain approximately constant. However, the contributions of the different components differ more for the different types of supporting structures. The beams have the second largest impact with a contribution between 9 and 23% of the total impact and an average value of 14%. Similarly, the columns have an average contribution of 11% and a minimum and maximum value of 7 and 17% respectively. Masonry infill walls determine 7 to 12% of the total impact and finally, connection components are responsible for 1 to 8%.

It is remarkable that the share of the connection components is much larger for the glulam frames. This is a consequence of the large difference in impact between glulam and steel and the quite large amount of steel necessary for glulam connections. Initially, the assumption was made that the connections represent 30% of the total impact of the frame in accordance with the results of [21] (LM). This assumption may have been too conservative because in [21] the environmental impact was expressed in kg CO_2-equivalent which results in a lower value of the impact for glulam structures and thus also a lower value for the impact of the connection components. This will be further investigated in Section 4.6.

It is shown that the columns and beams represent the largest share of the total impact for steel frames. This is a logical result because the impact of steel is much larger than that of concrete or timber products, as a consequence the relative share of the slabs becomes less important when they are supported by steel frames. The impact of steel beams is at least twice as high as that of the respective concrete variant which is in accordance with the results of [34] (LM).

For the CLT slab and the CLT-concrete slab, the largest impact is obtained for the functional unit with CLT walls as supporting structures. However, when taking into account the infill walls, approximately the same impact is obtained in combination with a steel frame. Besides, the glulam frames also have a larger environmental impact than the concrete frames. This result is somewhat contradictory to most results discussed in the literature study, where in general timber structures were depicted as the most environmentally friendly construction method. In [34] for example, according to the impact assessment with the ReCiPe endpoint method, glulam beams combined with any floor are the most ecological solution. This result can be a consequence of the chosen EIIs and the way in which biogenic carbon is treated in this research. However, it must be mentioned too that the glulam frames score only slightly worse than the concrete frames and in case no connection components would be considered, they would even have a slightly smaller impact than the concrete frames. Because in [34] the FU is a beam-floor combination, no connection components were taken into account and this can also explain the different outcomes.

Figure 4.13 shows the same results but without infill walls and subdivided according to the different modules of the LCA. The results for the entire functional unit are quite similar to those of the slabs separately regarding the share of the different modules. Again the largest impact is clearly represented by the production stage which represents 79 up to 90% of the total environmental impact with an average value of 85%. All other modules represent a much smaller average share of the total EI: 5% for A4 and A5, 3% for C1, 2% for C2 and finally 1% for C4. This result is in accordance with [35] (LM). The slab types are put in order from lightest (CLT) to heaviest (WS) from the bottom to the top of the graph. As a consequence, the impact of modules A4, C1 and C2 also increases from the bottom to the top of the graph because the transport (A4 and C2) of the components and the demolition (C1) are both related to the weight of the material. Module C4, including sorting, landfill and incineration, has again only a visible impact for the slab-support combinations that contain glulam or CLT components. As mentioned above, module A5 represents a fixed percentage of the total impact and module C3 has no visible impact.

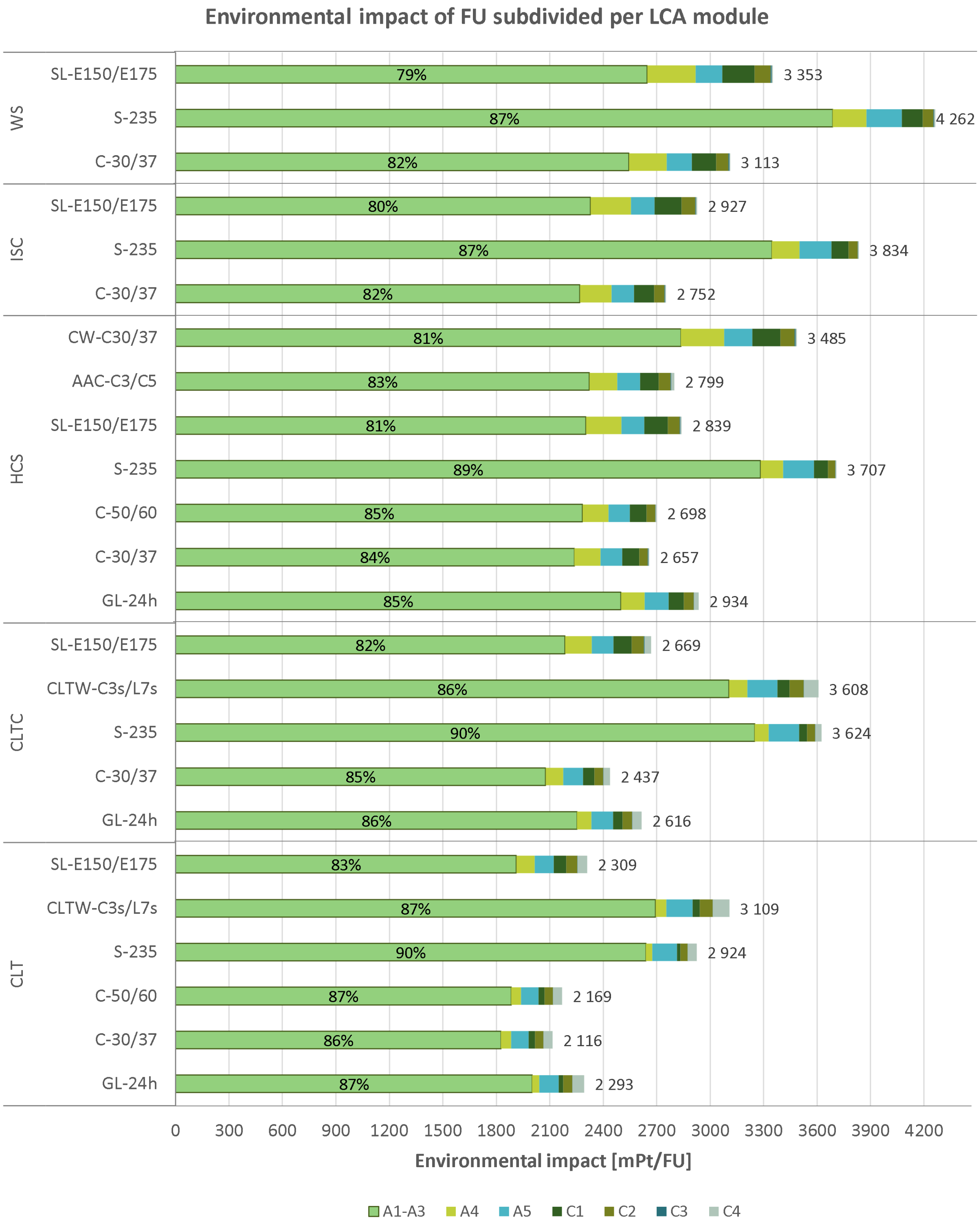


Figure 4.13: Environmental impact of the functional unit (without infill walls) for all calculated slab-support combinations, subdivided per module (A1-A3, A4, A5, C1, C2, C3, C4) - L01

Taking into account the total environmental impact of one functional unit, a ranking of the 24 slab-support combinations can be made from lowest to largest environmental impact as shown in Figure 4.14. The lowest value is obtained for the CLT slab in combination with sand-lime brick walls, while the largest environmental impact is attained for the wide slab supported by a steel frame for which the environmental impact has almost doubled. It is clear that the wide slab gives rise to the highest impact irrespective of the supporting structure. Similarly, the CLT floor slab leads to the functional unit with the lowest environmental impact, irrespective of the type of supporting structure. The gain in environmental impact when replacing a HCS, ISC slab or WS with a CLT slab can be calculated for the different supporting structures and results in average values of 19%, 21% and 30% respectively. It can also be seen that the three worst cases are all composed of a concrete slab and a steel frame. The large weight of the concrete slabs, combined with the high impact of the steel frames leads to these high total impacts.

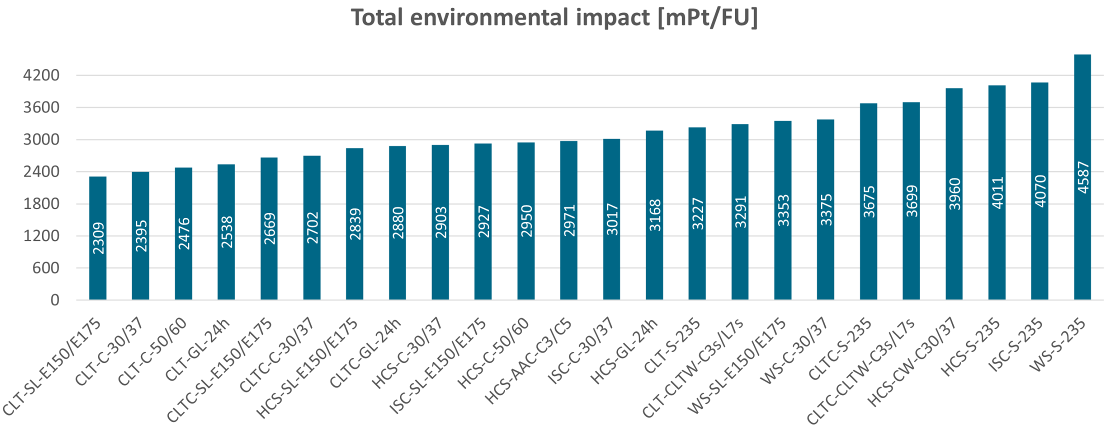


Figure 4.14: Ranking of all slab-support combinations according to total EI (with infill walls) - L01

It can be seen that multiple slab-support combinations result in a total environmental impact of approximately 3000 mPt. All eight combinations, going from HCS-SL up to HCS-GL, differ only 5% at maximum of the value of 3000 mPt. It can thus be stated that one third of the cases lie within a range of 3000 mPt ± 5%. The variability between the different cases is therefore quite limited.

The original design of the case study building consisted of wide slabs supported by sand-lime brick walls. This structural solution leads to a quite high environmental impact of 3353 mPt for one functional unit. A gain of 15% could be obtained by replacing the wide slabs with hollow core slabs which consume much less material to cover the same span.

Verification of results - Finally, the results obtained above can be compared to some results of similar studies that were discussed in the literature study. However, it is important to keep in mind that not all assumptions of these studies (e.g. FU, EIIs, system boundaries ...) are in line with the assumptions of the current study. Therefore, no absolute results can be compared and one must remain critical when evaluating a qualitative comparison.

In [35], 26 different structural floor-beam combinations for residential buildings were investigated. According to this study, an HCS floor supported by concrete beams has the lowest environmental impact, while a wide slab supported by steel girders seems to have the largest impact. This is a very similar result to what was found here, as the mentioned study did not examine a CLT slab. When leaving out the CLT slabs, the FU with HCSs supported by a concrete frame is the frame structure with the lowest impact. However, the order in which the slab types appear in the total ranking is not entirely the same. Light timber floors combined with a steel structure for example score quite well and the difference in impact between the HCS and WS is smaller than found in this study. Furthermore, the variability between the different structural designs is also quite limited in [35]. This is again a comparable result to what was found in Figure 4.14. However, as already mentioned above, in many other studies ([34], [60]) (LM) glulam is found to be the most environmentally friendly material for the frames supporting the slabs. It is expected that this difference can be attributed to the different assumptions in the LCAs such as the impact method and EIIs that are used, the way in which connections are taken into account, the treatment of biogenic carbon etc. The influence of the EIIs will be further discussed in the sensitivity analysis.

According to [50] (LM), replacing reinforced concrete with CLT and glulam in the load-bearing structure of a building can give rise to significant environmental benefits, among which an average reduction of the GWP of 26.5% on the level of the entire building. These results are also calculated excluding the emissions related to biogenic carbon. When calculating the gain in environmental impact by replacing the HCS, ISC slab and WS supported by a concrete frame with a CLT slab or a CLT-concrete slab supported by a glulam frame, the results in Table 4.14 are obtained. It can be seen that the gain in environmental impact for the CLT slab varies from 13% for the HCS up to 25% for the WS, while for the CLT-concrete slab, the gain is only 1% up to 15%. On the one hand, the smaller gains can be attributed to the efficient material use in HCS. On the other hand, it can be caused by the difference in environmental impact indicators because in this study the single score is used instead of only the GWP which is mostly more beneficial for timber products.

Table 4.14: Decrease of EI of FU when replacing a concrete slab and frame with a CLT slab and glulam frame - L01

Slab type	**HCS**	**ISC**	**WS**
CLT slab	13%	16%	25%
CLT-concrete slab	1%	5%	15%

According to [30] the environmental impact of a building can be decreased by 12.2% by replacing an in situ concrete slab with a precast HCS. Table 4.15 shows an overview of the decrease in environmental impact when replacing the ISC slab or wide slab with a HCS floor. On average the decrease that is obtained equals 2.74% for the ISC slab and 13.96% for the wide slab. Although the HCS floor has a 20% lower material use than the in situ concrete slab, only a small gain in environmental impact is obtained due to the larger impact related to concrete class C50/60 compared to C30/37. For the wide slabs, the gain is larger due to the larger thickness of this floor type and corresponds better to the results of [30].

Table 4.15: Decrease of EI of FU when replacing ISC or WS with HCS - L01

Decrease EI	**ISC**	**WS**
C-30/37	3.76%	13.99%
S-235	1.46%	12.57%
SL-E150/E175	3.01%	15.32%
Average	2.74%	13.96%

Summary - Figure 4.15 shows a short recapitulation of all the results that were discussed above. Related to part I, a ranking of the different slab types is given based on their environmental impact as a function of the slab span. The results of the supporting structures for the HCS, calculated in part I, are added to part II of this scheme to compare them to the other slab-support combinations calculated in part II. For part II, a similar ranking of the supporting structures is given as a function of the slab types (including concrete or CLT), for the cases with and without infill walls.

The main conclusion for part I is that the environmental impact of the slabs is proportional to their weight for a 5.20 m span. Due to the more efficient material use in HCS, they are more suited for larger spans and as a consequence have a smaller environmental impact as can be seen in the ranking for the 8.20 m span.

In case the impact of infill walls is taken into account, the results of part II show that the lowest environmental impact is obtained in combination with sand-lime bricks for all slab types. Subsequently, the concrete frames have the lowest impact, followed by the glulam frames and finally, the steel frames have the largest impact. The support types that were only calculated for a few slab types are shown in grey.

In case the impact of the infill walls is omitted, the impact of the concrete frame becomes smaller than that of the sand-lime brick walls. The further ranking remains quite similar. However, it can be noticed that in combination with light CLT slabs, the glulam frames also have a slightly smaller impact than the sand-lime brick walls, while it is the opposite way around for the concrete slabs.

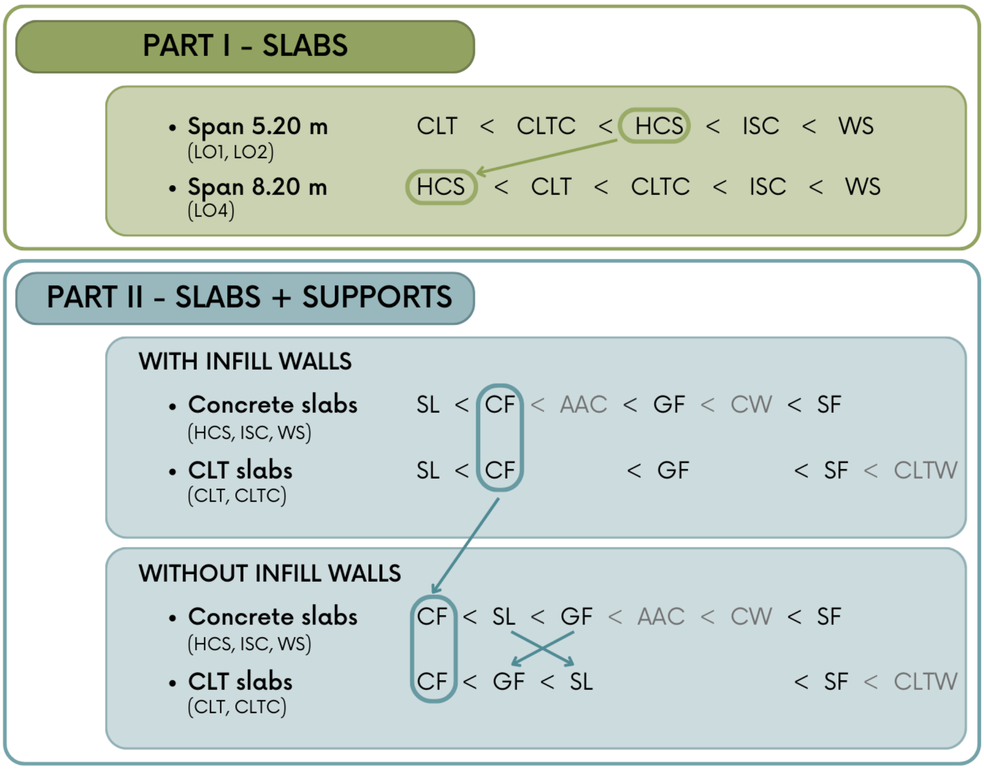


Figure 4.15: Summary of the results of the calculations of part I and part II

4.6 Sensitivity analysis

Because multiple assumptions are made in the LCA and structural calculations, a sensitivity analysis will be performed to check the sensitivity of the results to changes in the assumptions. First, it will be further investigated whether the results obtained for configuration LO1 remain valid with other configurations e.g. with larger beam or slab spans. To do so, additional calculations will be done for the FU in LO4 and for a simplified alternative FU. Thereafter, the importance of the chosen environmental impact indicators and the way in which biogenic carbon is treated will be discussed. Finally, the sensitivity of the results to the inclusion or exclusion of Module D will be examined.

4.6.1 Configuration of the frame

4.6.1.1 Original functional unit

In Section 4.2 some results were already compared for different column and beam configurations to decide which configurations would be further investigated in Section 4.5. In this section, it will be further investigated whether the results and conclusions from the previous sections remain valid when the span of the beams or slabs is increased. This verification is done by calculating the total environmental impact of one FU for LO2 (larger beam span) and LO4 (larger slab span) for different slab-support combinations and comparing the results with the original configuration LO1. In Figure 4.16 an overview is shown of the different configurations that will be compared in this section. The infill walls that were discussed earlier will not be considered for this comparison.

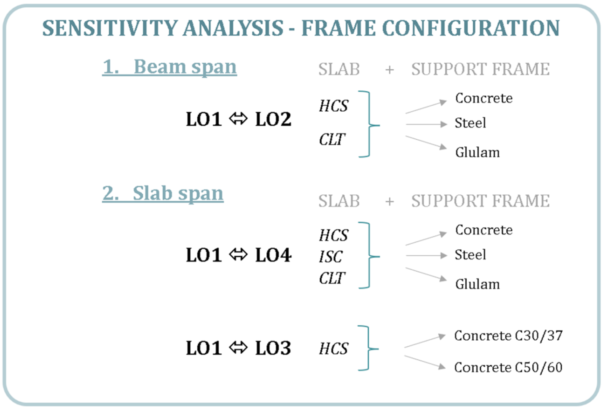


Figure 4.16: Overview of configurations that are compared

Configurations LO1 and LO2 were already compared for the steel, glulam and concrete frames supporting the HCS. In Figure 4.17 these results are repeated and additionally, the same comparison is made for the frames supporting a CLT slab. Related to the span of the beams it can be concluded that increasing the beam span from LO1 to LO2 leads to an increase in the total environmental impact of one FU for all slab-support combinations. However, for the concrete frames, this increase is limited to 1.73% in combination with an HCS floor and to 1.86% in combination with a CLT floor. For the steel structures, on the other hand, much larger increases of 18.68% and 15.40% relatively are observed. It can be seen that the increase in environmental impact is mainly represented by the impact of the beams which need to be heavier due to their larger span. For the glulam frame, the increase is between, 6.78% and 6.36% respectively. All increases are summarized in Table 4.16. The conclusions related to the relative difference in environmental impact between the different slab-support combinations overall remain valid, irrespective of the configuration. It can still be concluded that a steel frame has the greatest environmental impact. The concrete frame always has the lowest environmental impact. The glulam frame has an environmental impact which is 8.4 up to 15.9 % larger than that of the concrete frame.

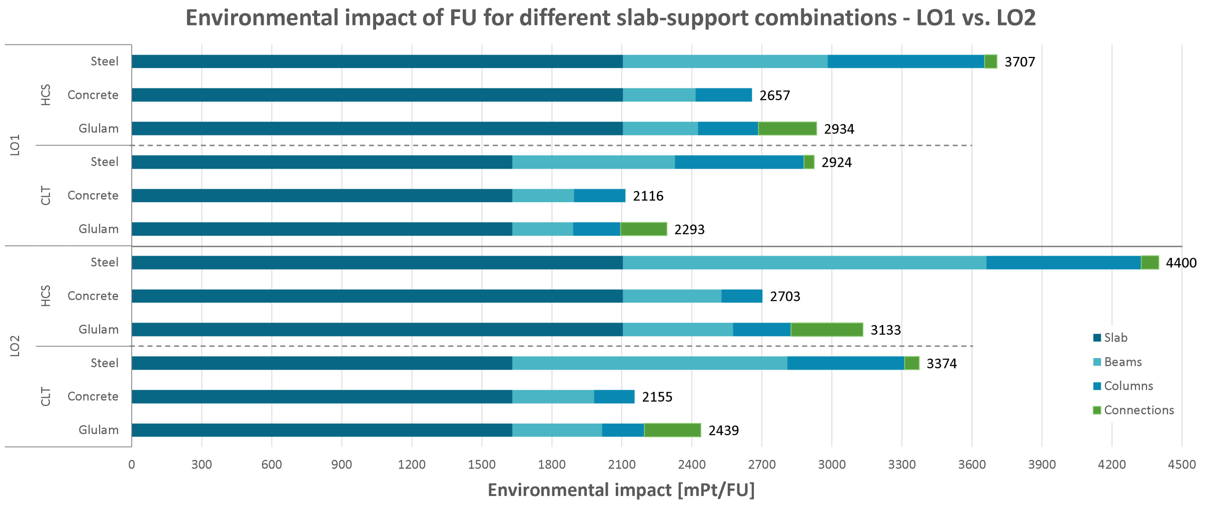


Figure 4.17: Comparison of the environmental impact of FU for different slab-support combinations in LO1 and LO2

Table 4.16: Increase in total environmental impact from configuration LO1 to LO2 for each slab-support combination

Increase total impact	**Glulam**	**Concrete**	**Steel**
CLT	6.36%	1.86%	15.40%
HCS	6.78%	1.73%	18.68%

As indicated in Figure 4.16, configuration LO1 and LO4 will be compared for a FU consisting of an HCS, ISC slab or CLT slab in combination with a concrete, steel or glulam frame. The results are shown in Figure 4.18. For LO1, it can immediately be perceived that the FU with an ISC slab has the highest environmental impact for all three supporting structures, followed by the HCS and finally, the FU with a CLT slab has the lowest environmental impact. However, for LO4 the impact of the CLT slab increased a lot while the impact of the HCS only slightly increased. As a consequence, the total impact of the FU with a CLT slab becomes slightly higher than that for an HCS for all supporting structures. It can thus be concluded that taking into account the environmental impact, HCS are the best option for large slab spans. As a result, the difference in environmental impact between the ISC slab and the HCS is even more pronounced for LO4 than for LO1. This can be explained by the large dead weight of the in situ concrete slab which becomes more determining for larger spans. As a consequence, a thicker slab is needed which drastically increases the environmental impact. The total environmental impact of the FU is larger for LO4 than for LO1 in eight out of the nine cases. In Table 4.17 the percentages representing this increase in total impact are shown. The only exception is the FU consisting of HCS supported by a steel frame. This can be explained by the fact that the impact and the weight of the slab only slightly increase. As a consequence, the beams and columns are only slightly larger and the total impact of the frame decreases because fewer columns and beams are needed in LO4 than in LO1. However, this impact still remains larger than that of the concrete and glulam frames.

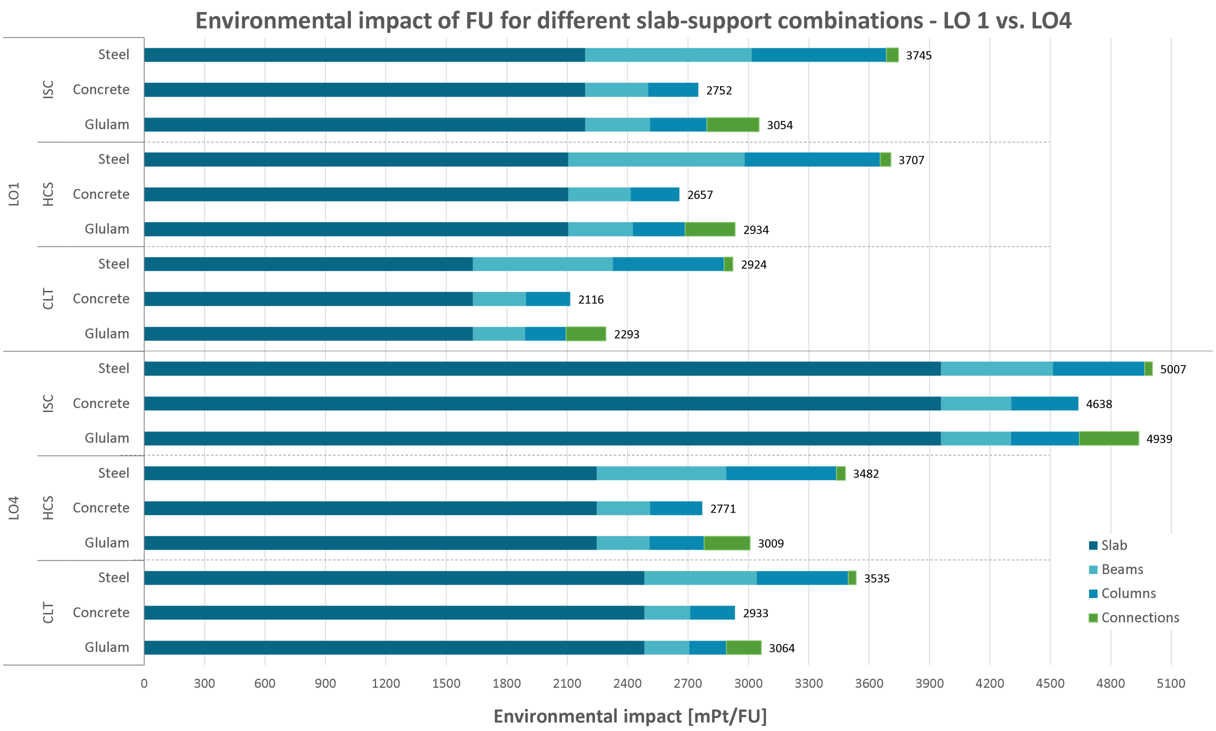


Figure 4.18: Comparison of the environmental impact of FU for different slab-support combinations in LO1 and LO4

Table 4.17: Increase in total environmental impact from configuration LO1 to LO4

Slab-Support	CLT	HCS	ISC
Glulam	33.64%	2.54%	61.73%
Concrete	38.64%	4.30%	68.56%
Steel	20.93%	-6.09%	33.70%

In general, considering the comparison between LO1 and LO2 and between LO1 and LO4, it can be decided that the frame configuration has no influence on the optimal material choice for the supporting structures based on their environmental impact. Besides that, it can also be decided that smaller beam and column spans usually lead to a smaller total environmental impact. Because the slabs represent the largest share of the total environmental impact, increasing the slab span will generally have a negative influence on the total environmental impact.

Verification of results - In [34] it was stated that beams bearing a floor with a 6 m span have a higher impact per square metre than beams bearing a floor with a 4 m span. However, the question was left open whether or not this could be countered by the decreasing amount of columns, which is now disproved. The results of [11] (LM) also confirm that increasing the column spacing increases the environmental impact.

4.6.1.2 Alternative functional unit

Due to the particular shape of the plan, some beams and columns with minimum dimensions needed to be included in the functional unit. Leaving out these parts can give a more general estimation of the environmental impact of the materials in relation to their load-bearing capacity. In this section, an alternative functional unit, derived from the original one, will be examined. The simplified conceptual structural design plan of this alternative functional unit is shown in Figure 4.19. As such it was aimed to find a more unambiguous relation between the load-bearing capacity and environmental impact of different structural materials. The results, shown in Figure 4.20, reveal a very similar outcome as figures 4.17 and 4.18. Again, the steel frames result in the largest environmental impact, while the concrete structures have the lowest impact. The quite large share of connection components for the glulam frames in the total impact leads to a larger impact than the concrete frames. Therefore, it can be decided that the choice of the functional unit will only slightly influence the results as long as the functional unit is chosen on the level of the entire building taking into account slabs, beams, columns and connections.

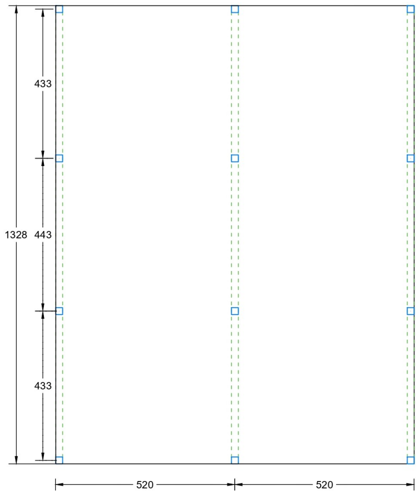


Figure 4.19: Floor plan of the alternative functional unit

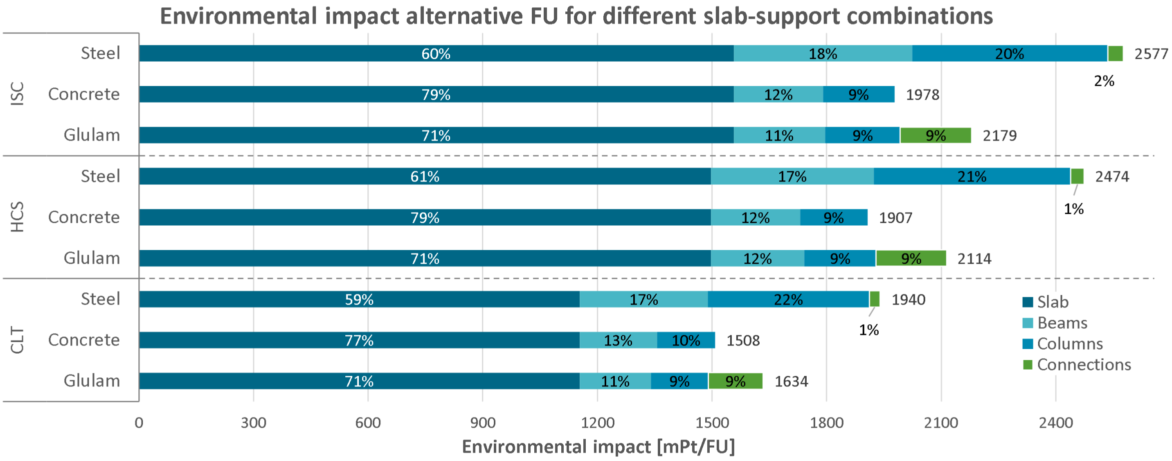


Figure 4.20: Comparison of the environmental impact of alternative FU for different slab-support combinations

4.6.2 Environmental impact indicators

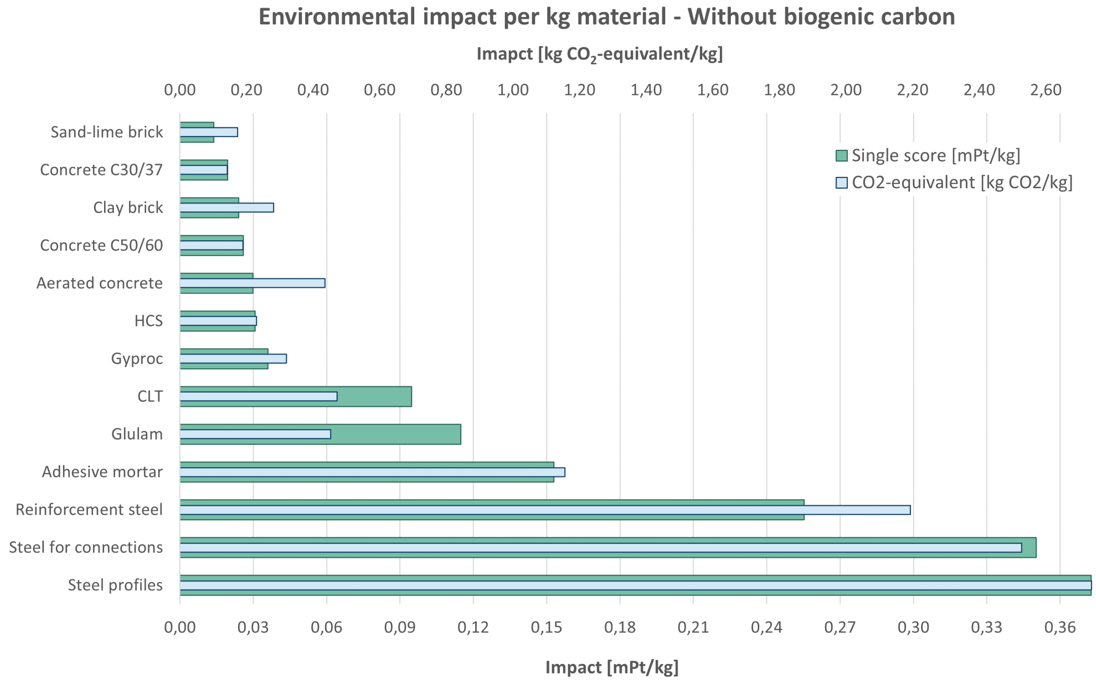


Figure 4.21: EI of building materials expressed in mPt/kg and in kg CO_2-equivalent/kg - without biogenic carbon

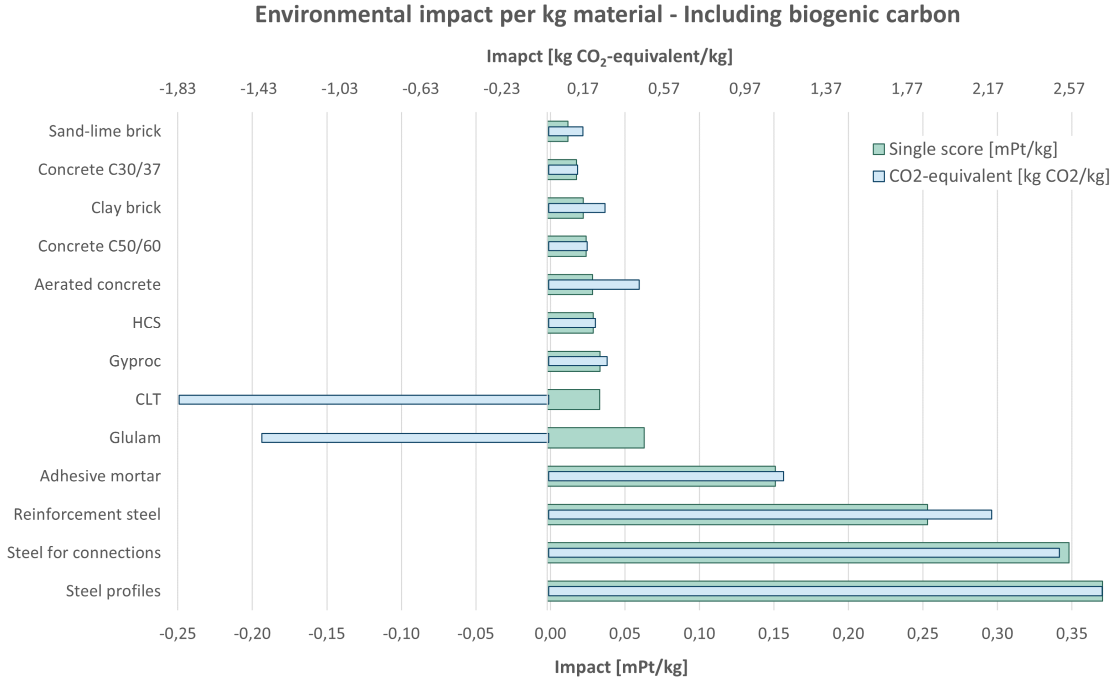


Figure 4.22: EI of building materials expressed in mPt/kg and in kg CO_2-equivalent/kg - with biogenic carbon

Up to this point, the environmental impact (EI) has always been expressed as a single score in mili-points representing a weighted average of the different environmental impact indicators being part of the EN 15804 + A2 impact method. A small adaptation was done to this method, to set the biogenic carbon equal to zero in all modules. As such the assumption of carbon neutrality for biogenic carbon was realized which assumes that the CO_2 that is captured during the lifetime of the trees is released during incineration at the end-of-life. In this section, the effect of the assumptions related to the choice of environmental impact indicators and the way in which biogenic carbon is treated on the results will be further investigated. The graphs in figures 4.21 and 4.22 show the environmental impact expressed as a single score on the bottom axis and as a CO_2-equivalent on the top axis, both per kg of material. To allow easy comparison between the different materials and EIIs, both axes are scaled to the maximum environmental impact which is obtained for steel profiles.

Figure 4.21 shows the environmental impact of the used materials expressed per kilogram when no biogenic carbon is taken into account (as for all the previous results). The light-coloured thin bars represent the climate change impact expressed in kg CO_2-equivalent per kg material on the top axis, while the blue bars represent the single score environmental impact in mPt/kg on the bottom axis. The CO_2-equivalent only represents the climate change impact indicator, often referred to as the global warming potential. Overall the bars scale quite proportional to each other, however, there are some exceptions for which very different results would be obtained when expressing the total impact in mPt or kg CO_2-equivalent.

For all bricks (sand-lime, clay and AAC) it is clear that an environmental impact expressed as a CO_2-equivalent results in a much larger value relative to the other materials. In Figure 4.23 it is shown that the climate change impact indicator represents a large share of the total environmental impact of bricks (32% up to 41%). The largest share is obtained for the AAC (41%), consequently, this material will have the largest relative increase in environmental impact when it is expressed as a CO_2-equivalent compared to when it is expressed with a single score impact.

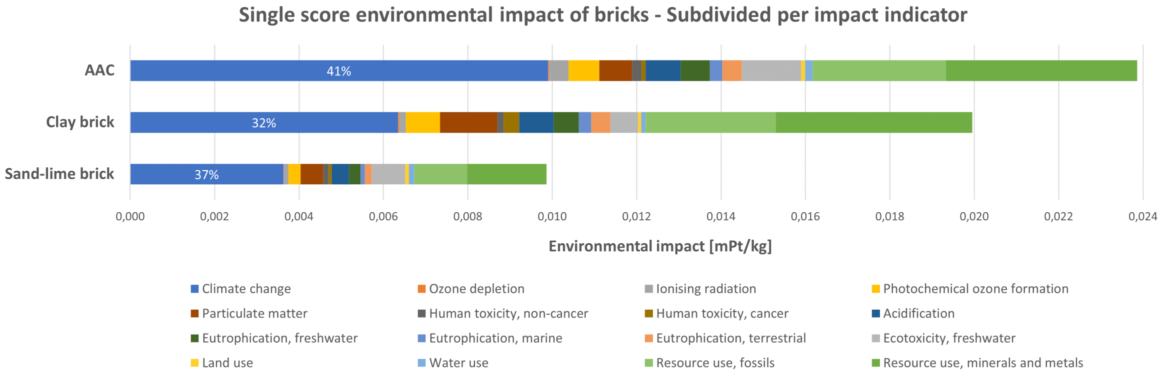


Figure 4.23: EI of bricks per kg material subdivided per environmental impact indicator, without biogenic carbon

Similarly, the environmental impact of reinforcement steel becomes larger relative to the one of steel profiles in case only climate change is taken into account. In Figure 4.24 it is shown that for reinforcement steel the share of the climate change indicator is larger than for steel profiles which explains the larger increase in environmental impact when expressed as a CO_2-equivalent. The larger environmental impact of steel profiles is more spread throughout the different EIIs.

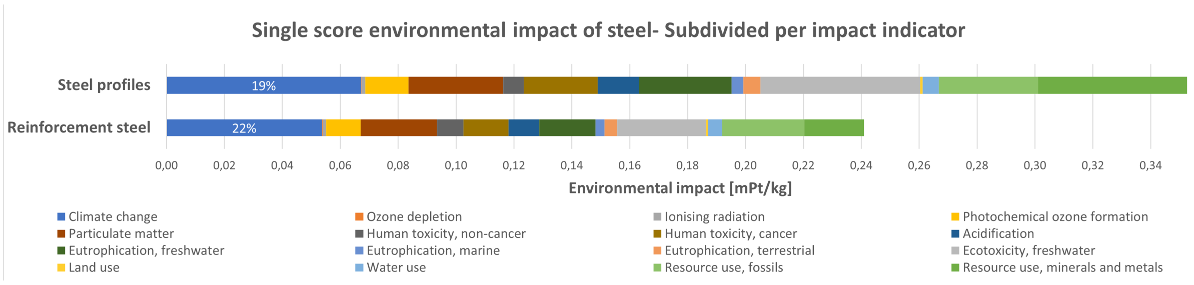


Figure 4.24: EI of steel per kg material subdivided per environmental impact indicator, without biogenic carbon

Because for concrete, the climate change indicator also represents 19% of the total impact (as for steel profiles), expressing the environmental impact as a single score or as a CO_2-equivalent does not influence the total impact relative to that of the steel profiles. This is illustrated in Figure 4.25.

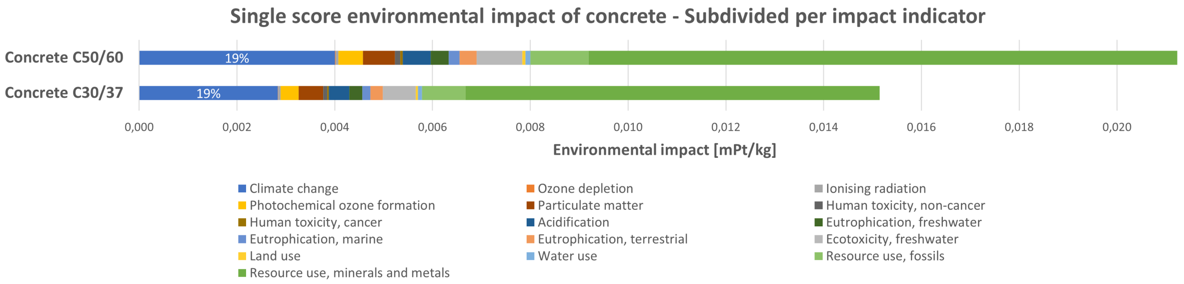


Figure 4.25: EI of concrete per kg material subdivided per environmental impact indicator, without biogenic carbon

The opposite effect is perceived for the timber products (glulam and CLT) which, relatively, have a larger value when expressed as a single score. As shown in Figure 4.26 the most important EII for timber products is land use, while climate change represents a much smaller share in the total impact (10% for glulam and 13% for CLT). As a consequence, the impact decreases when climate change is the only indicator taken into account. The main difference between CLT and glulam is caused by the increased emissions of particulate matter (PM) during glulam production. According to [85], PM is mainly generated during resizing operations such as jointing and finishing. Because the board lamellas that constitute a glulam components are finger-jointing, these require much more resizing operations which results in larger PM emissions.

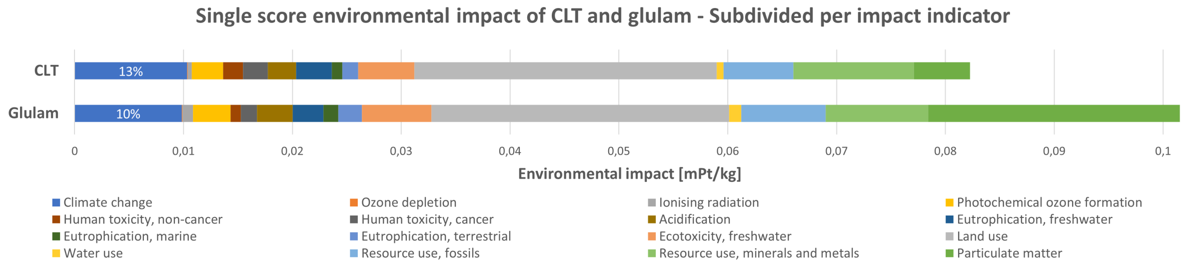


Figure 4.26: Environmental impact of glulam and CLT per kg material subdivided per environmental impact indicator, without biogenic carbon

As indicated previously, the assumption for the impact of the connections of the glulam frame may have been too conservative. Because the impact of the connections is calculated as 30% of the impact of the frame, this value also decreases relative to the impact of other materials, such as steel and concrete, when the impact is expressed as a CO_2-equivalent instead of a single score. When comparing the ratio of the impact of the connections to that of the slab, for a FU with an HCS and glulam frame, a value of 6% is obtained for the CO_2-equivalent and 12% for the single score. This confirms that the assumption may have been too conservative because it was based on [21] in which the results were expressed as a CO_2-equivalent.

In Figure 4.22, the same results are shown again but now taking into account biogenic carbon, which means that the EN 15804 + A2 impact method is used without adaptations. The same conclusions as stated above are still valid in this case. The only difference is that the environmental impact of timber elements is much lower and even negative when expressed as a CO_2-equivalent. This is due to the fact that the amount of biogenic carbon that is taken out of the atmosphere in the production process is larger than the amount of biogenic carbon that is released during the incineration process. This result is not realistic and therefore not further used in this study. For all materials that do not contain timber, including or excluding biogenic carbon does not influence the results.

Overall the results in figures 4.21 and 4.22 confirm the importance of taking into account all environmental impact indicators to make a meaningful comparison between the different types of materials. This is a consequence of the fact that different materials have an impact on different levels of the environment. When taking a closer look into the impacts related to the different environmental impact indicators it can be determined for each process in SimaPro to which impact indicator it contributes the most. As such it can be decided that for timber components the largest impact is related to land use, concrete on the other hand has a larger impact on the resource use of minerals and metals and finally, steel and bricks mainly contribute to climate change.

Figures 4.27 and 4.28 show the environmental impact of the functional unit for the 24 different slab-support combinations expressed as a single score in mPt and expressed as a CO_2-equivalent without taking into account biogenic carbon and subdivided according to the different LCA modules. Based on these graphs, approximately the same conclusions can be drawn as for the environmental impacts expressed per kg of material. Components containing timber perform better according to their CO_2-equivalent than according to the single score environmental impact. FUs using load-bearing walls of AAC or sand-lime bricks, on the contrary, have a larger environmental impact when expressed as a CO_2-equivalent. For concrete structures, the relative impact remains more or less the same. The relative shares of the different modules also remain very similar for both graphs because these are often proportional to the weight of the elements or the total impact.

Verification of results - A comparison is made with the results of [14] in which the climate change impact of timber structures is compared to that of reinforced concrete structures for different calculation approaches. This study was also discussed in Chapter 2. The results show that the climate change impact is at least 34% lower for a timber structure than for a reinforced concrete structure. When comparing the impact in modules A1-A3 of the concrete frames to that of the glulam frames for the HCS, CLT and CLT-concrete slabs, as shown in Table 4.18, an average gain of the climate change impact of 36% is obtained. This result is in line with the results from [14]. However, for the assumption of climate change neutrality for biogenic CO_2-emissions an average decrease of 70% was obtained in [14] which is much larger than the result from the current study. This difference can be the consequence of different assumptions such as whether or not connection components are considered. Without connection components, there is a decrease up to 60% which is much closer to the result of [14].

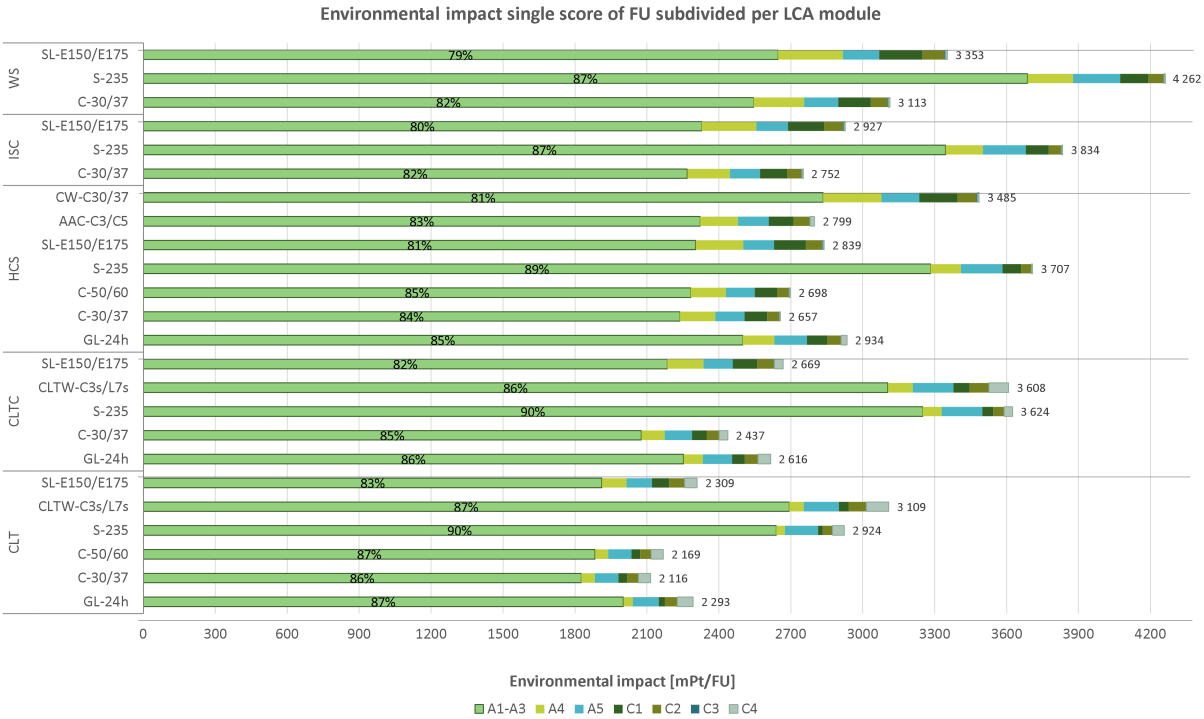


Figure 4.27: Environmental impact of FU (without infill walls) for different structural designs expressed in mPt

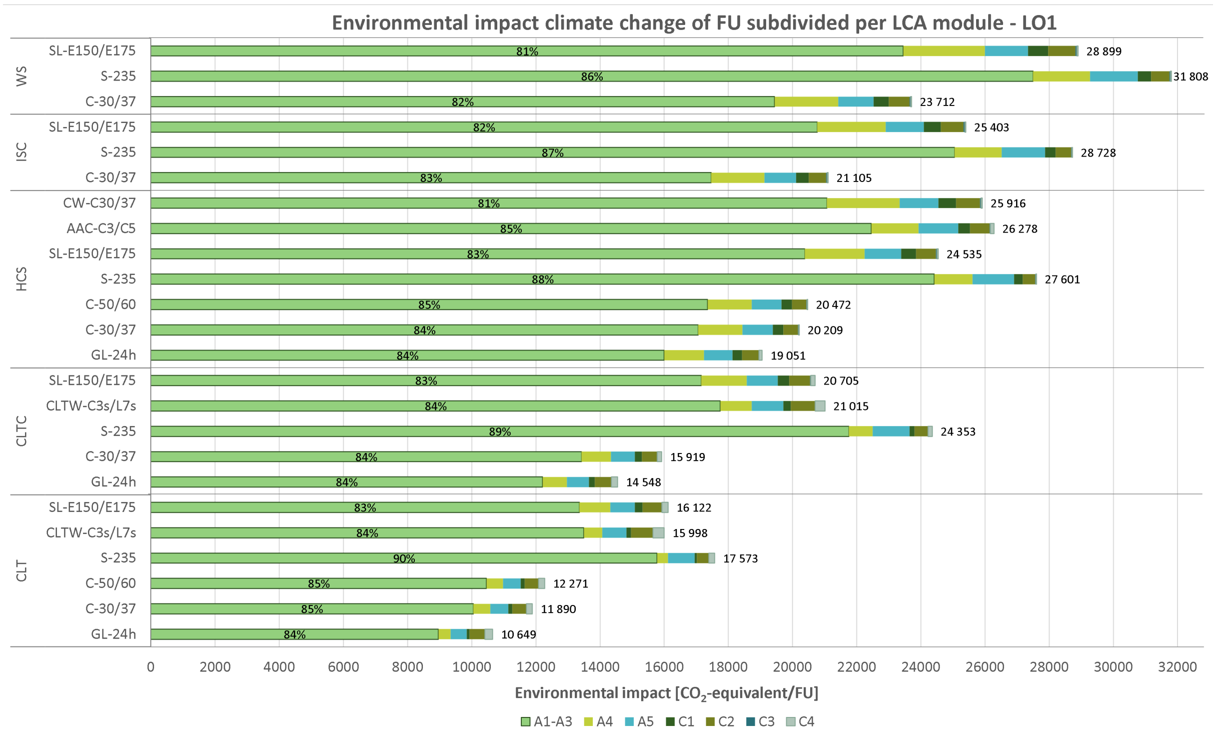


Figure 4.28: Environmental impact of FU (without infill walls) for different structural designs expressed in kg CO_2-equivalent

Table 4.18: Decrease of climate change impact by substituting concrete by glulam frame

Slab type	Concrete frame [kg CO_2-equiv/FU]	Glulam frame [kg CO_2-equiv/FU]	decrease
HCS	3728	2669	28%
CLT	3786	2129	44%
CLT-concrete	3444	2232	35%

Figure 4.29 shows the climate change impact of the different slab types separately, expressed in kg CO_2-equivalent taking into account module D. The general influence of module D will be further discussed in Section 4.6.3. The difference in net impact between the CLT and in situ concrete slab can be compared to the results of [12] in which a cross-laminated timber flooring is compared to a concrete slab flooring based on their CO_2-equivalent over the entire life cycle. The results of this study showed that a CLT slab has a lower environmental impact and is a good alternative for concrete slabs for spans up to 7 m. When comparing the net CO_2-equivalent value over the entire lifetime for a CLT slab to an in situ concrete slab, an increase of 250% is obtained according to [12], while in this study an increase of 277% is obtained. These results are very similar. However, in case the single scores are compared, only an increase of 55% is calculated. This confirms again the importance of taking into account all environmental impact indicators when assessing the impact of a material.

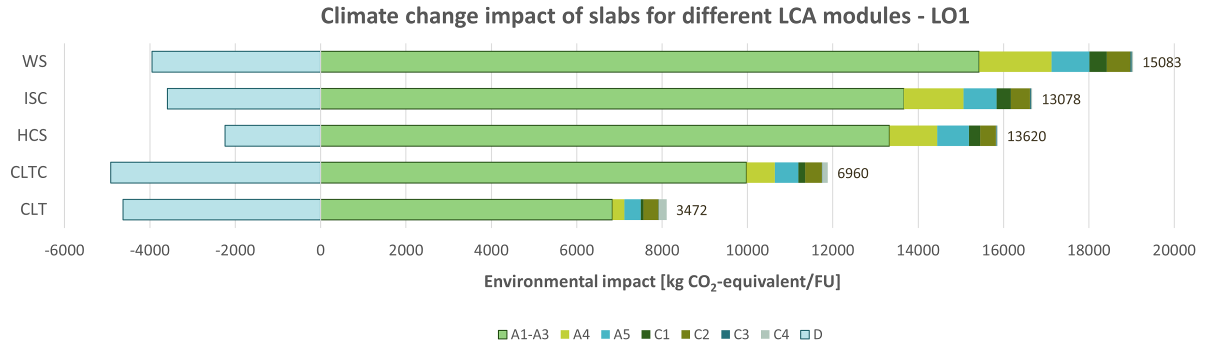


Figure 4.29: Climate change impact of different slab types for one FU expressed in kg CO_2-equivalent

4.6.3 Module D

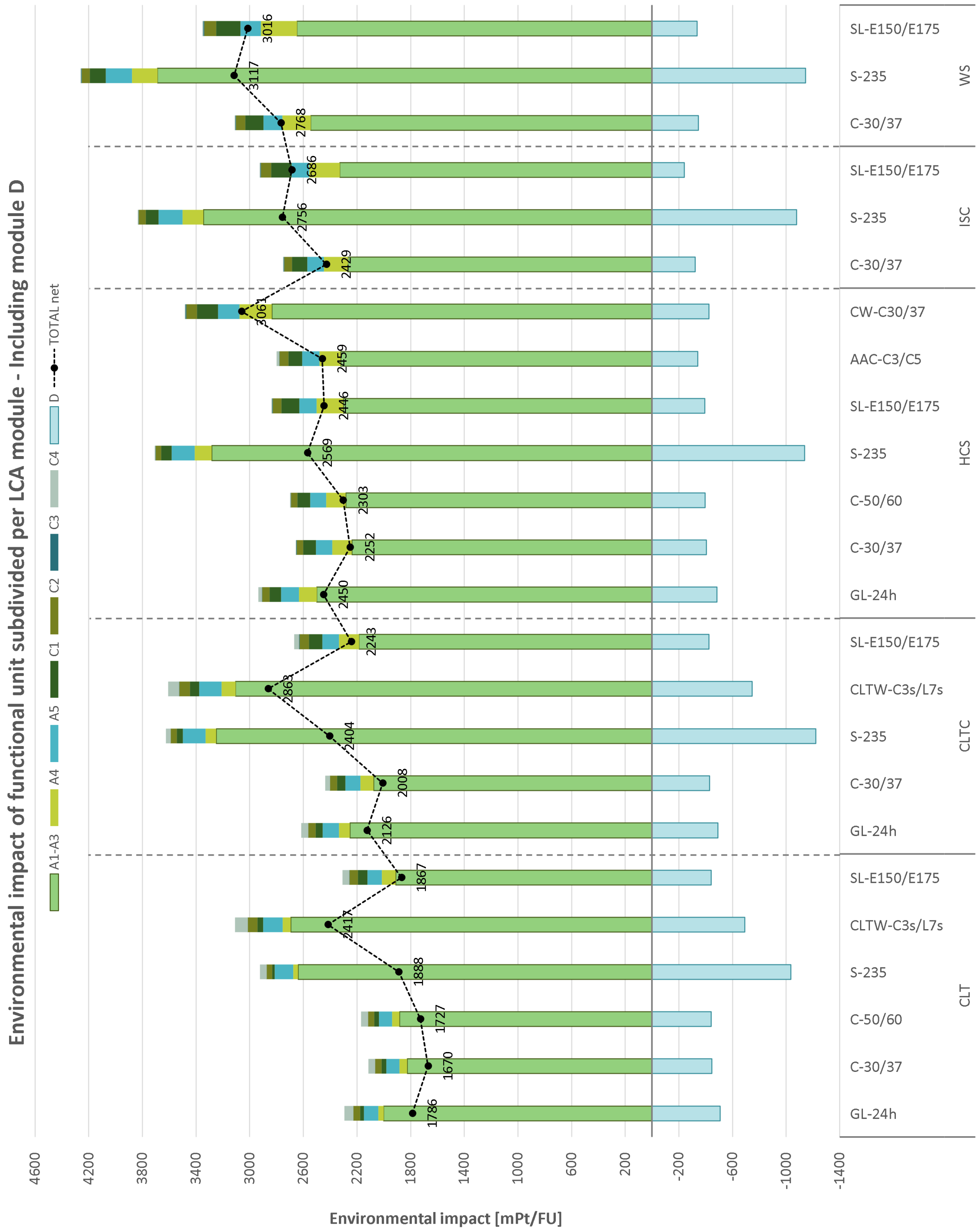


Figure 4.30: Environmental impact of FU (without infill walls) for different structural designs, taking into account Module D - L01

For the LCA calculations up to this point, module D was not taken into account. In this section, the influence of including the additional loads and benefits related to recycling, reuse and energy recovery on the results will be examined. Because the calculations of module D have a large uncertainty, the savings are not directly subtracted from the production stage (A1-A3), but this module is represented by a separate bar with a negative value in Figure 4.30. As such the difference between the impacts within and beyond the system boundaries remains visible. The net impact, when all modules are summed up, is indicated with the black dots in Figure 4.30. The different types of slabs and supporting structures are put in the same order as in the previous graphs.

It is clear that the impact due to module D is not equally proportional to the total impact for each slab-support combination. Especially for steel structures, module D has a quite large impact due to the high-grade recycling process. In the ranking in Figure 4.31, which shows the total impact of each design including module D, it can also be seen that the steel structures shifted some places to the left compared to Figure 4.14. For concrete, on the other hand, module D has a lower impact. As a consequence, the FU consisting of HCS supported by concrete walls has the largest impact of all 24 cases when module D is taken into account. The impact of module D for the glulam and CLT components is in the same order of magnitude as the one for concrete. As a consequence, including module D has no big influence on the relative difference in total impact between glulam and concrete frames. For masonry structures, consisting of AAC or sand-lime bricks, the impact of module D is even more limited than for concrete structures. Consequently, these designs score slightly worse relative to the other ones when taking into account module D.

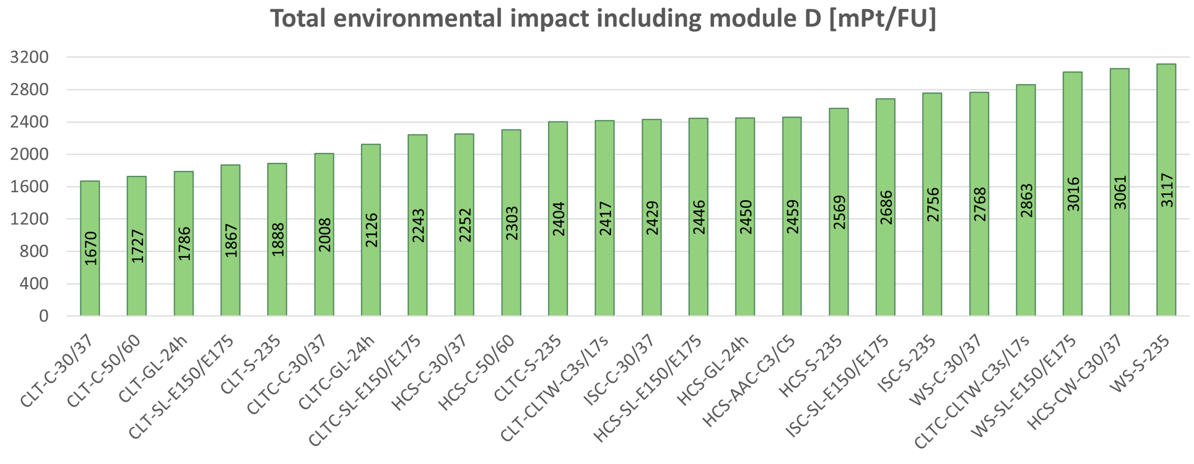


Figure 4.31: Ranking of all slab-support combinations according to total EI (without infill walls) including module D - L01

When module D is not taken into account, the total impact for the CLT and CLT-concrete slabs is approximately the same when supported by a steel frame or by CLT walls. However, when module D is taken into account, a large gain is obtained for the steel frames due to the recycling process, while for the CLT walls, only a small gain is obtained from energy recuperation during the incineration process. Consequently, the CLT walls now clearly become the worst solution from an environmental point of view as shown in Figure 4.30. The other supporting structures for the CLT and CLT-concrete slabs, scale more proportional to one another when module D is included. As a consequence, their position in the ranking with respect to each other remains the same as shown in Figure 4.31. Overall, it can be stated that module D does not negatively affect the position of the designs using a CLT slab in the total ranking. These designs still have the lowest total impact. The largest influence of module D is recognized for the FU consisting of a CLT-concrete slab and a steel frame. Due to the large influence of module D for steel and the limited influence of CLT in module A, this design now has a total impact in the same order of magnitude as the other FUs using a CLT-concrete slab. By adding module D, the total impact is reduced from 3675 mPt to 2404 mPt.

Similarly, it can be seen that the environmental impact of the HCS-steel FU decreased a lot and, as a consequence, shifted some places to the left in the ranking. Moreover, it can be stated that taking into account module D averages out the results for the FU with an HCS. Except for the one with the concrete walls, all FUs have a net impact between 2252 and 2569 mPt, which is only a difference of 12% instead of the initial 28% when module D was not considered.

For the FUs consisting of an ISC slab or wide slab, the inclusion of module D has a similar effect of averaging out the large impact of the steel frame. While initially, the minimum and maximum case of the FU with a wide slab differed 27% (28% for the ISC slab), after including module D this difference is only 11% (12% for the ISC slab).

The next paragraphs will examine the effect of a different end-of-life treatment for timber and steel structures on the final impact. In Figure 4.32 the environmental impact of the FU consisting of a CLT slab supported by glulam beams and columns in L01 is compared for different calculations of module D. For the upper case no impact of module D is taken into account, the second case takes into account 75% recycling and 25% incineration and the last case 95% incineration and 5% recycling.

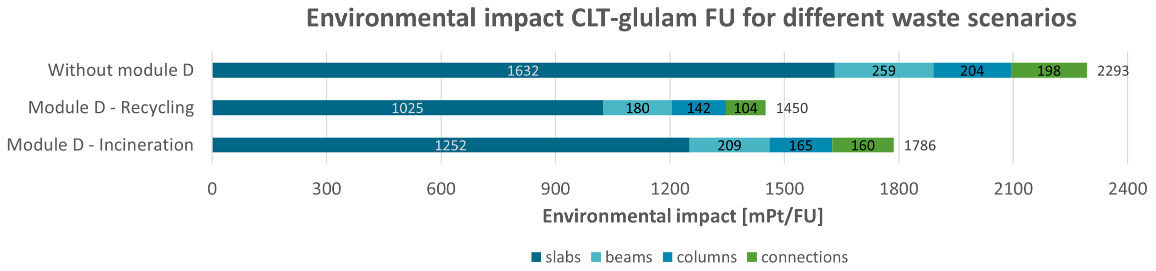


Figure 4.32: Environmental impact of CLT-glulam FU for different calculations of Module D - L01

The results show that a smaller environmental impact is obtained when recycling timber products than in the case of incineration with heat recovery. Recycling leads to a gain of 37% of the total environmental impact while incineration leads to a gain of 22%. The largest gain is obtained for the slab which represents the largest share of the total impact. These results are not completely in accordance with the outcome of [15] in which it was stated that the most advantageous waste treatment for wood is to use it as an energy source due to the exported heat of the incineration process. This difference is probably a consequence of the way in which biogenic carbon was treated in this study and the different EIIs that are evaluated.

Figure 4.33 shows a similar comparison for the functional unit consisting of an in situ concrete slab supported by a steel frame. Initially, recycling steel was considered in module D. However, when the steel structures are designed for disassembly, using bolts in connections, it can be assumed that 80% of the construction steel will be reused. The assumptions for module D when taking into account the reuse of steel can be based on the EPD discussed in the literature study [38]. According to this EPD, a decrease of the environmental impact of 60% can be obtained for 80% material reuse. The graph in Figure 4.33, comparing the different assumptions for module D, again confirms the conclusions of Chapter 2. First, a large gain in environmental impact can be obtained by including module D for steel and secondly, reusing steel without additional processing is the best end-of-waste process. However, the additional gain when reusing steel instead of recycling it is not very large. By applying recycling, the impact of the frame can be reduced by 50%, while reuse reduces the initial impact of the frame by 65% according to these calculations. The gain obtained by recycling the ISC slab is limited.

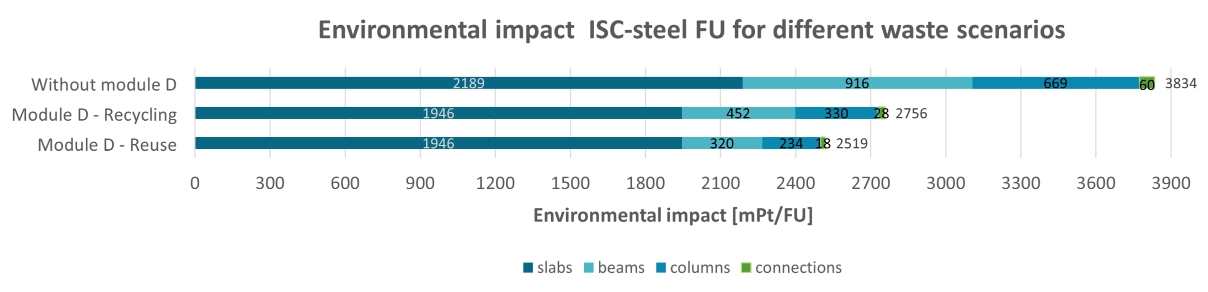


Figure 4.33: Environmental impact of ISC-steel FU for different calculations of Module D - L01

For the sake of completeness, the same results as shown in Figure 4.30 are shown in Figure 4.34 but now expressed as a CO_2-equivalent instead of as a single score. While in Figure 4.30 only a gradual increase in environmental impact is perceived from the bottom to the top of the graph with a maximum of 87%, in Figure 4.34 this increase is much more pronounced and has a maximum value of 455%. These results are more in line with some of the studies discussed in the literature study which focused on global warming potential as environmental impact indicator. In [14] for example, the impact of timber structures was also found to be much lower than that of reinforced concrete structures, while according to [21], steel frames have on average 2.66 times higher carbon emissions than wooden frames. This confirms that focusing on climate change impact instead of a single score taking into account multiple impact indicators, gives rise to a higher variability of the results.

Finally, related to module D, it can be concluded that this module mainly influences the total impact of steel structures because this is the only material for which high-grade recycling is common practice. Because this is also the material to which the largest impact can be attributed in modules A and C, the inclusion of module D leads to averaging out the main results per slab type. Taking into account the obtained results, it can be stated that the more factors are taken into account in the LCA, e.g. more EIIs, and more life cycle stages, the smaller the relative differences between the different slab-support combinations become. However, for this study only a simplified calculation for module D was applied and more elaborate research is necessary to sharpen these conclusions.

Verification of results - The large influence of module D on the environmental impact of steel structures corresponds to what was discussed in [13] (LM). As previously stated, the results related to the different end-of-life treatments for timber structures are in accordance with the results of [50]. Similarly, the results for the comparison between recycling and reusing steel are analogous to the results of the EPD [38]. Additionally, the results of [40] (LM), in which different end-of-life scenarios for steel are compared, confirm a gain in carbon emissions of up to 80% when reusing steel.

In general, considering the results of all three parts of the sensitivity analysis, it can be stated that the assumptions made for the LCA calculations have a more significant influence on the final results than the assumptions for the structural calculations. Alternatively, it can also be stated that the structural calculations entail smaller uncertainties compared to LCA calculations.

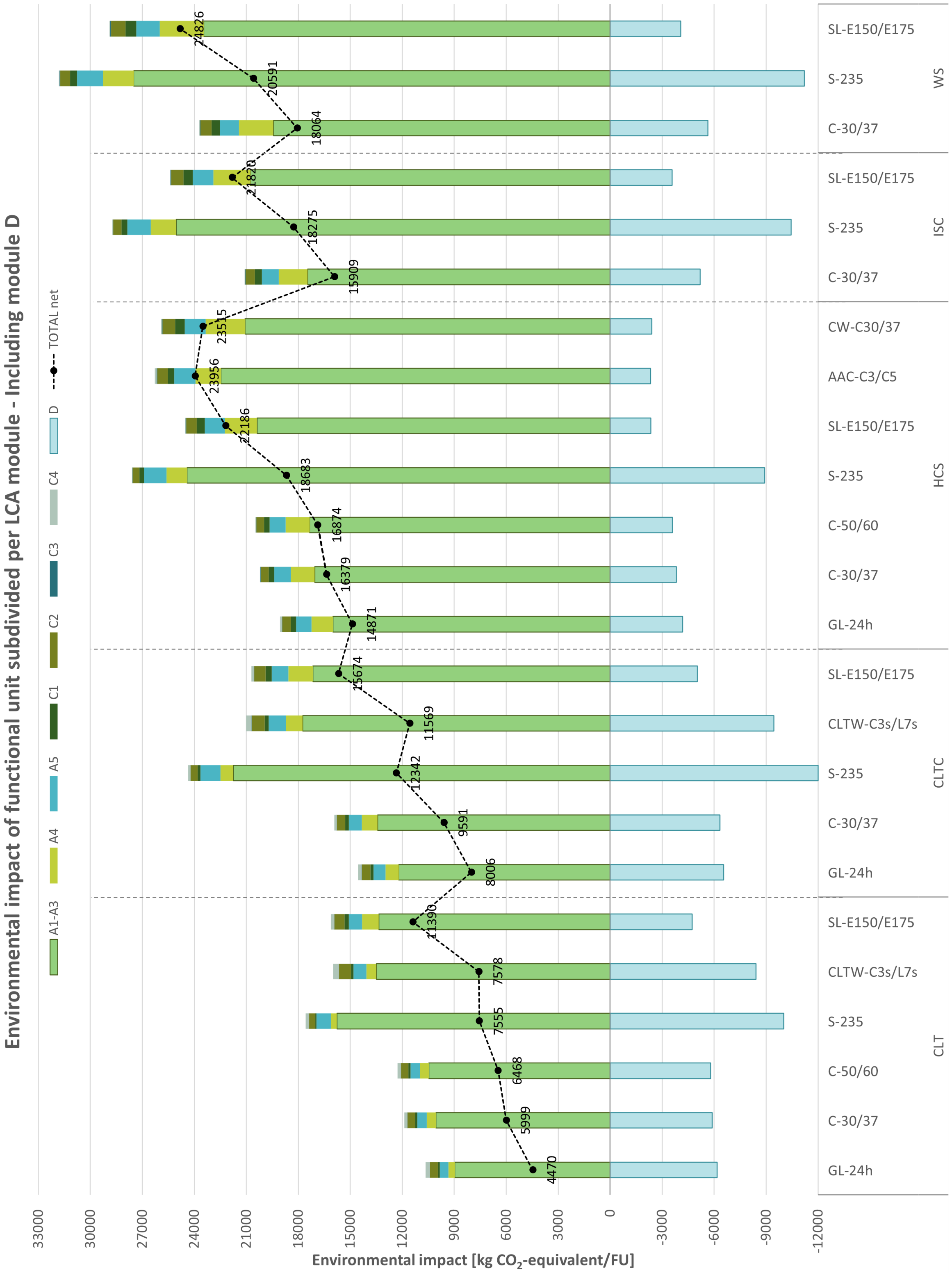


Figure 4.34: Environmental impact of FU (without infill walls) expressed in kg CO_2-equivalent for different structural designs, taking into account Module D - LO1

5

Conclusion

5.1 Conclusion of this research

The present section will formulate an answer to the research questions that were set up at the beginning of this study. The main objective was to determine which structural slab-support combination has the smallest environmental impact based on a cradle-to-grave LCA. Considering the five slab types, it could be decided that the CLT slab has the smallest environmental impact. For the remainder of the slab types, which are all (composite) concrete slabs, a proportionality could be found: the larger the weight of the slab, the larger the environmental impact. Due to the fact that the CLT slab has the smallest weight, the supporting structures supporting this slab have the smallest dimensions and hence the smallest environmental impact. As a consequence, the slab-support combination that has the smallest total impact consists of a CLT slab supported by sand-lime brick walls. However, in case no infill walls are taken into account, the lowest impact is achieved in combination with a concrete frame. The steel frame, on the other hand, resulted in the largest environmental impact. The same results were obtained for the other slab types. However, the heavier the slab becomes the larger the total impact of the FU. In general, the differences in environmental impact between the different slab-support combinations for the FU are smaller than initially expected based on the results from the literature study.

The results were further examined taking into account the share of the different structural components, namely the slab, beams, columns, connection components and (infill) walls. With a total share of 50 to 75 % and an average value of 65%, the slabs represent the largest share of the total impact for all slab-support combinations. Secondly, the beams represent a contribution between 9 and 23% of the total impact with an average value of 14%. For each slab type, the largest value is represented by the steel frame while the smallest value corresponds to the glulam and concrete frames. The same holds for the columns which have an average contribution of 11% (7-17%). Masonry infill walls determine 7 to 12% of the total impact and finally, connection components are responsible for 1 to 8%. The largest impact of the connections corresponds to a glulam frame due to the quite large amount of steel necessary to connect the glulam beams and columns.

Similarly, the share of the different LCA modules in the total environmental impact was examined. The production stage dominates the total environmental impact in all cases and represents a share of 79 up to 90% of the total impact related to modules A and C. All other modules represent a much smaller average share of the total environmental impact: 5% for A4 and A5, 3% for C1, 2% for C2 and finally 1% for C4. Because the impacts related to modules A4, C1 and C2 depend on the weight of the materials, there is quite some variability in the results for these modules.

Besides the production (A) and end-of-life (C) stages, the benefits and loads beyond the system boundaries, represented by module D, were also investigated. This module seemed to have the largest impact on the steel frames due to their high initial environmental impact and high recycling rate by which a large gain can be obtained. For concrete and wood products the impact of module D seemed to be less determining. As a consequence, it could be seen that the results were averaged out. Especially for the ISC slab and the wide slab, the difference between the minimum and maximum total impact changed from 28% to 12% and from 27% to 11% respectively. Another remarkable outcome is that, for CLT and CLT-concrete slabs, the CLT walls have the largest impact when module D is taken into account. Due to the large gain for steel structures, their net impact becomes smaller than that of the CLT walls.

The sensitivity analysis also investigated the influence of the column-beam configuration of the frames on the results of the LCA. In general, considering the comparison between L01 and L02 and between L01 and L04, it could be decided that the configuration of columns and beams has no influence on the optimal material choice for the supporting structures based on the environmental impact. Besides that, it could also be decided that smaller beam and column spans usually lead to a smaller total environmental impact. Because the slabs represent the largest share of the total environmental impact, increasing the slab span has a negative influence on the total environmental impact. Changing the functional unit to a more regular shape did not influence the results.

Finally, the results were compared for different environmental impact indicators to verify whether the choice of the impact indicators is a determining assumption for the LCA results. The initial results were all expressed as a single score in milipoints which is a weighted average of the EIIs according to the EN 15804 + A2 impact method. Because in many studies the EI is expressed as a global warming potential or a climate change impact in kg CO_2-equivalent, the climate change impact indicator was further investigated. When looking at the climate change indicator only, the results seemed to be more optimistic for timber structures than when expressed as a single score. This led to a larger variability in the results over the 24 cases, namely 455% instead of 87% for the single score values. In general, the materials for which the climate change indicator represents a large share of the total impact, get a worse evaluation, while the materials for which this indicator only represents a small share get a better evaluation. As a result, the different types of bricks, which have a large share of climate change impact, have a relatively larger impact according to the climate change indicator separately. Taking into account these results, it can be stated that the single score gives a more realistic estimation of the EI of the functional unit because more different aspects are considered. For timber structures, for example, the land use impact is much more important but not taken into account when only the global warming potential is evaluated. Finally, it was perceived that the results are more sensitive to changes in the assumptions of the LCA calculations compared to changes in the structural calculations such as the frame configuration or concrete class. Therefore, it is crucial to compute the EI as precisely as possible for each case study, including all requisite EIIs and life cycle stages, in order to draw the right conclusions related to the material selection and to facilitate an unbiased comparison among the various materials.

5.2 Perspectives for future research

To finish this study, some perspectives for future research can be given. Related to the structural calculations it would be recommended to calculate the connections more in detail to make a better estimation of the necessary material quantities, especially for timber structures where the connections represent a large share of the total EI. Moreover, instead of working out the calculations for one typical floor level, it would be more precise to actually use the entire building as a functional unit and take into account the foundations and central core as well. For the concrete components, in particular, an optimum between the amount of concrete and reinforcement can be sought that leads to the lowest impact. Additionally, it would be interesting to make the results more generally applicable, by coming loose from the case study building and trying to find a more unambiguous relation between load-bearing capacity and EI of different structural materials. Due to the particular shape of the plan of the FU, some beams and columns with minimum dimensions needed to be included in the functional unit. Leaving out these parts and working with standard dimensions would give a more general estimation of the EI of the different materials. However, it is expected that this will only slightly influence the results as the change in column and beam configuration and the calculations for the alternative functional unit also did not have a large effect on the results. Concerning the LCA calculations, a more correct estimate of the total environmental impact would be obtained in case more project-specific parameters would be taken into account. In this research, for example, transport distances were determined based on the recommendations of TOTEM [20], although site-specific transport distances could have been used. Whenever a generally accepted calculation method for module D would be available, it is also recommended to make a more detailed evaluation of the impact beyond the system boundaries. Another assumption that could be questioned is the lifetime of the structure which is now set equal to 60 years for all materials. Taking into account a smaller lifetime for timber compared to steel would further decrease the benefits of timber structures. However, because the production stage represents on average 85% of the total impact, it is expected that changes in these assumptions will also only slightly influence the total impact of the FU. Finally, it would be interesting to link the LCA calculations to life cycle cost (LCC) calculations. In the current practice, the choice for a specific structural design is mostly based on financial incentives, finding an optimum between both environmental and financial considerations would be an interesting addition to the topic. All conclusions and perspectives for future research are also summarized in Figure 5.1.

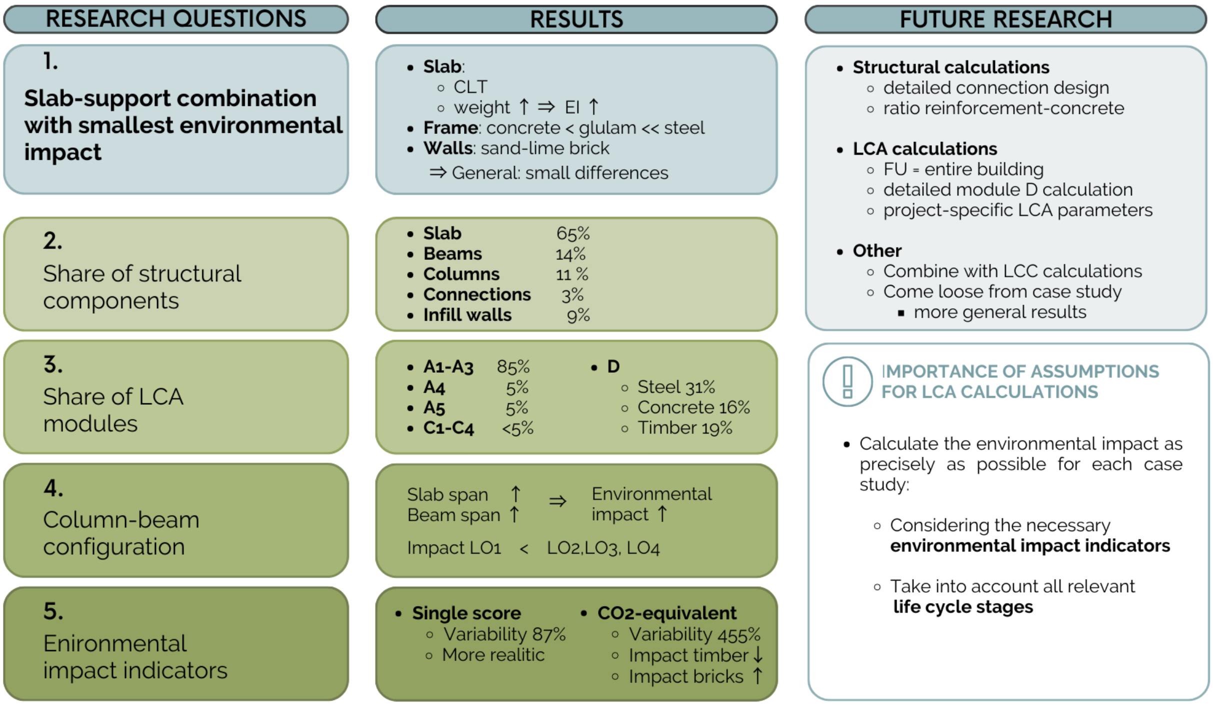


Figure 5.1: Summarizing figure of research conclusions

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Appendices

A Literature matrix

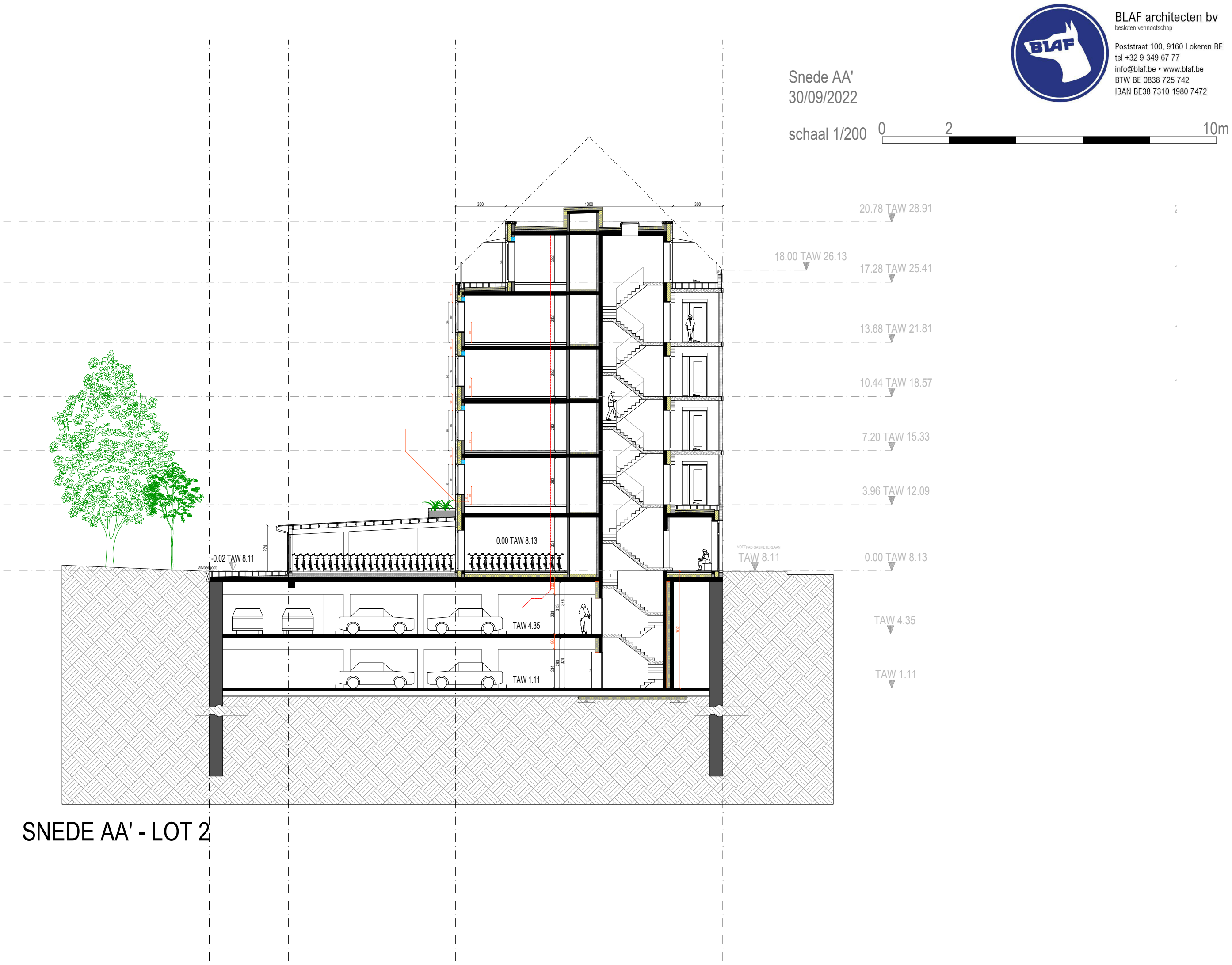
LITERATURE MATRIX

Bibliographical information				Research topic				LCA assumptions					
Nr.	**Title**	**Authors**	**Year**	**Problem statement**	**Parameters**	**Materials**	**Conclusion**	**Software/method**	**Typology**	**Functional Unit**	**System Boundaries**	**Lifetime**	**EII**
1	GWP of multi-storey timber buildings	Ruben Dierikx	2019	Several researches show that when a multi storey building is redesigned using mass timber as load-bearing structure, a smaller carbon footprint can be achieved. Existing studies are always focused on a definite timescale for one specific case. This study performs a meta-analysis on the existing literature concerning the potential reductions in GHG emissions achieved by timber multi-storey buildings. This is both done at the level of the material and at the level of the building.	/	CLT , Glulam	For all the cases that focuses on the overall GWP, the timber variant of the multi-storey building caused the least carbon emissions. The reduction in GWP between the reinforced concrete and timber benchmark of the building ranged from 1.22% to 219.92%. Between steel and timber, the GWP reduction varied between 1.20% and 144.11%. The proportion of this carbon reduction is highly dependent on the chosen end-of-life scenario of the construction waste. However, the latter is a matter where a lot of uncertainty remains.	36 comparative LCA's, 60 EPD's and additional relevant literature were collected and compared	Multi-storey building	/	/	/	/
2	Invloed van eindelevensduur-behandeling op de milieu-impact van betonnen constructies	Suzanne Kelem	2022	This thesis examines the influence of end-of-life treatment on the environmental impact of concrete structures, using a life cycle assessment with the focus on module C and D.	Type of recycling	Concrete	It is important to include the end of lifetime in a life cycle assessment. Using high-grade recycling can significantly reduce the environmental impact. The best scenario for the environment is to high-grade recycle the entire building.	SimaPro 9.1.1.1 Ecoinvent .36 ReCiPe 2016 method	/	1m^3 concrete and S4 building	A, C, D	60 year	Single score environmental impact [Pt/m^3]
3	Environmental performance of ordinary and new generation concrete structures—a comparative analysis	Daniel Wałach Piotr Dybe Joanna Sagan Magdalena Gicala	2019	The new generation of cement-based concretes (e.g. high-performance concrete, self-compacting concrete and high-performance, self-compacting concrete) are characterised by better parameters in terms of strength and durability but also rheology of the mixtures. The greater share of cement in these concretes causes an increase in the energy consumption and emissions (per unit of concrete volume) at the production stage. However, these concretes allows for a reduction of overall dimensions of a structural element, due to the increased strength parameters. Such a solution may finally result in lower consumption of resources and energy, as well as a decrease of gas emissions.	Variants of material properties of concrete	Concrete	The use of new generation concrete of high resistance allows a reduction of total environmental impact of the structure by means of a reduction of the geometrical dimensions of the structure, what is particularly observed in compressed elements (columns) rather than bending elements (slabs). Compared to ordinary concrete, for the analysed high-performance concrete mixtures, a reduction of structural dimensions from 8.9 to 18.7% is required, depending on the amount of cement in the concrete mix. Preparing different variants of materials and calculation of total impact of the structure based on the environmental profile of material, as well as characteristics of the work of the structure, is a favourable approach to structural design.	Gabi Software Autodesk Robot Structural Analysis Professional 2013 software	Office building	a 12-floor building, of 50 m × 25 m, with 3.7 m floor height	A1-A5	/	Ecopoint (= weighted average of 11 impact indicators)
4	Comparison of environmental impacts of building structures with in situ cast floors and with precast concrete floors	Belinda Lo´pez-Mesa, A´ngel Pitarch, Ana Toma´s, Teresa Gallego	2009	The study compares the environmental impact of two slab types used for residential buildings: a massive in situ concrete floor and a floor of prefabricated hollow core slabs.	Floor type: in situ vs. prefabricated	Concrete	Hollow core slabs have 12.2% reduction in environmental impact. Precast concrete floors have a higher impact than the in situ cast floors. ↔ Tthe columns and foundation have a lower impact, and columns represent a high percentage of total structural impact. → Lower environmental impact of the precast concrete floors + higher quality + quickness to install: choose this type of slab instead of in situ cast floors for residential buildings of 7 floors.	EPS2000 method Software SimaPro 7.0 Ecoinvent v1.1 database	Residential building	1m^2 = not representative → work with 1 case study	Not menioned: but in EPS200, all life cycle stages are implemented	/	Single score environmental impact [Pt]
5	Environmental performance of off-site constructed (OSC) facilities: A critical review	Ruoyu Jin, Jingke Hong, Jian Zuo	2019	There is not much to be found about detailed investigation of volumetric constructions and building operational stage for OSC as well as the comparison between offsite manufacturing and on site assembly to cast-in-situ methods.	Level of prefabrication Type of building Building performance Methodology	Steel, concrete	Existing studies use sub-assembly components as functional unit. Carbon emissions are examined but other environmental impacts (global warming, ozone exhausting ...) receive less attention. Operation and end-of-life stages were largely overlooked. → Challenge = acquire data of these stages.	/	/	mostly sub-assembly components	Only A → B-C-D are overlooked	/	/
6	Optimising flat plate buildings based on carbon footprint using branch-and-reduce deterministic algorithm	Hoang Tran Mai Kim Trinh, Sanaul Chowdhury, Minh Tuong Nguyen, Tingting Liu	2021	It is hard for structural engineers to apply mitigation rules for carbon footprints in a real project. This paper introduces a design methodology for carbon optimization of reinforced concrete structures.	Number of investigated stories Different column grids	Reinforced concrete	Optimized designs achieve 5.3-17.7% reduction in carbon emissions. Most significant variables: column concrete strength, column size and building's height. The balance between design constraints, ratio of concrete and reinforcement consumption and ratio of concrete and steel carbon coefficients determines the most eco-friendly design. Decrease slab emissions and increase column impacts to obtain the least environmental impact. Slab impacts have the largest share in the total carbon footprint. Although structural weight was found to be highly correlated with the total EC, material efficiency did not always lead to better building's environmental performance.	Simplified method: optimisation problem Advanced branch-and-reduce algorithm for MINLP	Flat plate buildings	Entire building structure	Cradle to point of sale A1-A3	/	Total Embodied Carbon (EC) [ton CO$_2$]
7	Comparative material-based life cycle analysis of structural beam-floor systems	Charlotte Dossche, Veerle Boel, Wouter De Corte	2018	For spans 4m-6m and a predetemrined column grid distinnct combinations of wood, steel and concrete elements can be implemented as beam-floor system. Besides comparing these beam-floor systems based on weight, cost, speed of installation, a comparison can also be based on their environmental impact.	different impact categories assesment methods types of floor systems	steel, timber, concrete and combinations	Influence of impact assesment method is important, especially regarding wooden structural elements. The ratio virgin-recycled steel in a beam-floor system can result in widely varying impact on the environment, BEAMS 1. IPE beams = largest impact, 2x concrete impact for equal spans 2. Glulam has higher impact on eco-systems ↔ steel and concrete BEAMS + FLOOR 1. Concrete beams + pretensioned hollow core slabs = lowest impact, also reduction with glulam+Ijoist+OSB and steel+hollow core slab 2. Steel + light steel floor joist + OSB = ecological solution 3. Glulam beams high impac ton agricultural land occupation 4. RC and wood most ecological materials for beams	SimaPro EcoInvent 3.1	/	a square meter of a structural beam-floor system of an arbitrary composition	cradle to grave: A1-A4 C2-C4 D (limited)	/	Recipe endpoint single score [Pt]

8	Vergelijkende materiaaltechnische LCA-studie van structurele vloer-balk systemen	Jens Baetens, Cedric Vennens	2016	This study envestigates a cradle-to-grave comparison of 26 different structural floor-beam systems that span two different span lengths in residential buildings.	slab type beam type	(aerated) Conccrete, steel, timber	The advised solution consists of cocnrete beams in combination with pretensioned hollow core slabs spanning 4m or 6m. In this study, regarding the applied system boundaries, wooden beams with an aerated concrete floor spanning 4m and wooden beams with OSB sheating are the worst solution.	Ecoinvent database SimaPro	Residential building	a beam-floor system which can bear a permanent load of 1,5 kN/m² and an imposed load of 2,0 kN/m²	cradle-to-grave, use and demolition are not included	/	Single score environmental impact [Pt]
9	Investigating the environmental impact of reinforced-concrete (RC) and structural-steel (SS) frames on sustainability criteria in green buildings	Nima Ranjbar, Amirhossein Balali, Alireza Valipour, Akilu Yunusa, Rodger Edwards, Gloria Pignatta, Robert Moehler, Wei Shen	2021	This study investigates how structural building frames perform according to sustainability criteria. A questionnaire was used to identify the relevant sustainability criteria, and a hybrid Delphi-SWARA model was used to deter-mine the relative importance of 8 comprehensive prioritized criteria. A building was simulated to quantify the environmental impact of 2 structural frames (RC vs. SS) on sustainability criteria.	Type of frame: steel vs concrete	Structural steel (SS) vs Reinforced Concrete (RC)	RC-framed buildings have a less detrimental impact on the environment due to less energy consumption and carbon emissions. 88 tonnes of CO2 emission can be reduced with this type of frame in a 50-year lifecycle	DesignBuilder and EnergyPlus software Fuzzy-Delphi method SWARA method	5-storey building	frame	/	30 year and 50 year	Energy management GHG management Material management Water management Innovation and engineering Site management Transportation Internal air quality
10	Evaluating the embodied environmental impacts of major building tasks and materials of apartment buildings in Korea	Seungjun Roha, Sungho Taeb, Sung Joon Sukc, George Ford	2017	The paper evaluates the emodied environmental impact of appartmentbuildings in Korea based on five major biuilding tasks and six building materials.	° Buildign type: walls, rigid frame, flat plate ° 5 building tasks ° 6 building materials	RC Concrete, Steel	Concrete contributed to > 50% of all environmental impact. The amount of rebar increased in the following order: flat plate > rigid-frame > wall structures of appartment buildings. If the quantity of concrete decreases, GWP decreases but other parameters increase due to increased amounts of rebars.	Korean LCI DB	Apartment building	Gross floor area [m²]	only stage of building material production (A)	/	Global warming, acidification, eutrophication, ozone layer depletion, photochemical oxidation and abiotic depletion potentials.
11	Cross-laminated timber flooring and concrete slab flooring: A comparative study of structural design, economic and environmental consequences	Osama A.B. Hassana, Fredrik Öbergb, Emil Gezeliusc	2019	In this paper the cost, strucutral deisgn and greenhouse gas emissions of concrete slabs and CLT slabs are compared. The effect of floor span on design values, costs, and carbon dioxide emissions is analysed in terms of structural design, economy, and environmental impact.	span length imposed load: cat A for family houses and C5 for crowded rooms	CLT vs. Concrete	CLT flooring has significantly lower emissions of climate-impact greenhouse gases ↔ CLT material is more expensive than concrete. The estimated “ready-to-assemble” cost of both floor types is quite similar. CLT flooring can compete with a concrete slab floor for spans <7m wide without violating the structural requirements. With an increase in span, it is more difficult to meet the requirements for vibration for a CLT floor than for a concrete slab. *Shorter spans* : moment capacity = decisive factor for concrete slabs ↔ deformation is decisive factor for a CLT floor. *Larger spans* : resonance frequency and deformation = crucial for the CLT floor ↔ long-term deformation of concrete is decisive.	Software Bidcon for material prices and labour costs	/	1 kg of material	entire life cylce	50 year	Global warming potential (GWP) Carbon dioxide equivalent [kg CO_2/kg]
12	Assessment on carbon footprint of steel frames for building structures	Eres Berki	2020	New carbon assessment guides exclude contributions from connection components in load carrying frames and impact of embodied carbon emissions has relatively been creased leading to encouraged use of timer over steel for building structures. This study aimed to determine the contribution of the frame types to the total carbon footprint of the steel framed building structures.	Stiffness of connections Span length Profile type	Steel	Frames with mast columns and pinned beam connections performed better than the other frame typesthe studied. Semi-rigid frames had the highest carbon emissions. Frames made of open profiles performed better than the ones made of tube profiles of higher steel strength. Steel frames had 2.66 x higher emissionscompared to the wooden frames (operating time set to 100 years). Connections are responsible for 13-33 % of carbon emissions.	Ideastatica Dubal RFEM 5.20 Tekla Structures 2018 Excel sheets	Steel frames	Frame	A1-5, C, D	100 year	GWP [kg CO_2]
13	Environmental Impact of Demolishing a Steel Structure Design for Disassembly	El˙ zbieta Broniewicz, Karolina Dec	2022	Design for Disassembly appears in the literature more and more often to offer clear environmental advantages. The authors used the LCA method during the demolition and operation of steel structure. Steel is completely recyclable . 3 scenarios were assessed: (1) complete re-remelting (recycling)of the structure (2) partial reuse of construction elements + remelting (3) complete reuse of the structure (recovery)	Different end-of-life scenarios	Steel	It wasfound that the environmental impact varied significantly among the examined scenarios. The first scenario poses the greatest environmental burden. Compared to Scenario 1, Scenario 3’s environmental impact is more than 70% lower.	GaBi software	Hollow section steel hall	One 135 t steel structure	A3-A5, C1-C3	100 years	Global warming potential [t CO_2 eq] Primary energy use [GJ]
14	Environmental performances of residential buildings with a structure in cold formed steel or reinforced concrete	Pierluca Vitale, Antonio Spagnuolo, Carmine Lubritto, Umberto Arena	2018	This study compares the LCA of a detached house designed following two different approaches for its structural components: cold formed steel (with sheathing and insulation panels) or more conventional reinforced concrete structure with masonry brick walls.	Phases: pre-use, use and end-of-life Type of structure: concrete ⍰ CFS Waste treatment: base vs. alternative scenario	Steel vs Concrete	The contributions of pre-use and use phases to the overall environmental performance are significant CFS has a better performance for the most important impact categories due to the lower energy consumption in use phase. If easy disassembly of the CRS structure is taken into account the advantages can increase up to 24%	Impact 2002+v2.11 SimaPro 8.0.2	Residential building	total floor area of the building	A1-3, C3-4, D	50 year	Global warming Respiratory inorganics Non-renewable energy
15	Environmental Performances of a Cubic Modular Steel Structure: A Solution for a Sustainable Development in the Construction Sector	Sebastian George Maxineasa, Dorina Nicolina Isopescu, Ioana-Roxana Baciu and Marius Lucian Lupu	2021	In this paper the environmental impact of different steel structural elements are analysed based on a dwelling steel structure with cubic modules having a high structural modularity.	end-of-life treatment	Steel	Steel cubic modules could be a solution to minimize the environmental burdens of the construction sector. The high recyclability of steel represents another important advantage to turn it into a more suited material. The modularity of the structure leads to lower costs for the users. If the steel production industry would supplement its efforts steel could have a neutral environmental footprint.	GaBi software	single-family dwelling	steel cubic module	A1, A2, A3, A4, C1, C2, C3, D	/	GWP [kg CO2-eq] HTPc (human toxicity potential, cancer) [CTUh] Ozone Depletion indicator (ODP) [kg CFC-11 eq]
16	Sustainability of Cold-formed Steel Portal Frames in Developing Countries in the Context of Life Cycle Assessment and Life Cycle Costs	Ross P.D. Johnston, Teresa McGrath, Sree Nanukuttan, James B.P. Lim, Marios SoutsosMei, Chee Chiang, Rehan Masood	2018	Conventional hot-rolled steel sections are commonly used for the primary column and rafter members, for frames of modest span (up to 30 m), a viable alternative can becold-formed steel sections. This paper compares both types of portal steel buildings in terms of a life-cycle assessment (LCA) and a life-cycle cost (LCC).	span length cold formed vs. hot rolled steel	Steel	It is shown that in terms of the primary framing, use of cold-formed steel for the 18 m and 24 m span buildings can result in up to 30% less embodied carbon than hot-rolled steel. When secondary members and cladding are taken into account in the LCA, the differences in embodied carbon of cold-formed and hot-rolled steel are found to be negligible.	LCA: ISO 14040 LCC: ISO 15686	Single-storey buildings	the functional unit of steel may be expressed as kg of steel or the m^2 of a steel construction	Cradle to grave	/	Embodied carbon [kg CO2 eq /m²] Life cycle cost of frames [RM/m²] Embodied energy [MJ/m²]

17	Whole life embodied carbon in multi-storey buildings	Jim Hart, Bernardino D'Amico, Francesco Pomponi	2021	Comparisons are made between mass and whole-life embodied carbon (WLEC) emissions of building superstructures using identical frame configurations in steel, reinforced concrete, and engineered timber frames. These are assessed and compared for 127 different frame configurations, from 2 to 19 stories.	Frame configuration Material # Stories	Steel, timber, concrete	Results show differences between the masses of the 3 structural typologies: concrete frame approximately 5x the mass of the timber frame, and 50% higher than the steel frame. The WLEC emissions are mainly governed by the upfront emissions (cradle to practical completion), but subsequent emissions are still significant — particularly in the case of timber for which 36% of emissions, on average, occur post-construction Despite the advantage for timber in this comparison, there is overlap between the results distributions, meaning that close attention to efficient design and procurement is essential.	SimaPro 9 Ecoinvent 3.5	multi-storey building	1m² GEA of superstructure	Cradle to grave	50 year	EC per unit floor area [kg CO2 / m²]
18	Development of q-L-EIV interactive curves for comparison of the environmental performance of composite slabs and RC slabs from the perspective ofmechanical features	Chen Zhu, YuanChang , Shu Su, Xiaodong Li, Zhihui Zhang	2019	To better understand environmental performance of various slabs and assist design decision-making considering environmental protection and structural requirements, this paper evaluated EIs of two commonly used slabs (RC slabs and composite slabs) with various sectional forms from the perspective of mechanical features.	Floor types	Concrete vs. composite concrete steel	Combining EIV and permitted load-span (q-L) curve, q-L-EIV interactive curves were developed to illustrate the structural and environmental performance of slabs. The results indicated that there are large differences between the EIs of various slabs. Composite slabs were widely recommended in engineering applications from the view of environmental sustainability.	BEPAS model	/	Cross-sectional area of a slab satisfying certain structural span and load requirements.	production, construction and demolition, NOT stage B	/	EIV (environmental impact value)
19	High-Rise Timber Buildings as a Climate Change Mitigation Measure - A Comparative LCA of Structural System Alternatives	Julie Lyslo Skullestad, Rolf André Bohne, Jardar Lohne	2016	Report on a study examining the potential of reducing greenhouse gas (GHG) emissions from the building sector by substituting multi-storey steel and concrete building structures with timber structures.	#storeys: 3, 7, 12, 21	Timber	Timber structures are found to cause a CC that is 34-84 % lower than RC structures, for all structures, in all approaches and scenarios. The CC saving per m² floor area decrease slightly with building height up to 12 storeys, but increase from 12 to 21 storeys. Constructing timber structures can result in avoided GHG emissions, indicated by a negative CC.	Sofistik SimaPro v7 Ecoinvent v.3.2 ReCiPe method ISO standard	High-rise buildings	Building structural system including foundations with a certain load bearing capacity and a given number of storeys,	A1-3 and D	60 year	Climate change [kg CO^2-eq/m²]
20	Regional environmental life cycle consequences of material substitutions: The case of increasing wood structures for non-residential buildings	Sylvain Cordier, François Robichaud, Pierre Blanchet, Ben Amor	2021	The objective of this paper is to assess the life cycle environmental consequences of wood substitutions at a regional scale for the non-residential construction sector using 3 substitution scenarios and 4 impact categories.	Substitution scenario, impact categories	Timber	Tehre is an advantage when using wood in 7/12 combinations. Ecosystem quality indicator is the most unfavourable one. Wood can contribute to avoid 2.6 Mt of CO2 eq.	LCA method: IMPACT 2002+ V2.15 SimaPro 9 and ecoinvent 3.6	non-residential buildings	this research doesn't focus on a comparative LCA or an analysis of a given product	/	until 2050	Climate change [CO_2 eq] Human health [daly] Ecosystem quality [PDF*m²*year] Resources [MJ primary]
21	Environmental benefits of using hybrid CLT structure in midrise nonresidential construction: An LCA based comparative case study in the U.S. Pacific Northwest	FrancescaPierobon, MonicaHuang, KathrinaSimonen, IndroneilGanguly	2019	The environmental impact of a hybrid, mid-rise, cross-laminated timber (CLT) commercial building is evaluated and compared to that of a reinforced concrete building with similar functionalcharacteristics.	Material: CLT vs. Concrete Fire protection design	CLT vs. Concrete	On average, the total primary energy in the hybrid CLT buildings and concrete building are similar. Non-renewable energy (fossil-based) use in the hybrid CLT building is 8% lower compared to the concrete building. As compared to the concrete building, additional 1556 tCO2e and 2567 tCO2e are stored in the wood components of the building (long-term storage of biogenic carbon) in the scenario with fireproofing and charring, respectively.	TRACI 2.1 Cumulative Energy Demand impact method	Midrise non-residential construction	Entire building	Cradle-to-gate acquisition of the raw materials until the construction of the building	100 year	Ozone depletion [kg CFC 11eq] Global warming [kg CO_2 eq] smog [kg O_3 eq] acidificaion [kg SO_2 eq] Eutrophication [kg N eq]
22	Design optimization of hybrid steel/timber structures for minimal environmental impact and financial cost: a case study	D. Van Cauteren, D. Ramon, J. Stroeckx, K. Allacker, M. Schevenels	2022	The construction materials with the lowest environmental impact are not always the cheapest ones, hybrid structures can offer a solution to find a trade-off between environmental and financial cost.	Type of structure: statically (in)determinate section types → 3 design scenarios	Steel / Timber	Depending on the design conditions hybrid steel/timber structures can be pareto-optimal. The ratio of timber and steel elements is a good indicator for the location of a structure in the E-LCC – LCC spectrum.	Matlab toolbox Stabil MMG+ _KULeuven tool Ecoinvent (v3.3)	/	1m of a structural element with an identical load bearing capacity	A1-5, B1-7,C1-4	80 years	Environmental costs [€/m² floor]
23	Sustainability choice of different hybrid timber structures for low medium cost single-story residential building: Environmental, economic and social assessment	Ali Tighnavard Balasbaneha, Abdul Kadir Bin Marsonob, Seyed Jalal Khaleghic	2018	One wants to find the most optimum choice of hybrid timber structure for Malaysian low income housing taking into account environmental, economic and social parameters.	Building components Building scheme Thickness Total weight	Timber	The manufacturing sector generates a high environment impact. T2 (Hybrid steel stud & timber) is best option: elimination of concrete + highest possible percentage of timber, also in full LCC. Recycling of steel has positive impact on environment and costs.	SimaPro v.8.0.4.30 ReCiPe method	Single-storey residential building	Whole structural scheme of single story residential building	Cradle to grave	50 year	GWP [kg CO_2 eq] Fossil depletion [kg oil eq] Human-toxicity potential [kg 1.4 DB eq] Acidification [kg SO_2 eq] Eutrophication [kg PO_4 eq]
24	A comparative study between glulam and concrete columns in view of design, economy and environment	Sama Hassan, Nour Emad, Gabriel Abdulahad	2022	This study makes a comparison between columns in glued laminated timber and concrete columns regarding their environmental impact, economic impact and structural design.	dimensions of columns	Timber vs. Concrete	Structural design: with small axial forces, glulam columns will result in smaller cross-sectional areas ↔ at larger axial forces, concrete columns will result in smaller cross-sectional areas than glulam columns. An increased column length also means larger dimensions for glulam columns, this does not always apply to concrete columns. Using glulam columns is more environmentally friendly option.	CO2 equivalent calculated by hand, using values from other papers.	/	One column that needs to resist a specified load combination.	/	/	Carbon dioxide equivalent [kg CO_2]
25	Improved environmental impact in the architecture industry: LCA analysis of an alternative masonry element	Zoltan Szamosi, Istvan Bodnar, Gabor L. Szepesi, Martí Rosas-Casals, Laszl o Berenyi	2020	The role of masonry elements is especially important when taking the entire life cycle of a building into consideration. This paper aims to analyze the environmental impacts of producing and using an alternative masonry element (AME) which is composed of cellulose and biodegradable 3-component glue.	Alternative plant installation possibilities, types of brick	Masonry: brick and cellular concrete	Results of the study show that remarkably saving can be achieved when using the new alternative masonry element.	GaBi professional software	A building used for living or working	Heat-insulated masonry element with an area of 1 m² and a thermal transfer coefficient of 0.15 W/m²K.	cradle to grave: A1-A5 C1-C4	50 years	GWP [kg CO_2-eq] AP [kg SO_2-eq] EP [kg phsophorous-eq] ADP fossil [MJ] HTTP [kg DCB-eq]

B Case study - Sections



SNEDE AA' - LOT 2

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30/09/2022

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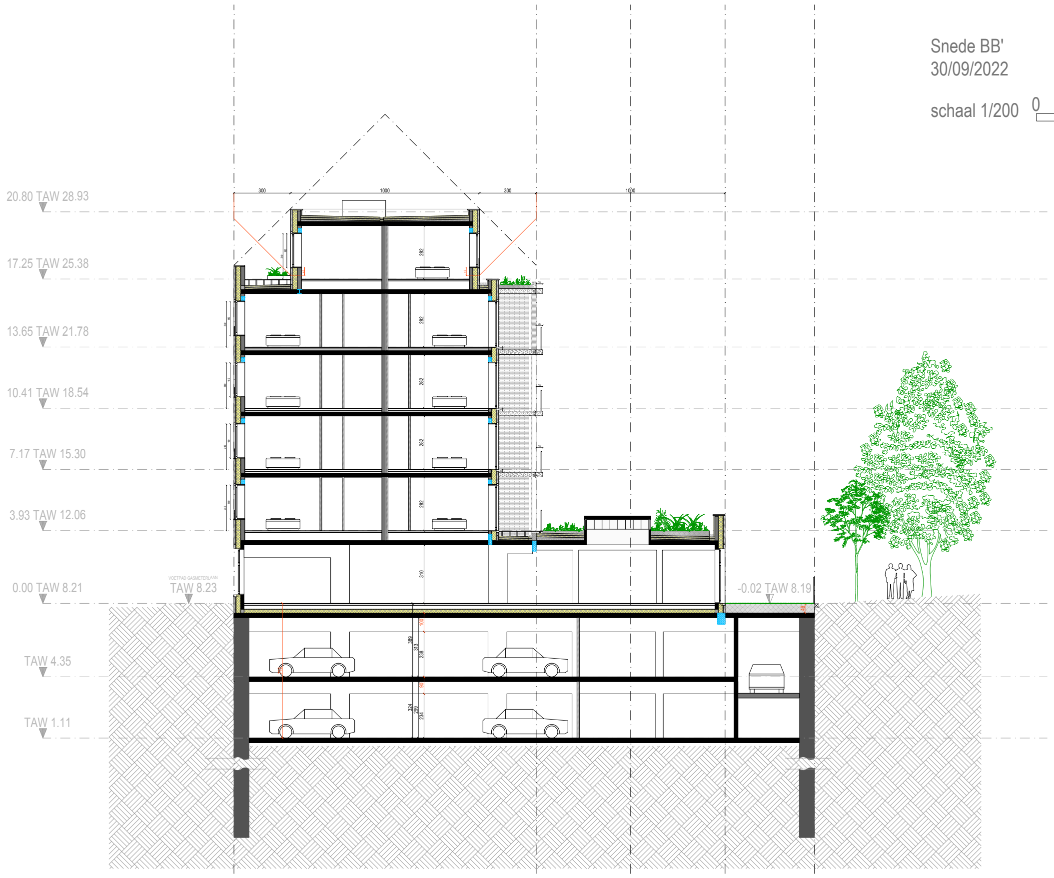

SNEDE BB' - LOT 5

C Roadmap adjustment Ecoinvent process to Belgian context

Production process

Choose a transformation process, never choose an obsolete process:

1. Choose an 'RER' process when possible.
2. If not, choose a 'Europe without Switzerland' process when possible.
3. If not, choose a 'CH' process to adjust. (If there is no 'CH' process available, choose a specific (European) country.)
    (a) Copy the 'CH' process and rename it (here 'EC' and 'adjusted Belgium' were added).
    (b) 'RER', 'Europe without Switzerland' and 'GLO' process are not adjusted.
    (c) Other processes are adapted by market processes:
        i. Choose an 'RER' process when possible.
        ii. If not, choose a 'Europe without Switzerland' process when possible.
        iii. If not, keep the 'CH' process.

The adjustment is always mentioned in the comment, e.g. 'CH > RER'.

Waste process

Choose a transformation process:

1. Choose a 'BE' process when possible.
2. If not, choose a 'RER' process when possible.
3. If not, choose a 'Europe without Switzerland' process when possible. In case a 'RER' or 'Europe without Switzerland' process was chosen, adjust all processes related to heat, water and electricity:
    (a) To 'BE' processes when possible.
    (b) If not, to 'RER' processes.
4. If not, choose a 'CH' process to adjust. (If there is no 'CH' process available, choose a specific (European) country.)
    (a) Copy the 'CH' process and rename it (here 'EC' and 'adjusted Belgium' were added).
    (b) 'RER', 'Europe without Switzerland' and 'GLO' process are not adjusted, except for heat, electricity and water which should be adjusted to 'BE' or 'RER'.
    (c) Other processes are adapted by market processes:
        i. Choose an 'RER' process when possible.
        ii. If not, choose a 'Europe without Switzerland' process when possible.
        iii. If not, keep the 'CH' process.

D Material processes - Module A1-A3

Processes from the 'Ecoinvent 3 - allocation, cut-off by classification' libraries were used. To take into account the geographical specifications, in general as much as possible processes with a 'BE', 'RER' or 'Europe without Switzerland' mark are chosen because these are most representative for Belgium.

Furthermore, a choice must be made between unit processes and system processes. System processes give an overview of the input and output but their origin can not be traced. This has the advantage that the calculations need less time. Unit processes are more transparent and show all the subprocesses of which they are built. This gives the possibility to adjust some subprocesses to the Belgian context. Therefore, whenever adjustments needed to be made, unit processes were used and when possible system processes were used to limit the calculation time.

The processes in tables A.1 and A.2 start with 'EC' because they were composed or adapted by the author. The basic material processes were always chosen to be a transformation process which include all impacts of stages A1 up to A3. Subsequently, the processes were adjusted according to Appendix C. These adjusted processes are indicated by expanding the geographical information code with 'adjusted Belgium'. The processes that are aligned to the right of the second column are the subprocesses of which the process above, that is aligned to the left, is composed.

Table A.1: EcoInvent processes module A1-A3 - Concrete and steel

Type of material	Process
CONCRETE	
Hollow core slabs	EC_Hollow Core Slabs, 15cm height adjusted Belgium
	EC_Hollow Core Slabs, 18cm height adjusted Belgium
	EC_Hollow Core Slabs, 20cm height adjusted Belgium
	EC_Hollow Core Slabs, 32cm height adjusted Belgium
	EC_Concrete, 50MPa RoW|adjusted Belgium,kg| concrete production 50MPa | Cut-off, U
	Reinforcing steel RER| production | Cut-off, U
Wide slab	EC_Concrete, 30MPa RoW|adjusted Belgium,kg| concrete production 30MPa | Cut-off, U
In situ concrete slab	EC_Concrete, 30MPa RoW|adjusted Belgium,kg| concrete production 30MPa | Cut-off, U
Concrete beams / columns - C30/37	EC_Concrete, 30MPa RoW|adjusted Belgium,kg| concrete production 30MPa | Cut-off, U
Concrete beams / columns - C50/60	EC_Concrete, 50MPa RoW|adjusted Belgium,kg| concrete production 50MPa | Cut-off, U
STEEL	
Steel beams/columns hot rolled	EC_Steel, low-alloyed, hot rolled RER| production | Cut-off, U
	Hot rolling, steel RER| processing | Cut-off, U
	Steel, low-alloyed RoW| steel production, converter, low-alloyed | Cut-off, U
Reinforcement	Reinforcing steel RER| production | Cut-off, U

Table A.2: EcoInvent processes module A1-A3 - Timber and masonry

TIMBER	
Glulam beams and columns	EC_Glued laminated timber, for indoor use RER|kg| production | Cut-off, U
	Glued laminated timber, for indoor use RER| production | Cut-off, U
CLT floor slab	EC_Laminated timber element, transversally prestressed, for outdoor use RER|kg| laminated timber element production, for outdoor use | Cut-off, U
	Laminated timber element, transversally prestressed, for outdoor use adjusted Belgium| market for | Cut-off, U
Steel for connectinos	EC_Cold formed bolts RER|adjusted Belgium
	Impact extrusion of steel, cold, deformation stroke RER| processing | Cut-off, U
	Steel, low-alloyed RoW| steel production, converter, low-alloyed | Cut-off, U

MASONRY	
Aerated autoclaved concrete	EC_Autoclaved aerated concrete block CH|adjusted Belgium| production | Cut-off, U
Adhesive mortar	EC_Adhesive mortar CH|adjusted Belgium| production | Cut-off, U
Sand-lime bricks	EC_Sand-lime brick DE|adjusted Belgium| production | Cut-off, U

E Transport processes - Module A4

For module A4, the choice is made to use the processes that represent EURO6 vehicles which have the lowest emissions. These processes are representative for Europe and thus do not need further adjustments.

Table A.3: Transport processes - Module A4

Transport means	SimaPro process
Lorry > 32 ton	Transport, freight, lorry >32 metric ton, EURO6 RER| transport, freight, lorry >32 metric ton, EURO6 | Cut-off, U
Lorry 16-32 ton	Transport, freight, lorry 16-32 metric ton, EURO6 RER| transport, freight, lorry 16-32 metric ton, EURO6 | Cut-off, U
Lorry 7.5-16 ton	Transport, freight, lorry 7.5-16 metric ton, EURO6 RER| transport, freight, lorry 7.5-16 metric ton, EURO6 | Cut-off, U
Lorry 3.5-7.5 ton	Transport, freight, lorry 3.5-7.5 metric ton, EURO6 RER| transport, freight, lorry 3.5-7.5 metric ton, EURO6 | Cut-off, U

F Landfill and incineration processes - Module C4

Table A.4: Summary of landfill and incineration processes for module C4

Material	Landfill process
Concrete C50/60	Waste concrete Europe without Switzerland| treatment of waste concrete, inert material landfill | Cut-off, S
Reinforcing steel BE500	Scrap steel Europe without Switzerland| treatment of scrap steel, inert material landfill | Cut-off, S
Concrete C30/37	Waste concrete Europe without Switzerland| treatment of waste concrete, inert material landfill | Cut-off, S
Steel profiles	Scrap steel Europe without Switzerland| treatment of scrap steel, inert material landfill | Cut-off, S
Glulam beams & columns	Waste wood, untreated CH| treatment of, sanitary landfill | Cut-off, S
CLT plates	Waste wood, untreated CH| treatment of, sanitary landfill | Cut-off, S
Steel for connections	Scrap steel Europe without Switzerland| treatment of scrap steel, inert material landfill | Cut-off, S
Aerated concrete	Inert waste, for final disposal CH| treatment of inert waste, inert material landfill | Cut-off, S
Adhesive mortar	Inert waste, for final disposal CH| treatment of inert waste, inert material landfill | Cut-off, S
Sand-lime brick	Inert waste, for final disposal CH| treatment of inert waste, inert material landfill | Cut-off, S
Material	**Incineration process**
Concrete C50/60	Municipal solid waste BE| treatment of, incineration | Cut-off, S
Reinforcing steel BE500	Scrap steel Europe without Switzerland| treatment of scrap steel, municipal incineration | Cut-off, S
Concrete C30/37	Municipal solid waste BE| treatment of, incineration | Cut-off, S
Reinforcing steel BE500	Scrap steel Europe without Switzerland| treatment of scrap steel, municipal incineration | Cut-off, S
Steel profiles	Scrap steel Europe without Switzerland| treatment of scrap steel, municipal incineration | Cut-off, S
Glulam beams & columns	Waste wood, untreated CH| treatment of, municipal incineration | Cut-off, S
CLT plates	Waste wood, untreated CH| treatment of, municipal incineration | Cut-off, S
Steel for connections	Scrap steel Europe without Switzerland| treatment of scrap steel, municipal incineration | Cut-off, S
Aerated concrete	Municipal solid waste BE| treatment of, incineration | Cut-off, S
Adhesive mortar	Municipal solid waste BE| treatment of, incineration | Cut-off, S
Sand-lime brick	Municipal solid waste BE| treatment of, incineration | Cut-off, S

G Recycling and reuse processes - Module D

Table A.5: Processes used in calculations of Module D for different materials

Material	**EcoInvent process**
E_{virgin}	
Steel - recycling	Steel, low-alloyed RER| steel production, converter, low-alloyed | Cut-off, U
Steel - reuse	Steel, low-alloyed RER| steel production, converter, low-alloyed | Cut-off, U
Wood - recycling	EC_Wood chips, dry, measured as dry mass RER| plywood production, for outdoor use | Cut-off, U
Concrete	EC_Limestone, crushed, for mill CH|adapted Belgium| production | Cut-off, U
Clay brick	EC_Gravel, crushed CH|adjusted Belgium| production | Cut-off, U
AAC	Sand GLO| market for | Cut-off, U
Sand-limestone	EC_Limestone, crushed, for mill CH|adapted Belgium| production | Cut-off, U
$E_{recycling}$	
Steel - recycling	Steel, low-alloyed RER| steel production, electric, low-alloyed | Cut-off, U
Steel - reuse	-
Wood - recycling	EC_Wood chips, measured as dry mass CH| treatment of waste wood, sorting and shredding | Cut-off, U
Concrete	-
Clay brick	-
AAC	-
Sand-limestone	-
Incineration processes	
Heat	EC_Heat, district or industrial, natural gas RoW| heat production, natural gas, at industrial furnace >100kW | Cut-off, U
Electricity	Electricity, high voltage BE| production mix | Cut-off, U

Table A.6: Total impacts per kilogram of material for module D

Material	**Impact [mPt/kg]**
Module D - Steel recycling	-0.1887
Module D - Steel reuse	-0.2423
Module D - Concrete	-0.0014
Module D - Wood - Incineration	-0.0211
Module D - Wood - Recycling	-0.0291
Module D - Clay brick	-0.0015
Module D - Sand-lime brick	-0.0014
Module D - AAC	-0.0006

H Material densities

Table A.7: Densities of materials used in calculations

Material	**Density [kg/m³]**
Unreinforced cocnrete	2400
Reinforced concrete	2500
Slope concrete	1000
Chape	1700
Steel	7850
Glulam	510
CLT	490
sand-lime brick	1800
AAC blocks	535
Clay brick	850
Cement mortar	1800
Insulation	40
Tiles	2200

Appendices

I Detailed design input for structural calculations

I.1 Hollow core slabs

For the hollow core slabs, it was decided to work with a 50 mm-thick in situ compression layer on top of the prefabricated elements to increase the slab action. The fire resistance class is chosen to be R60 for all structural components in this study.

Table A.8: Characteristics provided to the tool 'MyFloor' of Ergon to calculate the suited hollow core slab

Characteristic	**Value**	**Unit**
Fixed loading	2,8	kN/m²
Variable loading	2	kN/m²
Compression slab	50	mm
Fire resistance	60	min
Construction classification	A: residential areas	-
Standards	NBN	-
Concrete class	C55/67	-

I.2 Wide slab and in situ concrete slab

The design input inserted in ConCrete to determine the dimensions and reinforcement layout for the wide slabs is shown in Table A.9. For every calculation, a moment reduction on the intermediate supports of 15% with redistribution is taken into account as indicated in the last row. For the in situ concrete slab, the same characteristics are used as for the wide slabs in ConCrete and in SCIA Engineer, except for the moment reduction.

Table A.9: Design input wide slab and in situ concrete slab

Characteristic	**Symbol**	**Value**	**Unit**
Steel grade	-	BE500	-
Safety coefficient	γ_s	1,15	-
Maximum steel stress	σ_s	0,80*f_{yk}	
Concrete cover	c	25	mm
Concrete class	-	C30/37	-
Minimum reinforcement ratio	$_{min,top}$	0,0015	
Characteristic compressive strength	f_{ck}	30	N/mm²
Safety coefficient	γ_c	1,5	-
Elastic modulus	E	31939	N/mm²
Creep coefficient - crack width and deflection	ϕ(t,to)	1,29	-
Creep coefficient - concrete stress	ϕ(t,to)	1,4	-
Maximum crack with under QP combination	s	0,4	mm
Moment reduction	$M_{reduction}$	15	%

I.3 CLT slabs

For the calculation of the CLT slabs, the option 'Sylva Floors and Roofs' and subsequently the category 'CLT floor and roof element design' is used in Calculatis. The characteristics of the CLT slab were adjusted as indicated in Table A.10. The fire resistance class is taken equal to the one for the HCS to facilitate comparison.

Table A.10: Design input Calculatis - CLT slab

SYSTEM			
panel width	1 m	**edge gluing**	middle layers edge glued
Material	C24 spruce ETA (2019)	**consider self weight**	yes
service class	1	**support design**	yes
FIRE RESISTANCE			
Fire resistance class	R 60	**fire protection system**	no fire protection
Load combination factor	ψ_2	**fire protection layering**	no fire protection
SLS - DEFORMATION			
SLS - type of structure	important and regular structural elements	**SLS limit w_{inst}**	L/300
		SLS limit w_2	L/300
		SLS limit w_{fin}	L/250
VIBRATION			
Perform vibration analysis	yes	**damping coefficient**	4%
stiffness in cross direction by	CLT panel + screed	**thickness screed**	8 cm
stiffness in cross direction	1.109 MN/m²	**Young's modulus screed**	26000 N/mm²

I.4 CLT-concrete slabs

The design input for the CLT-concrete slab is very similar to that of the CLT slab except for the additional information related to the concrete. All necessary information is provided in Table A.11.

Table A.11: Design input Calculatis - CLT-concrete slab

SYSTEM DATA			
Panel width [m]	1	**edge gluing**	middle layers edge glued
Panel type	CLT 120 L5s	**Consider self weight**	yes
Material	C24 spruce ETA (2019)	**Design connection to rib**	yes
Service class	1	**Design connection to concrete**	yes

CONCRETE COMPOSITE DATA			
Thickness [cm]	8	**Cement class**	N
Material	C30/37	**Relative humidity**	0,6
Kser,28 [N/mm]	25000	**Creep coefficient**	2
Kser,∞ [N/mm]	16667	**Connectors**	rigid
Ku,28 [N/mm]	16667		SFS VB 48-7,5x165(45°/135°)
Ku,∞ [N/mm]	11111	**Connector spacing [mm]**	150

FIRE RESISTANCE DATA			
Fire resistance class	R 60	**Fire protection system**	no fire protection
Load combination factor	ψ2	**Fire protection layering**	no fire protection

SLS - DEFORMATION DATA			
SLS - type of structure	important and regular	**SLS limit** w_{inst}	L/500
	structural elements	**SLS limit** w_2	L/300
		SLS limit w_{fin}	L/300

VIBRATION			
Perform vibration analysis	yes	**Damping coefficient**	4%
Stiffness in cross direction by	CLT panel + screed	**Thickness screed**	8 cm
Stiffness in cross direction	1.109 MN/m^2	**Young's modulus screed**	26000 N/mm^2

I.5 Concrete frame

The concrete beams are calculated in ConCrete using the same design input as given above for the in situ concrete slab and the wide slabs. The concrete columns and their reinforcement are calculated in 12-Build using the design input shown in Table A.12. It is chosen to work with a constant width of the columns and let 12-Build calculate the necessary height of the cross-section and the reinforcement.

Table A.12: Design input 12-Build - Concrete columns

Characteristic	**Symbol**	**Value**	**Unit**
Fixed width	B	200	mm
Minimum height	H_{min}	200	mm
Maximum height	H_{max}	700	mm
Step	S	100	mm
Maximum relative deflection GGT QP	-	1/300	-
Characteristic compressive strength	f_{ck}	30	N/mm²
Steel grade	f_{yk}	500	N/mm²
Concrete cover	c	35	mm

I.6 Steel frame

For the steel frame, it is chosen to use bars of family HEA or HEB and to use the same cross-sections for in-line bars, which facilitates the connections. The detailed design input for 12-Build is shown in Table A.13.

Table A.13: Design input 12-Build - Steel frame

Characteristic	**Value**
All bars for the same profile class	HEA
Maximum relative deflection GGT QP	1/300
Steel grade (hot rolled)	S235
Standard	EN 1993 - Annex A

I.7 Glulam frame

The design input for the glulam beams and columns is shown in tables A.14 and A.15 and is similar to the design input for the CLT slabs.

Table A.14: Design input Calculatis - Glulam beams

SYSTEM DATA			
Inclination	0°	**support design**	yes
Material	GL 24 h	**Spacing of lateral bracing**	5 m
service class	1	$k_{sys,z}$	1
consider self weight	yes	**load on compression side**	yes

FIRE DESIGN DATA			
Fire resistance class	R 60	**fire protection system**	no fire protection
Load combination factor	2	**Fire protection layering**	no fire protection

SLS - DEFORMATION DATA			
SLS - type of structure	important and regular structural elements	**SLS limit** w_{inst}	L/300
		SLS limit w_2	L/300
		SLS limit w_{fin}	L/250

VIBRATION			
Perform vibration analysis	yes	**Design for class II only**	yes
Total width	5,20 m	**damping coefficient**	4%
Rib spacing on center	1 m	**thickness screed**	8 cm
stiffness in cross direction by	screed	**Young's modulus screed**	26000 N/mm²
stiffness in cross direction	1.109 MN/m²		

Table A.15: Design input Calculatis - Glulam columns

SYSTEM DATA			
Material	GL 24 h	**Consider self weight**	yes
Column height	3.24 m	**Spacing of lateral bracign**	5 m
Service class	service class 1	**ksys,z**	1
Support top Y	hinge	**Support top Z**	hinge
Support bottom Y	clamp	**Support bottom Z**	clamp

FIRE DESIGN DATA			
Fire resistance class	R 60	**fire protection system**	no fire protection
Load combination factor	ψ2	**fire protection layering**	no fire protection

J Inventory of material quantities and dimensions

J.1 Supporting structures - Hollow core slab

Table A.16: Column and beam characteristics - Reinforced concrete C30/37 - L01

L01-HCS-C-30/37	**Width [mm]**	**Height [mm]**	**Length [m]**	**Amount**	**Reinforcement [kg]**	**Concrete [kg]**
Central column	200	380	3.24	4	34	581
Edge column	200	230	3.24	7	21	351
Corner column	200	230	3.24	7	15	353
Beam 1	200	340	12.37	1	96	1989
Beam 2	200	370	12.23	1	244	2097
Beam 3	200	340	14.00	1	175	2231
Beam 4	200	300	7.53	1	72	1062
Beam 5	200	300	3.40	1	26	482
				TOTAL	1004	15114

Table A.17: Column and beam characteristics - Reinforced concrete C30/37 - L02

L02-HCS-C-30/37	**Width [mm]**	**Height [mm]**	**Length [m]**	**Amount**	**Reinforcement [kg]**	**Concrete [kg]**
Central column	300	440	3.24	2	16	1022
Edge column	200	380	3.24	6	9	588
Corner column	200	230	3.24	7	6	356
Beam 1	200	460	12.07	1	156	2617
Beam 2	200	540	11.65	1	304	2927
Beam 3	200	480	13.57	1	299	3035
Beam 4	200	300	7.38	1	72	1041
Beam 5	200	300	3.25	1	26	460
				TOTAL	1011	14555

Table A.18: Column and beam characteristics - Reinforced concrete C30/37 - L03

L03-HCS-C-30/37	**Width [mm]**	**Height [mm]**	**Length [m]**	**Amount**	**Reinforcement [kg]**	**Concrete [kg]**
Central column	300	370	3.24	2	45	849
Edge column	200	410	3.24	5	33	628
Corner column	200	230	3.24	7	21	351
Beam 1	200	370	12.01	1	244	2058
Beam 2	200	380	13.68	1	270	2413
Beam 3	200	300	7.35	1	72	1036
Beam 4	200	300	3.22	1	26	456
				TOTAL	1018	13257

Table A.19: Column and beam characteristics - Reinforced concrete C30/37 - L04

L04-HCS-C-30/37	Width [mm]	Height [mm]	Length [m]	Amount	Reinforcement [kg]	Concrete [kg]
Central column	300	470	3.24	2	44	1083
Edge column	200	390	3.24	7	27	598
Corner column	200	230	3.24	6	15	353
Beam 1	200	400	12.05	1	147	2269
Beam 2	200	430	11.57	1	277	2303
Beam 3	200	300	1.77	1	8	252
Beam 4	200	320	7.37	1	88	1105
Beam 5	200	340	3.24	1	24	522
				TOTAL	887	14924

Table A.20: Column and beam characteristics - Reinforced concrete C50/60 - L01

L01-HCS-C-50/60	Width [mm]	Height [mm]	Length [m]	Amount	Reinforcement [kg]	Concrete [kg]
Central column	200	300	3.24	4	32	457
Edge column	200	230	3.24	7	18	352
Corner column	200	230	3.24	7	15	353
Beam 1	200	330	12.37	1	104	1928
Beam 2	200	370	12.23	1	154	2125
Beam 3	200	340	14.00	1	299	2193
Beam 4	200	300	7.53	1	72	1062
Beam 5	200	300	3.40	1	26	482
				TOTAL	974	17796

Table A.21: Column and beam characteristics - Reinforced concrete C50/60 - L02

L02-HCS-C-50/60	Width [mm]	Height [mm]	Length [m]	Amount	Reinforcement [kg]	Concrete [kg]
Central column	200	450	3.24	2	10	697
Edge column	200	240	3.24	6	8	371
Corner column	200	230	3.24	7	8	355
Beam 1	200	450	12.35	1	174	2614
Beam 2	200	500	11.91	1	289	2770
Beam 3	200	480	13.69	1	206	3091
Beam 4	200	300	7.52	1	63	1064
Beam 5	200	300	3.39	1	27	480
				TOTAL	879	16245

Table A.22: Column and beam characteristics - Reinforced concrete C50/60 - L03

L03-HCS-C-50/60	**Width [mm]**	**Height [mm]**	**Length [m]**	**Amount**	**Reinforcement [kg]**	**Concrete [kg]**
Central column	200	230	3.24	2	39	346
Edge column	200	260	3.24	5	35	394
Corner column	200	380	3.24	7	18	586
Beam 1	200	370	12.31	1	244	2112
Beam 2	200	360	13.81	1	180	2331
Beam 3	200	300	7.50	1	63	1061
Beam 4	200	300	3.37	1	27	477
				TOTAL	644	12740

Table A.23: Column and beam characteristics - Reinforced concrete C50/60 - L04

L04-HCS-C-50/60	**Width [mm]**	**Height [mm]**	**Length [m]**	**Amount**	**Reinforcement [kg]**	**Concrete [kg]**
Central column	300	470	3	2	38	1085
Edge column	200	390	3	7	22	600
Corner column	200	230	3	6	15	353
Beam 1	200	400	12.05	1	147	2269
Beam 2	200	430	11.57	1	277	2303
Beam 3	200	300	1.77	1	8	252
Beam 4	200	320	7.37	1	88	1105
Beam 5	200	340	3.24	1	24	522
				TOTAL	694	14416

Table A.24: Column and beam characteristics - Steel S235 - L01

L01-HCS-S-235	**Width [mm]**	**Height [mm]**	**Length [m]**	**Cross-section [m²]**	**Amount**	**Steel [kg]**
Central column	180	180	3.24	0.00653	4	166
Edge column	160	160	3.24	0.00388	7	99
Corner column	120	120	3.24	0.00253	7	64
Beam 1	180	180	12.73	0.00453	1	453
Beam 2	240	240	12.61	0.00768	1	760
Beam 3	220	220	14.53	0.00643	1	733
Beam 4	180	180	7.82	0.00453	1	278
Beam 5	180	180	3.58	0.00453	1	127
					TOTAL	4157

Table A.25: Column and beam characteristics - Steel S235 - L02

L02-HCS-S-235	Width [mm]	Height [mm]	Length [m]	Cross-section [m²]	Amount	Steel [kg]
Central column	280	280	3.24	0.00653	2	166
Edge column	200	200	3.24	0.00388	6	99
Corner column	160	160	3.24	0.00253	7	64
Beam 1	240	240	12.56	0.01060	1	1045
Beam 2	300	300	12.40	0.01491	1	1451
Beam 3	260	260	14.00	0.01184	1	1301
Beam 4	180	180	7.82	0.00388	1	238
Beam 5	160	160	3.58	0.00453	1	127
					TOTAL	5538

Table A.26: Column and beam characteristics - Steel S235 - L04

L04-HCS-S-235	Width [mm]	Height [mm]	Length [m]	Cross-section [m²]	Amount	Steel [kg]
Central column	240	240	3.24	0.00768	2	195
Edge column	160	160	3.24	0.00388	7	99
Corner column	120	120	3.24	0.00253	6	64
Beam 1	200	200	12.73	0.00538	1	538
Beam 2	240	240	12.49	0.00768	1	753
Beam 3	100	100	1.88	0.00212	1	31
Beam 4	180	180	7.82	0.00453	1	278
Beam 5	180	180	3.58	0.00453	1	127
					TOTAL	3195

Table A.27: Column and beam characteristics - Glulam GL24h - L01

L01-HCS-GL-24h	Width [mm]	Height [mm]	Length [m]	Amount	Glulam [kg]
Central column	300	350	3.24	4	174
Edge column	300	250	3.24	7	124
Corner column	300	200	3.24	7	99
Beam 1	250	380	12.09	1	586
Beam 2	300	550	11.99	1	1009
Beam 3.1	250	450	11.99	1	688
Beam 3.2	200	200	1.70	1	35
Beam 4	250	300	3.56	1	136
Beam 5	250	350	7.62	1	340
				TOTAL	5049

Table A.28: Column and beam characteristics - Glulam GL24h - L02

L02-HCS-GL-24h	Width [mm]	Height [mm]	Length [m]	Amount	Glulam [kg]
Central column	300	550	3.24	2	273
Edge column	300	300	3.24	6	149
Corner column	250	250	3.24	7	103
Beam 1	350	500	12.28	1	1096
Beam 2	300	700	11.93	1	1278
Beam 3.1	300	620	6.87	1	651
Beam 3.2	350	650	6.87	1	797
Beam 3.3	200	200	2.00	1	41
Beam 4	250	350	4.11	1	183
Beam 5	250	300	3.61	1	138
				TOTAL	6344

Table A.29: Column and beam characteristics - Glulam GL24h - L04

L04-HCS-GL-24h	Width [mm]	Height [mm]	Length [m]	Amount	Glulam [kg]
Central column	350	450	3.24	2	260
Edge column	300	350	3.24	7	174
Corner column	250	250	3.24	6	103
Beam 1	260	460	12.09	1	737
Beam 2.1	280	600	3.90	1	334
Beam 2.2	280	550	7.79	1	612
Beam 3	200	300	1.75	1	54
Beam 4	260	400	7.62	1	404
Beam 5	260	340	3.26	1	147
				TOTAL	4643

Table A.30: Wall characteristics - Concrete walls C30/37 - L01

L01-HCS-CW-30/37	Width [m]	Height [m]	Length [m]	Reinforcement [kg]	Concrete [kg]
wall 1	0.18	3.04	13.28	212	17375
wall 2	0.18	3.04	13.28	212	17375
wall 3	0.18	3.04	15.28	244	19992
wall 4	0.18	3.04	4.12	66	5391
wall 5	0.18	3.04	8.16	130	10676
			TOTAL	865	70810

Table A.31: Wall characteristics - Sand-limestone walls - L01

L01-HCS-SL-E150/175	**Width [m]**	**Height [m]**	**Length [m]**	**Mortar [kg]**	**Sand-lime brick [kg]**
wall 1	0.150	3.04	13.28	101	10900
wall 2	0.175	3.04	13.28	121	12717
wall 3	0.175	3.04	15.28	139	14632
wall 4	0.150	3.04	4.12	31	3382
wall 5	0.150	3.04	8.16	62	6698
			TOTAL	455	48329

Table A.32: Wall characteristics - Aerated autoclaved concrete walls - L01

L01-HCS-AAC-C3/C5	**Width [m]**	**Height [m]**	**Length [m]**	**Mortar [kg]**	**AAC [kg]**
wall 1	0.24	3.04	13.28	247	5184
wall 2	0.3	3.04	13.28	309	6480
wall 3	0.3	3.04	15.28	355	7455
wall 4	0.2	3.04	4.12	64	1340
wall 5	0.24	3.04	8.16	152	3185
			TOTAL	1127	23644

J.2 Supporting structures - CLT slab

Table A.33: Column and beam characteristics - Concrete C30/37 - L01

L01-CLT-C-30/37	Width [mm]	Height [mm]	Length [m]	Amount	Reinforcement [kg]	Concrete [kg]
Central column	200	360	3.24	4	26	552
Edge column	200	230	3.24	7	15	353
Corner column	200	230	3.24	7	15	353
Beam 1	200	310	12.37	1	104	1809
Beam 2	200	330	12.35	1	152	1910
Beam 3	200	300	14.12	1	150	1987
Beam 4	200	300	7.53	1	49	1069
Beam 5	200	300	3.40	1	20	483
				TOTAL	791	14409

Table A.34: Column and beam characteristics - Concrete C30/37 - L02

L02-CLT-C-30/37	Width [mm]	Height [mm]	Length [m]	Amount	Reinforcement [kg]	Concrete [kg]
Central column	200	440	3.24	2	31	675
Edge column	200	230	3.24	5	18	352
Corner column	200	230	3.24	7	15	353
Beam 1	200	410	12.39	1	119	2402
Beam 2	200	460	12.18	1	294	2599
Beam 3	200	430	13.95	1	165	2829
Beam 4	200	300	7.53	1	49	1069
Beam 5	200	300	3.40	1	20	483
				TOTAL	903	14966

Table A.35: Column and beam characteristics - Concrete C30/37 - L04

L04-CLT-C-30/37	Width [mm]	Height [mm]	Length [m]	Amount	Reinforcement [kg]	Concrete [kg]
Central column	300	380	3	2	38	875
Edge column	200	310	3	7	22	475
Corner column	200	230	3	6	15	353
Beam 1	200	380	12.21	1	103	2196
Beam 2	200	400	11.91	1	178	2232
Beam 3	200	300	1.77	1	7	253
Beam 4	200	330	7.45	1	84	1154
Beam 5	200	330	3.32	1	26	518
				TOTAL	719	13549

Table A.36: Column and beam characteristics - Concrete C50/60 - L01

L01-CLT-C-50/60	**Width [mm]**	**Height [mm]**	**Length [m]**	**Amount**	**Reinforcement [kg]**	**Concrete [kg]**
Central column	200	240	3.24	4	21	367
Edge column	200	230	3.24	7	15	353
Corner column	200	230	3.24	7	15	353
Beam 1	200	310	12	1	97	1811
Beam 2	200	330	12	1	152	1910
Beam 3	200	300	14	1	150	1987
Beam 4	200	300	8	1	49	1069
Beam 5	200	300	3	1	20	483
				TOTAL	762	13672

Table A.37: Column and beam characteristics - Steel S235 - L01

L01-CLT-S-235	**Width [mm]**	**Height [mm]**	**Length [m]**	**Cross-section [m²]**	**Amount**	**Steel [kg]**
Central column	200	200	3.24	0.00538	4	137
Edge column	140	140	3.24	0.00314	7	80
Corner column	100	100	3.24	0.00212	7	54
Beam 1	220	220	12.81	0.00334	1	336
Beam 2	270	270	12.61	0.00459	1	454
Beam 3	240	240	14.55	0.00391	1	447
Beam 4	220	220	7.88	0.00334	1	207
Beam 5	200	200	3.62	0.00285	1	81
					TOTAL	3350

Table A.38: Column and beam characteristics - Steel S235 - L02

L02-CLT-S-235	**Width [mm]**	**Height [mm]**	**Length [m]**	**Cross-section [m²]**	**Amount**	**Steel [kg]**
Central column	240	240	3.24	0.00768	2	195
Edge column	160	160	3.24	0.00314	6	80
Corner column	140	140	3.24	0.00314	7	80
Beam 1	240	240	12.64	0.00768	1	762
Beam 2	280	280	12.52	0.00973	1	956
Beam 3	260	260	14.16	0.00868	1	965
Beam 4	160	160	7.78	0.00314	1	88
Beam 5	140	140	3.56	0.00388	1	237
					TOTAL	4437

Table A.39: Column and beam characteristics - Steel S235 - L04

L04-CLT-S-235	**Width [mm]**	**Height [mm]**	**Length [m]**	**Cross-section [m²]**	**Amount**	**Steel [kg]**
Central column	200	200	3.24	0.00538	2	137
Edge column	140	140	3.24	0.00314	7	80
Corner column	120	120	3.24	0.00253	6	64
Beam 1	180	180	12.77	0.00453	1	454
Beam 2	220	220	12.61	0.00643	1	636
Beam 3	160	160	1.88	0.00388	1	57
Beam 4	160	160	7.84	0.00388	1	239
Beam 5	160	160	3.60	0.00388	1	110
					TOTAL	2715

Table A.40: Column and beam characteristics - Glulam GL24h - L01

L01-CLT-GL-24h	**Width [mm]**	**Height [mm]**	**Length [m]**	**Amount**	**Glulam [kg]**
Central column	250	350	3.24	4	145
Edge column	250	230	3.24	7	95
Corner column	200	230	3.24	7	76
Beam 1	200	360	12.37	1	454
Beam 2	250	450	12.48	1	716
Beam 3.1	250	380	4.08	1	198
Beam 3.2	250	400	4.08	1	208
Beam 3.3	250	450	4.20	1	241
Beam 3.4	200	200	1.54	1	31
Beam 4	250	310	7.53	2	298
Beam 5	200	270	3.63	3	100
				TOTAL	4022

Table A.41: Wall characteristics - CLT walls - L01

L01-CLT-CLTW-C3s/L7s	**Width [m]**	**Height [m]**	**Length [m]**	**CLT [kg]**
wall 1	0.080	3.06	13.28	1593
wall 2	0.260	3.06	13.28	5177
wall 3	0.260	3.06	15.28	5957
wall 4	0.060	3.06	3.86	347
wall 5	0.080	3.06	8.41	1009
			TOTAL	14083

Table A.42: Column and beam characteristics - Glulam GL24h - L02

L02-CLT-GL-24h	Width [mm]	Height [mm]	Length [m]	Amount	Glulam [kg]
Central column	230	230	3.24	2	87
Edge column	300	250	3.24	5	124
Corner column	300	350	3.24	7	174
Beam 1	300	460	12.27	1	864
Beam 2	300	570	12.23	1	1067
Beam 3.1	300	530	6.14	1	497
Beam 3.2	300	570	6.12	1	533
Beam 3.3	200	200	1.77	1	36
Beam 4	250	310	3.38	1	134
Beam 5	200	270	7.51	2	207
				TOTAL	5347

Table A.43: Column and beam characteristics - Glulam GL24h - L04

L04-CLT-GL-24h	Width [mm]	Height [mm]	Length [m]	Amount	Glulam [kg]
Central column	300	350	3.24	2	174
Edge column	250	260	3.24	7	107
Corner column	250	200	3.24	6	83
Beam 1	230	400	12.37	1	580
Beam 2.1	260	520	4.02	1	277
Beam 2.2	260	480	8.05	1	512
Beam 3	200	220	1.80	1	40
Beam 4	260	350	7.76	2	360
Beam 5	230	310	3.40	3	124
				TOTAL	3489

Table A.44: Wall characteristics - Sand-limestone - L01

L01-CLT-SL-E150/E175	Width [m]	Height [m]	Length [m]	Mortar [kg]	Sand-lime brick [kg]
wall 1	0.150	3.06	13.28	102	10972
wall 2	0.150	3.06	13.28	102	10972
wall 3	0.150	3.06	15.28	117	12624
wall 4	0.150	3.06	3.86	30	3189
wall 5	0.150	3.06	8.41	64	6948
			TOTAL	414	44706

J.3 Supporting structures - CLT-concrete slab

Table A.45: Column and beam characteristics - Concrete C30/37 - L01

L01-CLTC-C-30/37	Width [mm]	Height [mm]	Length [m]	Amount	Reinforcement [kg]	Concrete [kg]
Central column	200	410	3.24	4	31	628
Edge column	200	230	3.24	7	17	353
Corner column	200	230	3.24	7	14	353
Beam 1	200	320	12.37	1	81	1875
Beam 2	200	320	12.01	1	253	1767
Beam 3	200	320	13.78	1	113	2082
Beam 4	200	300	7.53	1	73	1062
Beam 5	200	300	3.40	1	26	482
				TOTAL	886	14723

Table A.46: Column and beam characteristics - Steel S235 - L01

L01-CLTC-S-235	Width [mm]	Height [mm]	Length [m]	Cross-section [m²]	Amount	Steel [kg]
Central column	200	200	3.24	0.00538	4	137
Edge column	140	140	3.24	0.00314	7	80
Corner column	100	100	3.24	0.00212	7	54
Beam 1	180	180	12.81	0.00453	1	456
Beam 2	220	220	12.61	0.00643	1	636
Beam 3	200	200	14.55	0.00538	1	614
Beam 4	180	180	7.88	0.00453	1	280
Beam 5	160	160	3.62	0.00388	1	110
					TOTAL	3581

Table A.47: Wall characteristics - Sand-limestone walls - L01

L01-CLTC-SL-E150/E175	Width [m]	Height [m]	Length [m]	Mortar [kg]	Sand-lime brick [kg]
wall 1	0.150	3.06	13.28	102	10972
wall 2	0.175	3.06	13.28	122	12801
wall 3	0.175	3.06	15.28	140	14728
wall 4	0.150	3.06	3.86	30	3189
wall 5	0.150	3.06	8.41	64	6948
			TOTAL	458	48638

Table A.48: Wall characteristics - CLT walls - L01

L01-CLTC-CLTW-C3s/L7s	**Width [m]**	**Height [m]**	**Length [m]**	**CLT [kg]**
wall 1	0.090	3.06	13.28	1792
wall 2	0.260	3.06	13.28	5177
wall 3	0.300	3.06	15.28	6873
wall 4	0.060	3.06	3.86	347
wall 5	0.090	3.06	8.41	1135
			TOTAL	15325

Table A.49: Column and beam characteristics - Glulam GL24h - L01

L01-CLTC-GL-24h	**Width [mm]**	**Height [mm]**	**Length [m]**	**Amount**	**Glulam [kg]**
Central column	250	350	3.24	4	145
Edge column	250	230	3.24	7	95
Corner column	250	200	3.24	7	83
Beam 1	250	350	12.43	1	555
Beam 2	250	450	12.48	1	716
Beam 3.1	250	350	4.08	1	182
Beam 3.2	250	420	4.08	1	218
Beam 3.3	250	450	4.23	1	243
Beam 3.4	200	200	1.57	1	32
Beam 4	250	330	7.59	1	319
Beam 5	250	270	3.66	1	126
				TOTAL	4213

J.4 Supporting structures - In situ concrete slab

Table A.50: Column and beam characteristics - Concrete C30/37 - L01

L01-ISC-C-30/37	Width [mm]	Height [mm]	Length [m]	Amount	Reinforcement [kg]	Concrete [kg]
Central column	300	310	3.24	4	38	712
Edge column	200	230	3.24	7	19	352
Corner column	200	230	3.24	7	14	353
Beam 1	200	340	12.37	1	94	1990
Beam 2	200	360	12.21	1	253	2032
Beam 3	200	340	13.98	1	181	2226
Beam 4	200	300	7.53	1	73	1062
Beam 5	200	300	3.40	1	26	482
				TOTAL	1011	15575

Table A.51: Column and beam characteristics - Steel S235 - L01

L01-ISC-S-235	Width [mm]	Height [mm]	Length [m]	Cross-section [m²]	Amount	Steel [kg]
Central column	240	240	3.24	0.00643	4	164
Edge column	160	160	3.24	0.00388	7	99
Corner column	120	120	3.24	0.00253	7	64
Beam 1	200	200	12.73	0.00538	1	538
Beam 2	240	240	12.49	0.00768	1	753
Beam 3	220	220	14.41	0.00643	1	727
Beam 4	200	200	7.82	0.00538	1	330
Beam 5	160	160	3.58	0.00388	1	109
					TOTAL	4253

Table A.52: Wall characteristics - Sand-limestone walls - L01

L01-ISC-SL-E150/E175	Width [m]	Height [m]	Length [m]	Mortar [kg]	Sand-lime brick [kg]
wall 1	0.150	3.06	13.28	102	10972
wall 2	0.175	3.06	13.28	122	12801
wall 3	0.175	3.06	15.28	140	14728
wall 4	0.150	3.06	3.86	30	3189
wall 5	0.150	3.06	8.41	64	6948
			TOTAL	458	48638

J.5 Supporting structures - Wide slab

Table A.53: Column and beam characteristics - Concrete C30/37 - L01

L01-WS-C-30/37	**Width [mm]**	**Height [mm]**	**Length [m]**	**Amount**	**Reinforcement [kg]**	**Concrete [kg]**
Central column	300	340	3.24	4	38	781
Edge column	200	280	3.24	7	27	427
Corner column	200	230	3.24	7	14	353
Beam 1	200	350	12.27	1	124	2023
Beam 2	200	360	12.05	1	253	2005
Beam 3	200	340	13.87	1	150	2218
Beam 4	200	300	7.48	1	73	1055
Beam 5	200	300	3.35	1	26	474
				TOTAL	1072	16364

Table A.54: Column and beam characteristics - Steel S235 - L01

L01-WS-S-235	**Width [mm]**	**Height [mm]**	**Length [m]**	**Cross-section [m²]**	**Amount**	**Steel [kg]**
Central column	240	240	3.24	0.00768	4	447
Edge column	180	180	3.24	0.00453	7	250
Corner column	120	120	3.24	0.00253	7	110
Beam 1	200	200	12.69	0.00538	1	536
Beam 2	240	240	12.45	0.00768	1	751
Beam 3	220	220	14.39	0.00643	1	726
Beam 4	200	200	7.80	0.00538	1	329
Beam 5	180	180	3.56	0.00453	1	127
					TOTAL	6773

Table A.55: Wall characteristics - Sand-limestone walls - L01

L01-WS-SL-E150/E175	**Width [m]**	**Height [m]**	**Length [m]**	**Mortar [kg]**	**Sand-lime brick [kg]**
wall 1	0.150	3.04	13.28	101	10900
wall 2	0.214	3.04	13.28	145	15551
wall 3	0.214	3.04	15.28	167	17893
wall 4	0.150	3.04	3.86	29	3168
wall 5	0.150	3.04	8.41	64	6903
			TOTAL	507	54415

FACULTY OF ENGINEERING
AND ARCHITECTURE

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