

École polytechnique de Louvain

Analysis & Comparison of the Carbon Footprint of CLT Floor Systems

Baseline modelling and parametric optimisation

Author: **Eimantas JANUSIS**

Supervisor: **Pierre LATTEUR**

Readers: **Youri CARLSON, Hadrien RATTEZ, Martin STEINMETZ**

Academic year 2025–2026

Master [120] in Civil Engineering

Contents

1	Introduction	1
2	State of the Art	5
3	Research Objectives and Questions	8
4	Scope, Assumptions and Limitations	10
5	Methodology	12
6	Structural design framework of CLT floor systems	13
6.1	CLT panel configuration and structural behaviour	13
6.2	Actions and load effects	16
6.3	Ultimate Limit State Design	17
6.3.1	Bending verification	17
6.3.2	Shear verification	20
6.4	Serviceability Limit State verifications	25
6.4.1	Deflection verification	25
6.4.2	Vibration verification	31
7	Acoustic assessment	35
8	Fire resistance assessment	39
8.1	Fire action and design situation	39
8.2	Charring depth and residual cross-section	40
9	Environmental assessment	42
9.1	Environmental data for CLT	43

9.2	Environmental data for reinforced concrete	45
9.3	Calculation approach	46
10	Economic assessment	48
10.1	CLT floor systems	48
10.2	Reinforced concrete slabs	49
11	Results and discussion	51
11.1	Overview of the analysed configurations	51
11.2	Structural performance	51
11.2.1	Structural feasibility of CLT floor systems	52
11.2.2	Governing utilisation criteria	53
11.2.3	Influence of fire resistance requirements	55
11.3	Environmental performance	57
11.4	Economic performance	60
11.4.1	Material cost	60
11.4.2	Cost-carbon trade-off	61
11.5	Comparison with reinforced concrete floor systems	64
11.5.1	Structural comparison	64
11.5.2	Environmental and economic comparison	66
11.6	Application domains and design recommendations	69
12	Summary of the main findings	72
	References	74
A	Envelope-point utilisation ratios for representative CLT curves	80
B	Hand Calculation Note: Design of CLT Floor Systems	81

B.1	Worked Example: 7-Layer CLT Floor Panel	81
B.1.1	Problem Definition	81
B.1.2	Loads and Design Combinations	83
B.1.3	Position of the Centre of Gravity	83
B.1.4	Moment of Inertia	84
B.1.5	Section Modulus	85
B.1.6	Static Moments	85
B.1.7	Application of the Extended Gamma Method	86
B.1.8	Effective Moment of Inertia	88
B.1.9	Ultimate Limit State Bending and Shear Checks	89
B.1.10	Deformations (Serviceability Limit State)	89
B.1.11	Vibrations	91
B.1.12	Environmental Assessment – Life Cycle Assessment (A1–A3)	92
B.1.13	Cost Assessment	93

1 Introduction

The buildings and construction sector plays a dominant role in global energy demand and greenhouse gas emissions. According to the 2024/2025 Global Status Report for Buildings and Construction, the sector accounted for approximately 32% of global energy demand and 34% of global CO₂ emissions in 2023. These figures confirm that the built environment remains one of the largest contributors to climate change. A significant share of these emissions originates not only from building operation, but also from the production of construction materials such as concrete, steel and glass. As operational energy demand continues to decrease due to stricter energy-efficiency regulations, the relative importance of embodied carbon has steadily increased.

Embodied carbon refers to the carbon dioxide equivalent (CO₂e) emissions associated with the extraction, processing and manufacturing of construction materials and products. These emissions are largely determined during the early design phases, when structural systems, spans and material choices are defined. Consequently, structural design decisions now have a decisive influence on the overall environmental performance of buildings and represent a key lever for achieving the decarbonisation targets set by the Paris Agreement and the European Green Deal.

Among structural components, floor systems represent a substantial share of material quantities and embodied carbon in multi-storey buildings. This is particularly true for office, residential and hotel buildings, where large spans, high imposed loads and service integration requirements often lead to material-intensive structural solutions. The choice of a floor system directly affects the quantities of concrete, steel or timber required and, therefore, the associated environmental impact and cost. Traditionally, floor systems have been selected primarily on the basis of structural performance, constructability and economic considerations, while environmental aspects were often treated qualitatively or addressed only at a later stage of the design process.

Reinforced concrete slabs remain the conventional reference solution for floor systems in multi-storey construction. Their widespread use is explained by their robustness, stiffness, durability, fire resistance and the maturity of design and construction practices associated with them. However, concrete structures are also associated with significant embodied carbon, largely due to cement production. This issue is becoming increasingly important as the construction sector is subject to growing environmental pressure and progressively stricter carbon-related regulations. In France, for example, the RE2020 regulation introduces maximum whole-life carbon thresholds for new buildings. From 2025 onwards, the construction-stage carbon indicator $I_{c, \text{construction}}$ is limited to approximately 530 kgCO₂e/m² for single-

family houses, 650 kgCO₂e/m² for collective housing and around 810 kgCO₂e/m² for office buildings. In the Netherlands, the MPG regulation also requires the environmental performance of new residential buildings and office buildings larger than 100 m² to be assessed. These regulatory developments create a clear incentive to reduce the carbon footprint of structural systems and explain the growing interest in timber-based solutions such as CLT as potential low-carbon alternatives.

Among these systems, Cross-Laminated Timber (CLT) floor panels have emerged as a promising solution for low- and medium-rise buildings, and increasingly for certain taller applications. As a renewable material, timber offers the advantage of storing biogenic carbon, with approximately 50% of its dry mass consisting of carbon. Life-cycle assessment studies indicate that timber elements typically require less energy and fossil fuel to manufacture than conventional reinforced concrete solutions, particularly in floor structures. In addition, CLT systems offer a high degree of prefabrication, rapid on-site assembly and a favourable strength-to-weight ratio, making them attractive from both environmental and construction perspectives.

Nevertheless, the environmental advantage of CLT floor systems cannot be assumed by default. Their performance strongly depends on span length, loading conditions, panel thickness, number of layers and structural configuration. Moreover, CLT floors must satisfy strict structural requirements, including ultimate and serviceability limit state criteria such as bending, shear, deflection and vibration. In addition to these structural criteria, fire resistance and acoustic comfort must also be considered, as they can significantly influence the final floor build-up and the amount of material required. These requirements directly affect the embodied carbon and cost of the system. In practice, a solution with lower carbon intensity is not necessarily the most structurally efficient, the most economically competitive or the most suitable from a fire and acoustic performance perspective. Conversely, a more conventional reinforced concrete slab may remain more appropriate in certain situations, particularly when large spans, high stiffness requirements, vibration sensitivity, fire resistance or acoustic comfort govern the design.

The choice between CLT floor systems and reinforced concrete slabs should therefore not be approached as a purely material-based preference, but as a comparative design problem in which structural feasibility, embodied carbon and cost must be evaluated simultaneously. From this perspective, neither system is universally superior. Rather, their relative suitability depends on the design context, the governing structural criteria and the project priorities. A rational comparison is therefore needed to determine under which conditions CLT constitutes a competitive alternative to reinforced concrete and under which conditions concrete remains the more appropriate solution.

Despite the growing awareness of embodied carbon in construction, structural designers still lack practical tools that systematically connect structural performance requirements with material quantities, cost and carbon footprint at the early design stage. Existing studies are often project-specific, time-consuming or limited to environmental comparisons without fully integrating structural verification. Others remain disconnected from parametric design workflows, which reduces their applicability in engineering practice. There is therefore a clear need for structured and parametric methodologies capable of comparing alternative floor systems under equivalent design conditions and supporting early-stage decision-making.

This master's thesis is carried out within the framework of a broader research and development initiative at the BESIX Engineering Department, which aims to develop decision-support tools for the optimisation of structural systems in real engineering projects and tenders. In this context, the present work proposes a comparative and parametric methodology for assessing CLT floor systems and reinforced concrete slab systems with respect to structural performance, embodied carbon and material cost.

The main objective of this thesis is to develop a baseline comparative structural model for CLT floor systems and reinforced concrete slabs and to perform a parametric analysis of key design variables, including span, loading conditions, floor thickness and structural configuration. Based on these parameters, material quantities are quantified and the associated embodied carbon emissions for the A1–A3 life-cycle stages are evaluated and expressed in kgCO₂e per square metre, together with corresponding material costs. The study aims not only to assess the performance of CLT floor systems but also to identify the design situations in which CLT constitutes a competitive and relevant alternative to reinforced concrete slabs and those in which concrete remains the more advantageous solution. Office buildings are considered as the reference case due to their structurally demanding floor requirements and their significant contribution to embodied carbon, while ensuring full compliance with ultimate and serviceability limit state criteria.

This thesis is structured as follows. Chapter 2 presents the state of the art on CLT and reinforced concrete floor systems, focusing on structural behaviour, environmental performance, economic considerations and dynamic aspects. Chapter 3 defines the research objectives and questions, while Chapter 4 presents the scope, assumptions and limitations of the study. Chapter 5 describes the methodology and the parametric workflow developed to compare the investigated floor systems. Chapter 6 introduces the structural design framework for CLT panels, including ultimate and serviceability limit state verifications. Chapter 7 discusses the acoustic performance of CLT floors. Chapter 8 presents the fire resistance assessment, and Chapters 9 and 10 describe the environmental and economic assessment methods. Chapter 11 presents the results and discussion, including the structural, environmental and economic performance of the investigated configurations, their comparison with reinforced concrete floor

systems and the resulting application domains and design recommendations. Finally, the appendix provides additional utilisation-ratio data for representative CLT envelope points.

2 State of the Art

A growing body of literature has investigated the environmental performance of timber-based construction in comparison with conventional reinforced concrete or steel structures. In particular, Life Cycle Assessment (LCA) has been widely used to compare CLT buildings with functionally equivalent reference buildings. Several comparative studies have assessed CLT against reinforced concrete or steel benchmark structures, generally at building scale and primarily through environmental indicators. These studies differ significantly in geographical context, system boundaries, impact category coverage and building typology, which limits direct comparability. Only a limited number of them also include an explicit economic perspective.

Life Cycle Assessment (LCA) is a standardised method used to quantify the environmental impacts of a product, system or building over its life cycle. In the construction sector, an LCA generally accounts for several stages, including raw material extraction, transport, manufacturing, construction, use, maintenance and end-of-life. These stages are commonly divided into modules, from A1–A3 for the product stage, A4–A5 for transport and construction, B modules for the use stage and C modules for end-of-life. Depending on the objective of the study, the assessment may cover the whole life cycle or focus on specific stages only. This distinction is important because the conclusions of CLT–concrete comparisons can vary depending on the system boundaries adopted, particularly when biogenic carbon storage and end-of-life scenarios are considered.

Among the building-scale LCA studies identified in the literature, Andersen et al. (2022) carried out a consequential LCA of two similar mid-rise apartment buildings using either concrete or CLT as the main structural material, with particular attention to biogenic carbon. Their results showed that the CLT building achieved the lowest impact score in 11 out of 18 impact categories, including global warming. More generally, comparative assessments in the literature consistently report lower climate change impacts for CLT buildings than for conventional benchmark structures, although most of them remain focused on environmental indicators only.

The economic dimension has been addressed less systematically in the literature. Tokede et al. (2022) extended environmental analysis with life cycle costing, while Cazemier (2017) compared a CLT residential development with a concrete-and-steel reference building from a developer perspective using indicators such as development profit, development margin, return on equity and equity internal rate of return. These studies are useful in showing that the comparison between timber and conventional construction cannot be reduced to direct material cost alone. However, they remain focused on either whole-building LCA or

developer-level financial feasibility rather than on structural floor-system design.

Other studies have examined individual aspects relevant to structural comparison. Hassan and Girhammar (2013) investigated footfall-induced vibrations in timber and lightweight floor systems, highlighting the importance of dynamic behaviour in lightweight structures. Hassan and Johansson (2018) compared timber and steel beams in terms of structural, economic and environmental consequences, illustrating the value of integrated multi-criteria assessment. Petersen and Solberg (2002) also compared laminated wood and steel beams from an environmental and cost-efficiency perspective. In parallel, studies such as Sandin et al. (2013), Hill and Dibdiakova (2016), Sathre and O'Connor (2010), Cole (1999) and Gustavsson et al. (2006) have shown both the environmental potential of wood-based construction and the sensitivity of the results to modelling assumptions such as system boundaries, transport and end-of-life treatment.

Overall, the literature confirms that timber-based construction can offer significant environmental advantages compared with conventional materials and that economic and structural considerations strongly influence the relevance of alternative systems. However, most previous studies remain either building-scale environmental comparisons, developer-level financial analyses or studies focused on isolated aspects such as vibration or beam-level comparison. In order to clarify the scope of the existing literature, Table 1 provides a comparative overview of the main studies identified, highlighting whether they address structural, environmental, economic and dynamic aspects.

The present thesis is positioned within this gap. It develops a comparative parametric framework for CLT floor systems and reinforced concrete slab systems under equivalent design conditions. The aim is not only to compare both systems in terms of structural performance, embodied carbon and material cost, but also to determine under which conditions CLT constitutes a relevant alternative to reinforced concrete and under which conditions reinforced concrete remains the more appropriate solution.

Table 1: Overview of selected previous studies relevant to this thesis.

Authors	Scale	Comparison	Region	Struct.	Env.	Cost	Dynamic
Klein Goldewijk (2025)	Building	CLT vs concrete vs GPC	Netherlands	No	Yes	Yes	No
Andersen et al. (2022)	Building	CLT vs concrete	Norway	No	Yes	No	No
Duan et al. (2022)	Building	CLT vs RC	China	No	Yes	No	No
Tokede et al. (2022)	Building	CLT vs RC	Australia	No	Yes	Yes	No
Ryberg et al. (2021)	Building	CLT vs RC	Greenland	No	Yes	No	No
Allan and Phillips (2021)	Building	Timber vs steel	US	No	Yes	No	No
Liang et al. (2020)	Building	CLT vs RC	US	No	Yes	No	No
Y. Dong et al. (2020)	Building	CLT vs RC	China	No	Yes	No	No
Pierobon et al. (2019)	Building	CLT vs RC office	US	No	Yes	No	No
Cazemier (2017)	Building	CLT vs concrete/steel	Australia	No	No	Yes	No
Hassan and Girhammar (2013)	Floor	Timber/lightweight floors	Sweden	Partial	No	No	Yes
Hassan and Johansson (2018)	Element	Timber vs steel beams	Sweden	Yes	Yes	Yes	No
Petersen and Solberg (2002)	Element	Wood vs steel beams	Norway	No	Yes	Yes	No
Sandin et al. (2013)	Material	LCA methodology	Sweden	No	Yes	No	No
Hill and Dibdiakova (2016)	Review	Wood vs conventional	Sweden/Finland	No	Yes	No	No
Sathre and O'Connor (2010)	Review	Wood products vs alternatives	Canada	No	Yes	No	No
Cole (1999)	Material	Material transport/logistics	Canada	No	Yes	No	No
Gustavsson et al. (2006)	Material	Wood and GHG mitigation	Sweden	No	Yes	No	No

3 Research Objectives and Questions

Based on the literature reviewed in the previous section, a clear need exists for comparative methodologies capable of assessing CLT floor systems and reinforced concrete slabs under equivalent design conditions while simultaneously accounting for structural feasibility, embodied carbon and cost. The present thesis addresses this need through the development of a comparative parametric framework intended to support early-stage structural decision-making.

The main objective of this thesis is to develop a comparative structural model for CLT floor systems and reinforced concrete slabs and to evaluate their relative performance under varying design conditions. The comparison is carried out with respect to three principal dimensions: structural performance, embodied carbon and material cost. In this way, the study aims not only to assess the potential of CLT floor systems on their own but also to determine under which conditions they constitute a relevant and competitive alternative to reinforced concrete slabs.

More specifically, the thesis pursues the following objectives:

- to define equivalent reference conditions for the comparison of CLT floor systems and reinforced concrete slabs
- to develop a baseline structural model for both systems and verify their compliance with ultimate and serviceability limit state requirements
- to perform a parametric analysis of the main design variables, including span, loading conditions, floor thickness and structural configuration
- to quantify the material quantities associated with each solution and evaluate the corresponding embodied carbon for the A1–A3 life-cycle stages
- to estimate and compare the material cost of both systems
- to identify the design situations in which CLT floor systems are most competitive, as well as those in which reinforced concrete slabs remain the more appropriate solution

In order to achieve these objectives, the thesis is structured around the following research questions:

- How do span length, loading conditions and structural configuration influence the structural feasibility of CLT floor systems and reinforced concrete slabs?

- Which criteria govern the design of each system most frequently, particularly with respect to ultimate limit states, deflection and vibration?
- How do embodied carbon emissions and material cost evolve for both systems under equivalent design conditions?
- Under which design conditions does CLT constitute a competitive alternative to reinforced concrete in terms of structural performance, embodied carbon and cost?
- In which situations does reinforced concrete remain the more appropriate solution?

These objectives and questions define the framework of the study and guide the methodological developments presented in the following sections.

4 Scope, Assumptions and Limitations

This thesis compares CLT floor systems and reinforced concrete slabs at floor-system level under equivalent design conditions. The comparison is limited to the slab or panel elements themselves, without considering supporting beams or the wider structural system. Consequently, the study does not extend to the full building scale.

Both systems are modelled as simply supported one-way slabs supported either by load-bearing walls or by beams. The supporting elements themselves are not dimensioned in this study. Continuity over multiple supports is not considered, in order to maintain equivalent boundary conditions between the CLT and reinforced concrete alternatives and to focus the comparison on the floor elements themselves.

With respect to loading, the study considers imposed loads representative of office buildings as well as residential and hotel applications. This makes it possible to evaluate how the relative performance of CLT and reinforced concrete evolves under different practical occupancy scenarios.

For the CLT alternative, panel configurations composed of three, five and seven layers are considered. These configurations correspond to the most common CLT lay-ups used for floor applications and allow the influence of panel thickness and number of layers to be investigated. Only symmetrical lay-ups are adopted, meaning that the layer arrangement is mirrored about the mid-depth of the panel and that the neutral axis is located at the centre of the middle layer. This assumption is consistent with standard CLT practice, whereas unsymmetrical lay-ups are rarely used for conventional floor applications. The timber elements are assumed to be in service class 1. The timber strength classes considered are C14, C16, C24 and C30, as these are among the commonly used strength classes identified in the literature and in practice.

For the reinforced concrete alternative, in-situ reinforced concrete slabs are considered. Concrete strength classes C30/37, C35/45 and C40/50 are adopted, as these represent typical structural concrete classes used in building practice and allow the influence of concrete strength on the comparison to be assessed without extending the study to more specialised concrete types. Different cement mixtures are also considered, namely CEM I, CEM III/A, CEM III/B and CEM V/A, in order to capture the influence of cement composition on the environmental performance of the slab. Reinforcement is provided by B500B rebars.

The environmental assessment is limited to the A1–A3 life-cycle stages, corresponding to raw material supply, transport and manufacturing. Later life-cycle stages are not considered, as they depend more strongly on project-specific assumptions.

The economic assessment is limited to material cost and ready-to-assemble cost. The economic data adopted for each floor type are based on cost information representative of the Belgian construction market, obtained from internal BESIX data and supplier-related information. Labour, transport, formwork, installation time, site equipment, construction duration and indirect project costs are not included unless already reflected in the adopted ready-to-assemble cost data.

5 Methodology

The methodology adopted in this thesis is based on a comparative parametric workflow developed to assess CLT floor systems and reinforced concrete slabs in terms of structural performance, embodied carbon and material cost. The objective is not only to generate structurally feasible solutions for both floor types, but also to enable a clear interpretation of the influence of the main design parameters on the final results.

For the CLT alternative, the main structural calculations were first implemented in an Excel sheet. This calculation framework was then connected to Grasshopper in order to automate the evaluation of multiple configurations and to generate the final outputs for a broad range of spans, loading conditions, panel thicknesses and material classes. This workflow made it possible to test a large number of CLT design combinations efficiently while maintaining a consistent calculation procedure.

For the reinforced concrete alternative, SCIA Engineer was used as the main structural analysis tool. SCIA was linked to Grasshopper in order to evaluate multiple slab configurations under varying design conditions and to extract the corresponding structural results. This approach allowed the reinforced concrete solutions to be analysed within a parametric workflow comparable to that used for the CLT floors.

Once the structural calculations had been carried out, only the solutions satisfying the required design criteria were retained for the subsequent comparison. The valid results were then processed in order to determine the corresponding embodied carbon and cost indicators for each floor configuration.

In addition to supporting the calculation process, the digital workflow was also developed to facilitate the interpretation of the results. The final outputs obtained from Excel, Grasshopper and SCIA were post-processed using Python and exported to Power BI, where they could be organised, visualised and compared more clearly. This made it possible to clean and structure the generated datasets, analyse trends, identify governing parameters and compare the relative performance of CLT floor systems and reinforced concrete slabs under different design scenarios.

The methodology therefore combines structural calculation tools, parametric modelling and data visualisation within a single workflow. In this way, the study does not only assess individual design solutions, but also provides a broader interpretation of the conditions under which each floor system becomes structurally, environmentally and economically relevant.

6 Structural design framework of CLT floor systems

The structural design of Cross-Laminated Timber (CLT) floor systems is based on the limit state design approach defined in the Eurocodes. The objective is to ensure both structural safety and satisfactory serviceability throughout the intended service life of the floor system.

Design verifications are carried out using the partial factor method, in which the design effects of actions are compared with the corresponding design resistances at the Ultimate Limit State (ULS). Structural safety is verified by ensuring that the effects of actions remain lower than the associated resistances. In parallel, the Serviceability Limit State (SLS) governs the behaviour of the floor under normal use, particularly with respect to deflection, vibration and overall usability. In addition to these structural verifications, fire resistance and acoustic performance are also considered, as they may influence the suitability of CLT floor systems and the final floor build-up required to meet project-specific performance requirements.

For CLT floor systems, the design process consists of determining the internal forces and deformations induced by permanent and variable actions and verifying the relevant limit states for the considered structural configuration. Since the floors are modelled as one-way spanning elements, the structural response is primarily assessed in the main spanning direction.

6.1 CLT panel configuration and structural behaviour

A CLT floor panel consists of several timber board layers stacked orthogonally and bonded together with structural adhesive to form a structural plate element. In practice, CLT panels generally contain an odd number of layers, so that the outer layers are oriented in the same direction and are located furthest from the neutral axis. This configuration is structurally favourable, since the outer longitudinal layers contribute most to the bending resistance and bending stiffness of the panel.

For the present study, the CLT floor is modelled as a one-way spanning element. The main spanning direction is denoted by x , while the perpendicular in-plane direction is denoted by y . The design span of the floor panel is denoted by L and the panel width is denoted by B . The outer layers are oriented parallel to the span direction x , which therefore corresponds to the strong direction of the panel, while the direction y represents the weak direction.

The thickness of each individual layer is denoted by $t_1, t_2, \dots, t_i$, counted from the bottom

to the top of the panel. The total thickness of the CLT element is denoted by h_{CLT} and corresponds to the sum of all layer thicknesses:

$$h_{CLT} = \sum_i t_i$$

In this study, symmetrical panel configurations are generated for 3-, 5- and 7-layer CLT panels. The individual layer thicknesses considered are 20, 30 and 40 mm, as these are among the most commonly used layer thicknesses in practice. Only symmetrical lay-ups are considered, which is consistent with standard CLT floor applications and ensures that the neutral axis remains located at the centre of the middle layer.

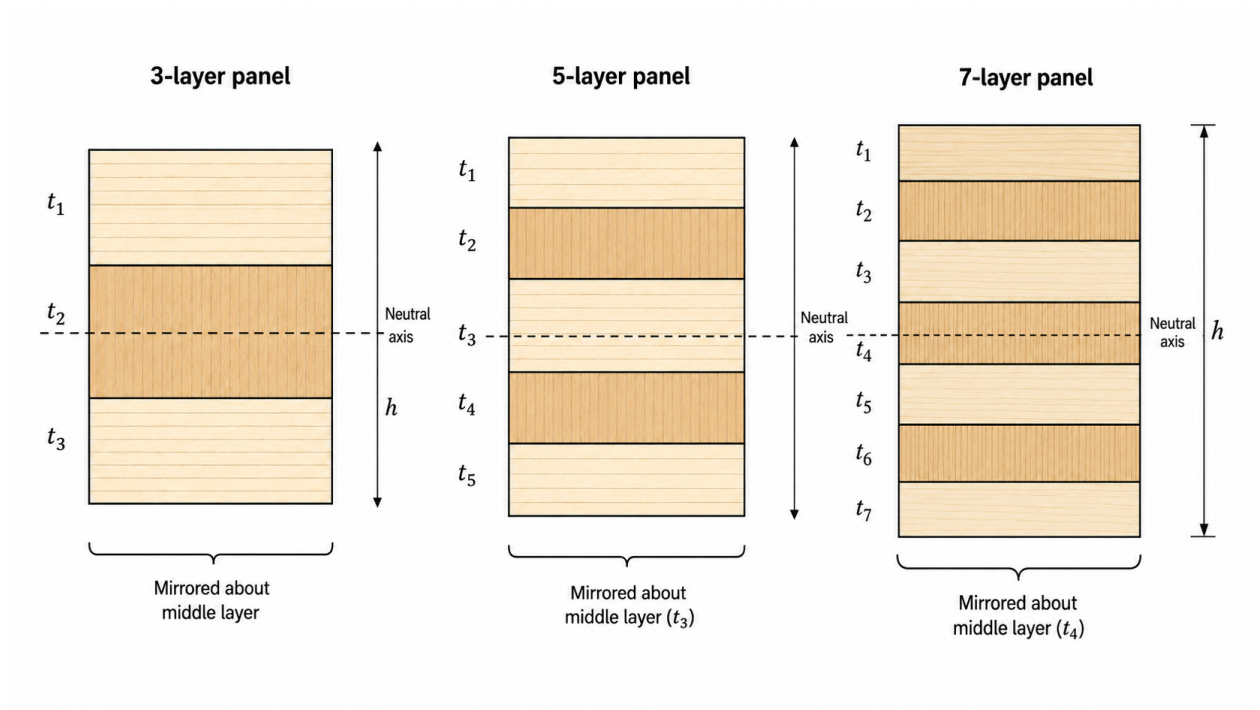


Figure 1: Symmetrical CLT panel configurations considered in the study.

Because the floor is assumed to span in one direction only, the structural response is primarily evaluated along the span direction x . In this case, only the longitudinal board layers, i.e. those oriented parallel to the design span L , are considered as load-carrying layers in bending. These layers provide the main contribution to bending stiffness and bending resistance. By contrast, the transverse layers, oriented perpendicular to the span direction, are mainly considered as intermediate layers and are primarily subjected to shear.

The orthogonal layup of CLT leads to different mechanical properties in the two principal directions. The net moment of inertia in the strong direction, denoted by $I_{\text{net},x}$, is therefore

significantly greater than the net moment of inertia in the weak direction, denoted by $I_{\text{net},y}$. This difference reflects the fact that the outer layers, which are furthest from the neutral axis and therefore most effective in bending, are aligned with the main spanning direction.

Although the transverse layers are not considered as the primary load-carrying layers in bending along the span direction, they remain mechanically important. These layers are mainly subjected to shear and in particular to rolling shear, which is the shear deformation that develops in timber loaded perpendicular to the grain direction.

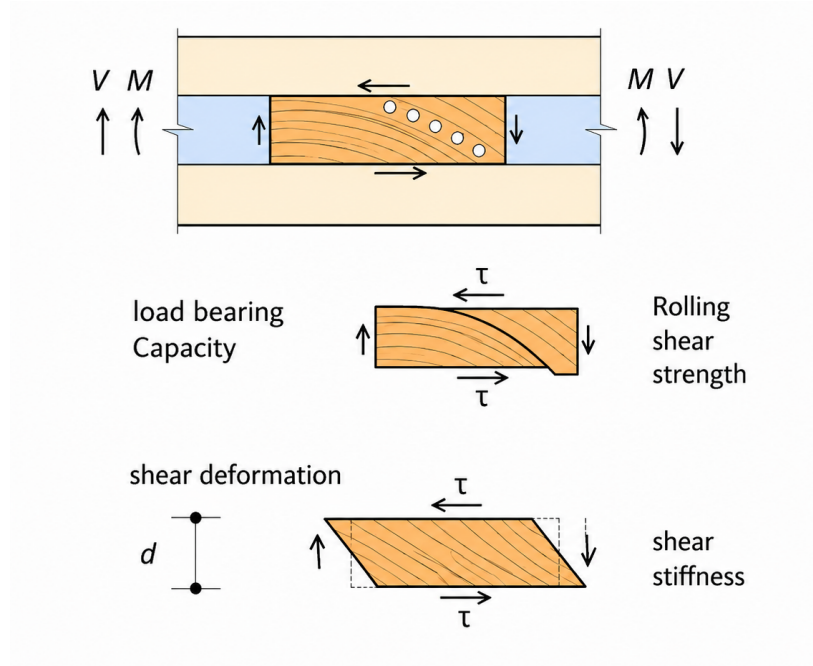


Figure 2: Conceptual illustration of shear transfer and rolling shear in the transverse layer of a 3-layer CLT panel.

As a result, a CLT panel cannot be treated as a fully rigid monolithic section, but rather as a partially composite structure. In Eurocode 5 based design, this effect is commonly taken into account through the Gamma method, which is used to determine the effective bending stiffness EI_{eff} of the panel. In this approach, the longitudinal layers are treated as the main bending-carrying layers, while the transverse layers are represented through their shear connection effect. The method therefore accounts for the horizontal shear deformation occurring in the layers oriented perpendicular to the design span direction. Shear deformation in the longitudinal layers is neglected in this approach.

A key parameter of the gamma method is the factor γ_i , which represents the degree of interaction between the longitudinal layers. A value of $\gamma_i = 1$ corresponds to fully effective interaction, while a lower value reflects reduced composite action due to shear deformability

in the transverse layers. In this way, the method provides a practical and code-consistent approximation of the partially composite behaviour of CLT floor panels.

6.2 Actions and load effects

The loading actions considered for the investigated floor systems consist of the characteristic permanent actions and the characteristic imposed action on the floor. The permanent actions include the self-weight of the structural element together with the non-structural layers permanently attached to the floor, such as floor finishes, partitions, ceilings and MEP-related components. The imposed action is selected according to the intended occupancy of the building.

For the present study, the imposed load is considered for typical office, apartment/hotel applications. In parallel with the imposed load, the associated permanent loads are chosen so as to represent realistic floor constructions for these occupancy types. The indicative values adopted in the study are summarised in Table 2.

Table 2: Indicative permanent and variable floor loads for typical building uses

Load component	Office [kN/m ²]	Apartment / hotel [kN/m ²]
Floor finishing (false floor / screed ~7 cm)	0.5	1.6
Partitions (dry partition / masonry)	1.2	2.5
Ceiling & MEP	0.2	0.2
Variable load	2.5	2.0
Total	4.4	6.3

The effects of actions correspond to the structural response generated by these loads, such as bending moments, shear forces and deflections. Their design values are determined by applying the load combinations adopted in this study.

At the Ultimate Limit State (ULS), the design uniformly distributed load is taken as:

$$q_{Ed} = 1.35 G_k + 1.5 Q_k$$

where G_k is the characteristic permanent action and Q_k is the characteristic variable action.

At the Serviceability Limit State (SLS), the characteristic load combination is adopted in the study:

$$q_{SLS,char} = 1.0 G_k + 1.0 Q_k$$

Since the floor systems are modelled as simply supported one-way slabs subjected to a uniformly distributed load, the principal load effects in the span direction are determined using standard beam theory. The design bending moment is given by:

$$M_{Ed} = \frac{qL^2}{8}$$

and the corresponding design shear force is:

$$V_{Ed} = \frac{qL}{2}$$

where q represents the relevant uniformly distributed load for the considered limit state.

6.3 Ultimate Limit State Design

At the Ultimate Limit State (ULS), the floor panel must satisfy the relevant strength requirements so that structural failure does not occur under the design load combination. For the CLT floor system considered in this study, the main ULS verifications are carried out in the spanning direction x , which corresponds to the strong direction of the panel.

6.3.1 Bending verification

Since the floor is modelled as a one-way spanning element, bending occurs about the major principal axis. The following requirement must therefore be satisfied:

$$\sigma_{m,d} \leq f_{m,d}$$

where:

- $\sigma_{m,d}$: design bending stress
- $f_{m,d}$: design bending strength of the CLT panel in the considered direction

The design bending strength is determined according to Eurocode 5 as:

$$f_{m,d} = \frac{k_{mod} f_{m,k}}{\gamma_M}$$

where:

- k_{mod} : modification factor accounting for load duration and service class
- $f_{m,k}$: characteristic bending strength
- γ_M : partial material factor

The characteristic bending strength $f_{m,k}$ depends on the selected timber strength class. The values considered in this study are summarised in Table 3.

Table 3: Characteristic bending strength $f_{m,k}$ for the timber strength classes considered in the study

Property	C14	C16	C24	C30
Bending strength $f_{m,k}$ [N/mm ²]	14	16	24	30

The partial material factor γ_M accounts for uncertainties related to material variability, production quality and the level of control. For CLT elements, the adopted values for ULS verifications are summarised in Table 4.

Table 4: Partial material factor γ_M adopted for CLT elements

Design situation	γ_M
ULS – fundamental combinations	1.25
ULS – accidental combinations	1.00

The modification factor k_{mod} accounts for the influence of load duration and service class on timber strength. For CLT elements, the same values as those defined for structural timber in Eurocode 5 are adopted. The corresponding values are summarised in Table 5.

Table 5: Modification factor k_{mod} for CLT as a function of service class and load duration

Service class	Permanent	Long-term	Medium-term	Short-term
1	0.60	0.70	0.80	0.90
2	0.60	0.70	0.80	0.90
3	0.50	0.55	0.65	0.70

In the present study, service class 1 is adopted for the CLT floor systems. For the ULS bending verification, the imposed occupancy load Q_k is treated as a medium-term action, while the permanent load G_k is classified as permanent. Since the governing variable action is therefore medium-term, the value adopted for the modification factor is:

$$k_{mod} = 0.8$$

For the fundamental ULS combination, the adopted partial material factor is:

$$\gamma_M = 1.25$$

The design bending stress is calculated from the design bending moment and the net section modulus of the panel:

$$\sigma_{m,d} = \frac{M_{Ed}}{W_{i,\text{net}}}$$

where:

- M_{Ed} : design bending moment
- $W_{i,\text{net}}$: net section modulus of the panel

For a simply supported one-way slab subjected to a uniformly distributed design load, the design bending moment is:

$$M_{Ed} = \frac{q_{Ed}L^2}{8}$$

The net section modulus is expressed as:

$$W_{i,\text{net}} = \frac{2I_{x,\text{net}}}{h_{CLT}}$$

where:

- $I_{x,\text{net}}$: net moment of inertia in the main spanning direction
- h_{CLT} : total thickness of the CLT panel

The net moment of inertia is obtained by summing the contribution of the longitudinal load-carrying layers only:

$$I_{x,\text{net}} = \sum \frac{E_{x,i}}{E_{ref}} \frac{b_i t_i^3}{12} + \sum \frac{E_{x,i}}{E_{ref}} b_i t_i a_i^2$$

where:

- E_{ref} : reference modulus of elasticity
- $E_{x,i}$: modulus of elasticity of layer i in the longitudinal direction

- b_i : width of layer i
- t_i : thickness of layer i
- a_i : distance between the centroid of layer i and the neutral axis of the panel

The modulus of elasticity used in the calculation depends on the selected timber strength class. The mean values adopted in this study are summarised in Table 6.

Table 6: Mean modulus of elasticity parallel to the grain for the timber strength classes considered in the study

Property	C14	C16	C24	C30
$E_{x,mean}$ [MPa]	7000	8000	11000	12000

In the present study, the same timber quality is assumed for all longitudinal load-carrying layers. As a result, $E_{x,i} = E_{ref}$ and therefore:

$$\frac{E_{x,i}}{E_{ref}} = 1$$

In accordance with the one-way bending assumption, only the layers oriented parallel to the span direction are considered as load-carrying in this verification.

For each panel configuration, the bending utilization ratio is finally evaluated as:

$$UC_m = \frac{\sigma_{m,d}}{f_{m,d}}$$

A configuration is considered satisfactory with respect to bending resistance when:

$$UC_m \leq 1$$

6.3.2 Shear verification

In addition to bending, the CLT floor panel must also be verified in shear at the Ultimate Limit State. For one-way floor action, two shear mechanisms are considered in the main spanning direction: rolling shear in the transverse layers and longitudinal shear in the layers oriented parallel to the grain. These two verifications are required because the orthogonal layup of CLT leads to different shear behaviours depending on the orientation of the layers.

Rolling shear verification

Rolling shear develops mainly in the transverse layers (layers oriented perpendicular to the design span). It corresponds to shear acting across the grain direction of the timber which is associated with a relatively low shear stiffness and shear strength compared with the longitudinal direction. As a result, the transverse layers can govern the shear resistance of the panel. The following requirement must therefore be satisfied:

$$\tau_{r,d} \leq f_{v,r,d}$$

where:

- $\tau_{r,d}$: design rolling shear stress
- $f_{v,r,d}$: design rolling shear strength

The design rolling shear strength is determined as:

$$f_{v,r,d} = \frac{k_{mod} f_{v,r,k}}{\gamma_M}$$

where:

- k_{mod} : modification factor accounting for load duration and service class
- $f_{v,r,k}$: characteristic rolling shear strength
- γ_M : partial material factor

In the present study, the same values adopted for the ULS bending verification are used, namely $k_{mod} = 0.8$ and $\gamma_M = 1.25$. For the characteristic rolling shear strength, the value

$$f_{v,r,k} = 0.7 \text{ N/mm}^2$$

is adopted. This value is consistent with commonly recommended design values for CLT rolling shear.

The design rolling shear stress is expressed as:

$$\tau_{r,d} = \frac{V_{Ed} S_{r,x,net}}{I_{x,net} b_x}$$

where:

- V_{Ed} : design shear force
- $S_{r,x,\text{net}}$: static moment for rolling shear in the main spanning direction
- $I_{x,\text{net}}$: net moment of inertia in the main spanning direction
- b_x : width of the considered layer

The static moment for rolling shear is given by:

$$S_{r,x,\text{net}} = \sum_{i=1}^{m_L} \frac{E_{x,i}}{E_{ref}} b_x t_i a_i$$

where:

- m_L : index of the longitudinal layers closest to the centre of gravity, counted from the top edge of the cross-section
- E_{ref} : reference modulus of elasticity
- $E_{x,i}$: modulus of elasticity of layer i in the longitudinal direction
- b_x : width of the element
- t_i : thickness of layer i
- a_i : distance from the centroid of layer i to the neutral axis of the whole cross-section

The rolling shear utilization ratio is finally written as:

$$UC_r = \frac{\tau_{r,d}}{f_{v,r,d}}$$

A configuration is considered satisfactory with respect to rolling shear when:

$$UC_r \leq 1$$

Longitudinal shear verification

Longitudinal shear acts in the layers oriented parallel to the design span (parallel to the grain). The corresponding verification is expressed as:

$$\tau_{v,d} \leq f_{v,d}$$

where:

- $\tau_{v,d}$: design longitudinal shear stress
- $f_{v,d}$: design longitudinal shear strength

The design longitudinal shear strength is determined as:

$$f_{v,d} = \frac{k_{mod} f_{v,k}}{\gamma_M}$$

where:

- k_{mod} : modification factor accounting for load duration and service class
- $f_{v,k}$: characteristic longitudinal shear strength
- γ_M : partial material factor

The characteristic longitudinal shear strength $f_{v,k}$ depends on the selected timber strength class. The values considered in this study are summarised in Table 7.

Table 7: Characteristic longitudinal shear strength $f_{v,k}$ for the timber strength classes considered in the study

Property	C14	C16	C24	C30
Shear strength $f_{v,k}$ [N/mm ²]	3.0	3.2	4.0	4.0

The design longitudinal shear stress is expressed as:

$$\tau_{v,d} = \frac{V_{Ed} S_{x,net}}{I_{x,net} b_x}$$

where:

- V_{Ed} : design shear force
- $S_{x,\text{net}}$: static moment in the main spanning direction
- $I_{x,\text{net}}$: net moment of inertia in the main spanning direction
- b_x : width of the considered longitudinal layer

The static moment $S_{x,\text{net}}$ depends on the position of the neutral axis. If the centre of gravity is located in the affected longitudinal layer, the static moment is expressed as:

$$S_{x,\text{net}} = \sum_{i=1}^{k_l} \frac{E_{x,i}}{E_{ref}} b_x t_i a_i + \sum_{i=1}^{k_l} \frac{E_{x,i}}{E_{ref}} b_x \left(\frac{t_i}{2} - a_k \right)^2$$

where:

- a_k : distance from the centroid of the layer containing the neutral axis to the neutral axis of the whole cross-section
- t_k : thickness of the layer containing the neutral axis
- k_l : index of the longitudinal layer closest to the neutral axis, counted from the top of the cross-section

If, on the other hand, the centre of gravity is not located in the affected longitudinal layer, the static moment is given by:

$$S_{x,\text{net}} = \sum_{i=1}^{k_l} \frac{E_{x,i}}{E_{ref}} b_x t_i a_i$$

As in the bending verification, the same timber quality is assumed for all longitudinal load-carrying layers. Therefore:

$$\frac{E_{x,i}}{E_{ref}} = 1$$

The longitudinal shear utilization ratio is finally written as:

$$UC_v = \frac{\tau_{v,d}}{f_{v,d}}$$

A configuration is considered satisfactory with respect to longitudinal shear when:

$$UC_v \leq 1$$

6.4 Serviceability Limit State verifications

At the Serviceability Limit State (SLS), the floor system must satisfy the performance requirements related to normal use. For CLT floor panels, the main SLS criteria considered in this study are deflection and vibration. Since CLT panels are relatively lightweight and deformable compared with conventional reinforced concrete slabs, serviceability requirements can become decisive for the design.

6.4.1 Deflection verification

Both instantaneous and final deflections are considered in the present study. The instantaneous deflection corresponds to the short-term elastic response under the applied loading, whereas the final deflection includes the influence of time-dependent effects through the deformation factor k_{def} .

For floor structures, deflection limits are commonly expressed as a fraction of the span. Eurocode 5 provides recommended ranges for beam and slab systems depending on the type of deflection considered. These indicative limits are summarised in Table 8. Since the investigated floor systems are simply supported one-way slabs, the corresponding limits for a slab on two supports are adopted as reference.

In the present study, the instantaneous deflection limit is taken as:

$$w_{inst} \leq \frac{L}{300}$$

while the final deflection limit is taken as:

$$w_{fin} \leq \frac{L}{250}$$

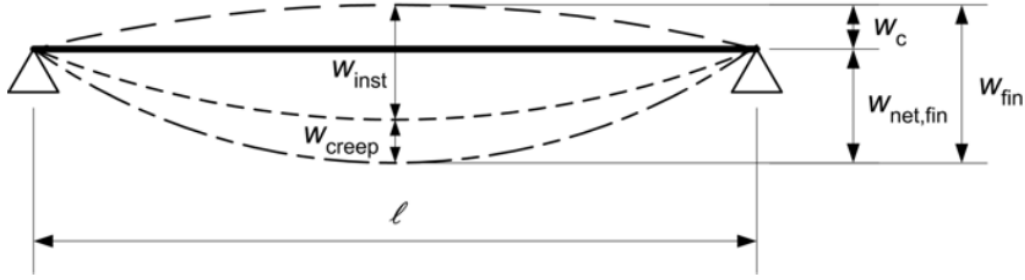


Figure 3: Components of deflection in timber floor structures

Table 8: Recommended deflection limits for timber members according to Eurocode 5

Structural system	w_{inst}	$w_{net,fin}$	w_{fin}
Beam or slab on two supports	$\ell/300$ to $\ell/500$	$\ell/250$ to $\ell/350$	$\ell/150$ to $\ell/300$
Cantilever beam or slab	$\ell/150$ to $\ell/250$	$\ell/125$ to $\ell/175$	$\ell/75$ to $\ell/150$

For a structural component subjected to sustained loading, the final deflection is obtained by combining the initial elastic deflection with the additional time-dependent deformation due to creep. This time-dependent part is taken into account through the deformation factor k_{def} , which depends on the service class and the CLT build-up considered.

The creep deflection may be written as:

$$w_{creep} = k_{def} w_{inst}$$

For the permanent action, the final deflection is therefore expressed as:

$$w_{fin,g} = w_{inst,g} + w_{creep,g} = w_{inst,g}(1 + k_{def})$$

For the variable action, the final deflection is written as:

$$w_{fin,q,i} = w_{inst,q,i} + w_{creep,q,i} = w_{inst,q,i}(1 + \psi_{2,i}k_{def})$$

where $\psi_{2,i}$ is the quasi-permanent factor associated with the considered variable action.

The final deflection of the floor system can then be written in the general form as:

$$w_{fin} = w_{fin,g} + w_{fin,q,1} + \sum w_{fin,q,i}$$

where:

- $w_{fin,g}$: final deflection due to the permanent action
- $w_{fin,q,1}$: final deflection due to the leading variable action
- $w_{fin,q,i}$: final deflection due to the accompanying variable actions

The values adopted for k_{def} are summarised in Table 9, while the combination factors ψ adopted for the considered occupancy categories are given in Table 10.

Table 9: Deformation modification factor k_{def} adopted for CLT panels

Service class	No. of layers ≤ 7	No. of layers > 7
1	0.85	0.80
2	1.10	1.00
3	—	—

Table 10: Combination factors ψ adopted for the considered building occupancies

Occupancy category	ψ_0	ψ_1	ψ_2
Category A: habitation, residential / hotel use	0.7	0.5	0.3
Category B: offices	0.7	0.5	0.3

In the present study, service class 1 is adopted for the CLT floor systems. Since the investigated CLT panels contain at most seven layers, the deformation factor is taken as:

$$k_{def} = 0.85$$

For the considered occupancy categories, the quasi-permanent factor adopted for the variable action is:

$$\psi_2 = 0.3$$

The instantaneous deflection caused by a uniformly distributed load is calculated using standard beam theory. For the permanent action:

$$w_{G,k} = \frac{5 G_k L^4}{384 E_{x,mean} I_{x,eff}}$$

and for the variable action:

$$w_{Q,k} = \frac{5 Q_k L^4}{384 E_{x,mean} I_{x,eff}}$$

The total instantaneous deflection is then given by:

$$w_{inst} = w_{G,k} + w_{Q,k}$$

where:

- G_k : characteristic permanent load
- Q_k : characteristic variable load
- L : span of the floor system
- $E_{x,mean}$: mean modulus of elasticity parallel to the grain
- $I_{x,eff}$: effective moment of inertia in the main spanning direction

The influence of shear deformations on the overall deformation must be considered for CLT elements because the panel behaves as a partially composite structure. For this reason, the effective moment of inertia $I_{x,eff}$ is used instead of the net moment of inertia $I_{x,net}$. This effective stiffness is determined using the Gamma method.

The effective moment of inertia is expressed as:

$$I_{x,eff} = \sum \frac{E_{x,i}}{E_{ref}} \frac{b_x t_i^3}{12} + \sum \gamma_i \frac{E_{x,i}}{E_{ref}} b_x t_i a_i^2$$

where:

- γ_i : reduction factor accounting for the partial composite interaction of layer i
- $E_{x,i}$: modulus of elasticity of layer i parallel to the grain
- E_{ref} : reference modulus of elasticity
- b_x : panel width
- t_i : thickness of layer i
- a_i : distance from the centroid of layer i to the neutral axis

The Gamma factor is calculated as:

$$\gamma_i = \frac{1}{1 + \frac{\pi^2 E_{x,i} t_i}{L_{ref}^2} \frac{t_y}{G_{90,mean}}}$$

where:

- γ_i : reduction factor associated with layer i
- $E_{x,i}$: modulus of elasticity of layer i parallel to the grain
- t_i : thickness of layer i
- t_y : thickness of the transverse layer
- L_{ref} : reference length, taken equal to the span L for a simply supported single-span panel
- $G_{90,mean}$: mean rolling shear modulus of the transverse layer

For layers oriented perpendicular to the grain, the longitudinal modulus of elasticity is taken as negligible, such that:

$$E_{90} \approx 0$$

In the present study, the mean rolling shear modulus of the transverse layers is taken as:

$$G_{90,mean} = 50 \text{ MPa}$$

For the symmetrical three-layer and five-layer configurations considered in this study, the Gamma factors are defined as follows.

For three-layer panels:

$$\gamma_1 = 1 \quad \gamma_3 = \frac{1}{1 + \frac{\pi^2 E_{x,3} t_3}{L_{ref}^2} \frac{t_2}{G_{90,2}}}$$

For five-layer panels:

$$\gamma_1 = \frac{1}{1 + \frac{\pi^2 E_{x,1} t_1}{L_{ref}^2} \frac{t_2}{G_{90,2}}} \quad \gamma_3 = 1 \quad \gamma_5 = \frac{1}{1 + \frac{\pi^2 E_{x,5} t_5}{L_{ref}^2} \frac{t_4}{G_{90,4}}}$$

For CLT panels with more than three longitudinal layers, such as seven-layer configurations, the standard Gamma method is no longer sufficient. In this case, the interaction between the longitudinal layers is represented using the Extended Gamma method.

The interaction between the longitudinal layers leads to a coupled linear equation system of the form:

$$\mathbf{V} \boldsymbol{\gamma} = \mathbf{s}$$

where:

- $\boldsymbol{\gamma}$ is the vector of Gamma reduction factors for the longitudinal layers.

The coefficients of the system matrix are defined as

$$C_{i,j} = \frac{b G_{R,i,j}}{d_{i,j}}$$

$$D_i = \frac{\pi^2 E_i b d_i}{l_{\text{ref}}^2}$$

where:

- $G_{R,i,j}$: rolling shear modulus of the transverse layer between longitudinal layers i and j
- $d_{i,j}$: thickness of the transverse layer between longitudinal layers i and j
- l_{ref} : effective span length

The entries of the system matrix $\mathbf{V}$ are given by

$$V_{i,i-1} = -C_{i-1,i} a_{i-1}$$

$$V_{i,i} = (C_{i-1,i} + C_{i,i+1} + D_i) a_i$$

$$V_{i,i+1} = -C_{i,i+1} a_{i+1}$$

The right-hand side vector is defined as

$$s_i = -C_{i,i+1} (a_{i+1} - a_i) + C_{i-1,i} (a_i - a_{i-1})$$

For a CLT cross-section comprising four longitudinal layers, the linear equation system can be written explicitly as

$$\begin{bmatrix} V_{1,1} & V_{1,2} & 0 & 0 \\ V_{2,1} & V_{2,2} & V_{2,3} & 0 \\ 0 & V_{3,2} & V_{3,3} & V_{3,4} \\ 0 & 0 & V_{4,3} & V_{4,4} \end{bmatrix} \begin{bmatrix} \gamma_1 \\ \gamma_2 \\ \gamma_3 \\ \gamma_4 \end{bmatrix} = \begin{bmatrix} s_1 \\ s_2 \\ s_3 \\ s_4 \end{bmatrix}$$

Following substitution of the stiffness and geometric terms, the system becomes

$$\begin{bmatrix} (C_{1,2} + D_1)a_1 & -C_{1,2}a_2 & 0 & 0 \\ -C_{1,2}a_1 & (C_{1,2} + C_{2,3} + D_2)a_2 & -C_{2,3}a_3 & 0 \\ 0 & -C_{2,3}a_2 & (C_{2,3} + C_{3,4} + D_3)a_3 & -C_{3,4}a_4 \\ 0 & 0 & -C_{3,4}a_3 & (C_{3,4} + D_4)a_4 \end{bmatrix} \begin{bmatrix} \gamma_1 \\ \gamma_2 \\ \gamma_3 \\ \gamma_4 \end{bmatrix} = \begin{bmatrix} -C_{1,2}(a_2 - a_1) \\ -C_{2,3}(a_3 - a_2) + C_{1,2}(a_2 - a_1) \\ -C_{3,4}(a_4 - a_3) + C_{2,3}(a_3 - a_2) \\ C_{3,4}(a_4 - a_3) \end{bmatrix} \quad (1)$$

Solving the linear equation system yields the Gamma reduction factors for each longitudinal layer:

$$\boldsymbol{\gamma} = \mathbf{V}^{-1}\mathbf{s}$$

Once the Gamma reduction factors have been determined, the effective bending stiffness of the panel can be evaluated through the effective second moment of area $I_{x,\text{eff}}$. This effective stiffness is then used to calculate both the instantaneous and the final deflections of the CLT floor panel.

The deflection verification is finally carried out by comparing the calculated deflections with the adopted span-based limits. The utilization ratio for the final deflection is expressed as:

$$UC_{w,\text{fin}} = \frac{w_{\text{fin}}}{L/250}$$

The utilization ratio for the instantaneous deflection is expressed as:

$$UC_{w,\text{inst}} = \frac{w_{\text{inst}}}{L/300}$$

A panel configuration is considered satisfactory with respect to deflection when both utilization ratios remain lower than or equal to unity:

$$UC_{w,\text{fin}} \leq 1 \quad \text{and} \quad UC_{w,\text{inst}} \leq 1$$

6.4.2 Vibration verification

At the Serviceability Limit State, CLT floor systems must also be verified with respect to vibrations in order to ensure acceptable comfort for users. Vibrations induced by normal human activities, such as walking, may cause discomfort even when the floor satisfies the strength and deflection requirements. This is particularly important for CLT floors, which are relatively lightweight and therefore more sensitive to dynamic effects than heavier floor systems.

When a person walks on a floor, the excitation is periodic. If the frequency of this excitation approaches the natural frequency of the floor, resonance may occur, leading to an amplification of the oscillation response. For this reason, the vibration verification is first based on the fundamental frequency f_1 of the floor.

According to Eurocode-based design recommendations for timber floors, a distinction is made between low-frequency and high-frequency floors. If $f_1 \leq 8$ Hz, the floor is considered to be in a low-frequency range and a more detailed dynamic analysis is generally required. If $f_1 > 8$ Hz, simplified verification criteria may be applied.

In the present study, the vibration performance of the CLT floor panels is assessed by calculating the fundamental frequency of the floor and, when $f_1 > 8$ Hz, by verifying the static deflection under a concentrated load.

The lowest natural frequency or fundamental frequency f_1 is determined according to EN 1995-1-1, Section 7.3.3:

$$f_1 = \frac{\pi}{2L^2} \sqrt{\frac{(EI)_{x,\text{eff}}}{m}}$$

where:

- f_1 : fundamental frequency of the floor [Hz]
- $(EI)_{x,\text{eff}}$: equivalent bending stiffness in the main spanning direction [Nm^2/m]
- L : floor span [m]
- m : mass per unit area of the floor [kg/m^2]

For floors with $f_1 > 8$ Hz, the vibration verification is then carried out by means of the static deflection under a concentrated load of $F = 1$ kN, written as:

$$\frac{w}{F} \leq a \quad [\text{mm}/\text{kN}]$$

where:

- w : instantaneous maximum vertical deflection caused by the concentrated load
- F : concentrated load, taken as 1 kN
- a : recommended limit value for the deflection criterion

For a one-way simply supported floor system, the corresponding instantaneous vertical deflection may be written as:

$$w = \frac{F L^3}{48 E I_{x,\text{eff}}}$$

where:

- w : instantaneous vertical deflection
- F : concentrated static load, taken as 1 kN
- L : floor span
- $E I_{x,\text{eff}}$: effective bending stiffness of the panel in the main spanning direction

Recommended values of the parameters a and b , together with the corresponding vibration comfort classes, are provided in Eurocode-based guidelines and are illustrated in Figure 4. The parameter a represents the acceptable limit for the static deflection criterion under a concentrated load, while b is associated with the peak velocity criterion used in more advanced vibration assessments. In the present study, the adopted values are:

$$a = 2 \text{ mm/kN} \quad \text{and} \quad b = 80 \text{ m/(Ns}^2\text{)}$$

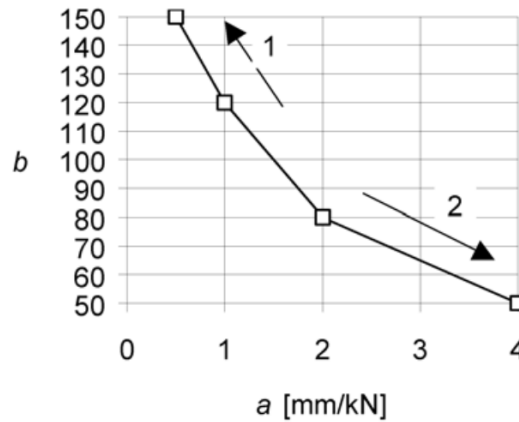


Figure 4: Recommended limit values for vibration performance parameters a and b for floor structures according to Eurocode-based guidelines

It should be noted that more advanced vibration criteria, such as peak velocity expressions for rectangular floors simply supported along four edges, are available in the literature. However,

such formulations are based on two-way plate behaviour and are therefore not adopted in the present study, which is based on a one-way slab assumption.

A panel configuration is considered satisfactory with respect to vibration when the fundamental frequency satisfies

$$f_1 > 8 \text{ Hz}$$

and the static deflection criterion satisfies

$$\frac{w}{F} \leq a$$

which, in the present study with $F = 1 \text{ kN}$ and $a = 2 \text{ mm/kN}$, is equivalent to:

$$w \leq 2 \text{ mm}$$

7 Acoustic assessment

In addition to structural performance, the acoustic behaviour of floor systems is an important aspect of building quality and user comfort. This is particularly relevant for timber floors, since their relatively low mass generally makes them more sensitive to sound transmission and vibration-related discomfort than heavier mineral constructions. For CLT floor systems, acoustic design must therefore be considered as an additional performance criterion alongside strength, stiffness, vibration comfort, environmental impact and cost.

From an acoustic point of view, a distinction is usually made between *airborne sound* and *impact sound*. Airborne sound corresponds to sound waves transmitted through the air, such as speech, music or traffic noise, which excite the building elements and generate sound radiation in adjacent spaces. Impact sound, by contrast, is generated by direct mechanical excitation of the structure, for example due to footsteps, moving furniture or objects falling on the floor.

For residential buildings in Belgium, acoustic requirements are commonly expressed in terms of airborne sound insulation and impact sound insulation measured *in situ*. For the level corresponding to normal acoustic comfort (NAC), the following criteria are typically adopted:

$$D_{nT,w} \geq 54 \text{ dB} \quad (2)$$

$$L_{nT,w} \leq 58 \text{ dB} \quad (3)$$

One of the main difficulties in the acoustic assessment of CLT systems is the limited amount of available data for complete building elements. In practice, manufacturers usually provide the structural panel only, while the final floor assembly is defined later according to the structural, thermal and acoustic requirements of the project. Because many different combinations of CLT panels, toppings, floor coverings and lining systems are possible, it is difficult to establish representative reference values for a generic CLT floor system.

In order to obtain simplified estimates for bare CLT panels, empirical expressions based on the mass law can be used. The equivalent airborne sound insulation and the normalized impact sound pressure level of bare CLT panels may be estimated as a function of the surface mass per unit area m' :

$$R_{w,eq} = 20.3 \log_{10}(m') \quad (4)$$

$$L_{n,w,eq} = 128 - 22 \log_{10}(m') \quad (5)$$

where m' is the surface mass in kg/m^2 . These expressions show that the acoustic behaviour of bare CLT panels depends primarily on their surface mass. In practice, this surface mass is governed by the thickness of the panel and the density of the timber and therefore also indirectly by the adopted wood class when different density values are considered.

Based on these empirical expressions, average reference values were calculated for the bare CLT panels considered in this study. The results are summarized in Table 11.

Table 11: Average airborne and impact sound insulation data for bare CLT assemblies

Material	Thickness [mm]	Surface mass [kg/m ²]	R_w [dB]	$L_{n,w}$ [dB]
Bare CLT 3-ply	60–120	21–55.2	31	94
Bare CLT 5-ply	100–200	35–92	36	89
Bare CLT 7-ply	140–280	49–128.8	39	86

As can be seen from Table 11, bare CLT panels alone provide limited acoustic performance. The airborne sound insulation remains relatively low, while the impact sound levels remain far above the Belgian target values. This shows that the CLT panel alone is not sufficient to satisfy typical residential acoustic requirements.

However, the acoustic behaviour of a CLT floor cannot be assessed on the basis of the timber panel alone. In practice, CLT is generally combined with additional layers providing thermal, finishing and acoustic functions, such as floating floors, resilient layers, suspended ceilings and absorbent materials. The final acoustic performance therefore depends on the complete floor build-up rather than on the structural panel only.

To illustrate this effect, three CLT floor assemblies are presented in Figure 5 and Table 12: a configuration without ceiling, a configuration with a channel ceiling and a configuration with a suspended ceiling.

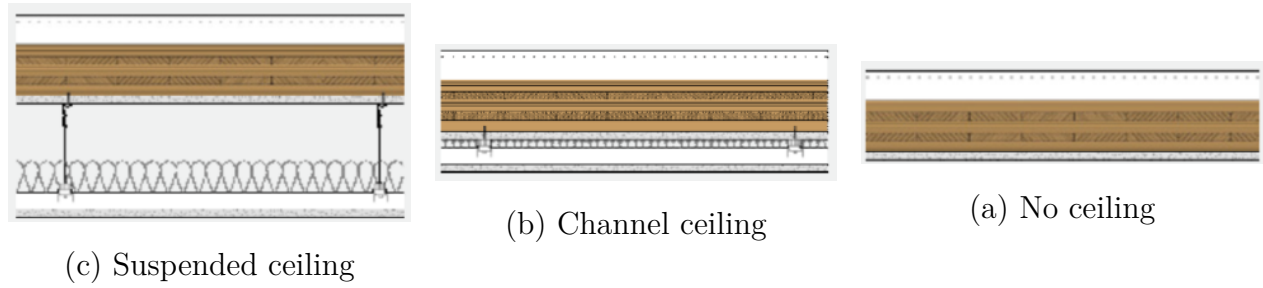


Figure 5: Illustration of three CLT floor build-ups used to highlight the influence of additional acoustic layers.

Table 12: Illustrative acoustic performances of lined CLT floor assemblies

Configuration Main components		Thickness [mm]	R_w [dB]	$L_{n,T,w}$ [dB]
Suspended ceiling	– 12 mm carpet on 8 mm chipfoam underlay	319	58	26
	– 170 mm CLT panel			
	– 16 mm fire-rated plasterboard			
	– 100 mm suspended ceiling			
	– Resilient mounts			
	– 75 mm glasswool batts			
	– 13 mm standard plasterboard			
Channel ceiling	– 10 mm ceramic tiles on 8 mm adhesive bed	334	62	53
	– 40 mm screed on 10 mm acoustic rubber underlay			
	– 170 mm CLT panel			
	– 16 mm fire-rated plasterboard			
	– Resilient mounts			
	– Furring channel			
	– 75 mm glasswool batts			
No ceiling	– 13 mm standard plasterboard	315	58	55
	– Floor topping			
	– 2×9 mm fibre cement boards			
	– 22 mm particleboard			
	– 90 mm timber battens on 15 mm rubber pads			
	– 90 mm glasswool batts			
	– 170 mm CLT panel			

These examples clearly show that the addition of non-structural layers significantly improves the acoustic behaviour of CLT floors. Compared to the bare panel, the lined assemblies achieve substantially higher airborne sound insulation and significantly lower impact sound levels. In particular, the results suggest that this improvement is strongly influenced by the depth of the ceiling cavity and by the presence of absorbent insulation such as glasswool within this cavity.

It should however be noted that the values reported for these built-up systems are laboratory-based indicators, whereas the Belgian criteria are expressed in terms of *in situ* quantities.

The comparison is therefore indicative rather than a strict verification. Nevertheless, the overall conclusion remains clear: the acoustic suitability of a CLT floor cannot be judged from the structural panel alone and the final performance depends to a large extent on the detailing of the complete assembly, especially the cavity depth and the insulation placed within it.

8 Fire resistance assessment

In addition to the structural verifications presented in Chapter 6, CLT floor systems must also satisfy fire resistance requirements. This is particularly important for timber structures, since timber is a combustible material whose mechanical properties are progressively degraded by the action of fire. In the parametric workflow, the fire resistance class is therefore treated as an additional design constraint applied on top of the ultimate and serviceability limit state verifications. For each combination of span, loading, layer configuration and timber strength class, the residual cross-section is evaluated for the targeted fire class and the panel is retained only if it also passes the fire verification. Three fire resistance classes are considered: R30, R60 and R90. By running the parametric study under each of these scenarios, the influence of the required fire resistance class on the structurally valid CLT configurations and on the resulting embodied carbon and material cost can be evaluated.

The fire design of CLT floor panels in the present study follows the reduced cross-section method defined in EN 1995-1-2. In this approach, the influence of fire on the structural element is represented through a notional charring of the cross-section, after which the residual section is verified for the relevant mechanical actions under the accidental design situation.

8.1 Fire action and design situation

When exposed to a standard fire, timber chars at a roughly constant rate, producing a layer of carbonised wood at the surface. This char layer is structurally ineffective but provides thermal insulation to the remaining timber. As a result, after a given fire duration, only the residual unburnt cross-section contributes to the load-bearing capacity of the element.

Fire is treated as an accidental design situation. The relevant load combination at the fire limit state is written, in accordance with EN 1990, as:

$$E_{d,fi} = \sum G_{k,j} + \sum_{i \geq 1} \psi_{2,i} Q_{k,i}$$

where:

- $G_{k,j}$: characteristic value of the permanent actions
- $Q_{k,i}$: characteristic value of the variable actions
- $\psi_{2,i}$: quasi-permanent combination factor for the variable actions

For the office and residential/hotel occupancies considered in this study, the quasi-permanent factor is taken as $\psi_{2,1} = 0.3$, in accordance with EN 1990. The resulting design uniformly distributed load under fire is therefore:

$$q_{Ed,fi} = G_k + 0.3 Q_k$$

As is standard for accidental design situations and in accordance with EN 1995-1-2, the partial material factor and the modification factor applied to the timber strength are taken as:

$$\gamma_{M,fi} = 1.0 \quad k_{mod,fi} = 1.0$$

In addition, a strength conversion factor k_{fi} is applied to the characteristic strength values to account for the use of 20% fractile values, rather than 5% fractile values, in the fire situation. According to EN 1995-1-2, this factor is taken as:

$$k_{fi} = 1.15$$

This value corresponds to the recommendation for glued laminated timber and is commonly extended to CLT panels in current design practice and in the upcoming revision of EN 1995-1-2.

8.2 Charring depth and residual cross-section

The charring depth after a fire exposure of duration t is calculated using the notional charring rate β_n defined in EN 1995-1-2:

$$d_{char,n} = \beta_n t$$

where:

- $d_{char,n}$: notional charring depth [mm]
- β_n : notional charring rate [mm/min]
- t : required fire resistance duration [min]

In the present study, the one-dimensional charring rate is taken as $\beta_0 = 0.65$ mm/min, in accordance with EN 1995-1-2. The resulting charring depths for the considered fire resistance classes are summarised in Table 13.

Table 13: Notional charring depth as a function of the required fire resistance class

Fire class	Duration [min]	$d_{char,n}$ [mm]
R30	30	19.5
R60	60	39.0
R90	90	58.5

To account for the additional loss of strength and stiffness in the heat-affected zone immediately below the char line, the reduced cross-section method introduced in EN 1995-1-2 adds a zero-strength layer of thickness d_0 . The effective charring depth is therefore written as:

$$d_{ef} = d_{char,n} + k_0 d_0$$

where:

- d_{ef} : effective charring depth [mm]
- $d_0 = 7$ mm: zero-strength layer thickness
- k_0 : coefficient accounting for the development of the zero-strength layer

For exposure times of at least 20 minutes, the coefficient k_0 reaches its full value of $k_0 = 1.0$. Since all three fire classes considered in this study correspond to exposure times greater than 20 minutes, this value is adopted throughout. The effective charring depth therefore simplifies to:

$$d_{ef} = d_{char,n} + 7 \text{ mm}$$

For CLT floor panels exposed to fire on the underside only, which is the most common configuration in practice, the residual thickness of the panel is then expressed as:

$$h_{CLT,fi} = h_{CLT} - d_{ef}$$

where h_{CLT} is the original total panel thickness and $h_{CLT,fi}$ is the residual thickness considered for the verification of the fire limit state.

9 Environmental assessment

The environmental assessment carried out in this thesis focuses on the embodied carbon of the investigated floor systems. In order to compare the environmental performance of CLT floor systems and reinforced concrete slabs on a consistent basis, the indicator adopted in the study is the Global Warming Potential (GWP), expressed in kgCO_2e . This indicator is commonly used in environmental assessments of construction materials and makes it possible to compare the contribution of different greenhouse gases through a single equivalent measure.

The carbon calculations in this thesis follow the standard life-cycle module approach used in environmental assessment. In this framework, the life cycle of a construction product is divided into several modules. The main comparative assessment carried out in this study is limited to the product stage A1–A3, which covers raw material supply, transport to the manufacturing plant and manufacturing. This corresponds to a cradle-to-gate assessment and is used as the principal basis for comparing the investigated floor systems.

This choice is made because the initial embodied carbon associated with the production of materials and the fabrication of structural elements constitutes a significant share of the whole-life carbon impact. In addition, later life-cycle stages depend more strongly on project-specific assumptions such as transport distances, construction methods, maintenance scenarios, demolition strategies and end-of-life treatments. However, for timber products, the end-of-life stages are particularly important for the interpretation of biogenic carbon. For this reason, the available data for the later modules are also reported and discussed separately, especially for the scenarios where the carbon stored in wood is either released at the end of life or kept stored for a longer period. Figure 6 illustrates the modular life-cycle framework and highlights the product stage A1–A3 adopted as the main boundary in this thesis.

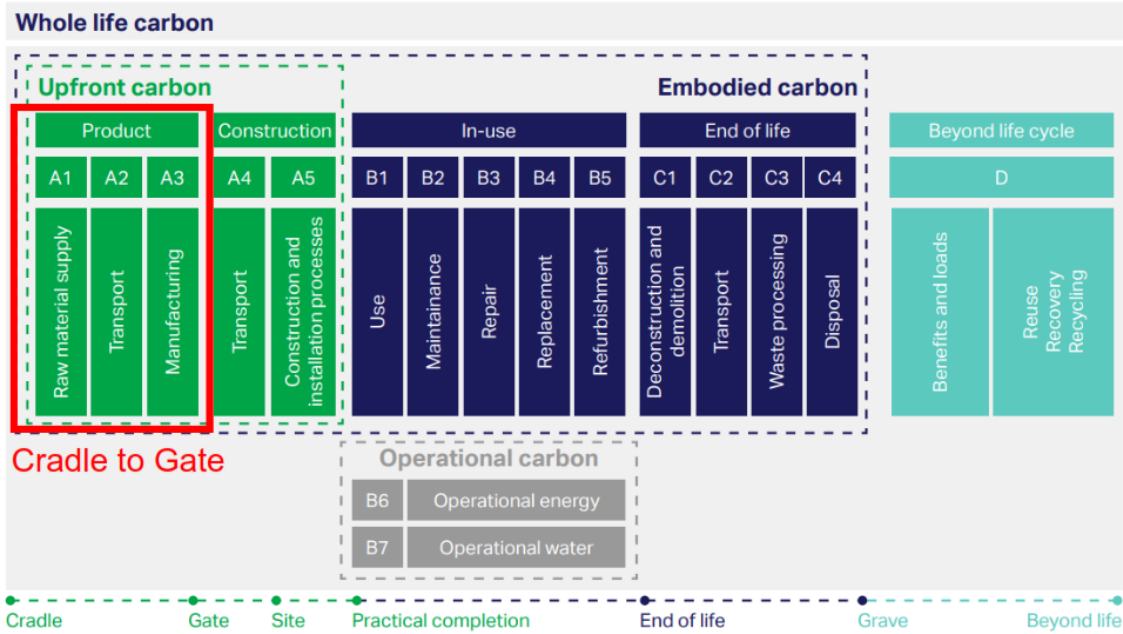


Figure 6: Life-cycle modules according to the modular assessment approach. The present study is limited to the product stage A1–A3, corresponding to a cradle-to-gate assessment.

Table 14: Comparison of environmental input data for CLT and reinforced concrete

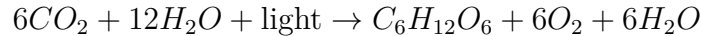
Material	A1–A3		A4	A5	C1	C2	C3		C4	
	Fossil	Biog.	Fossil	Fossil	Fossil	Fossil	Fossil	Biog.	Fossil	Biog.
	[kgCO ₂ eq/m ³]	[kgCO ₂ eq/m ³]	[kgCO ₂ eq/m ³]	[kgCO ₂ eq/m ³]	[kgCO ₂ eq/m ³]	[kgCO ₂ eq/m ³]	[kgCO ₂ eq/m ³]	[kgCO ₂ eq/m ³]	[kgCO ₂ eq/m ³]	[kgCO ₂ eq/m ³]
CLT (Cross Laminated Timber)	163	-653	6.7	8.7	0	3.7	0.32	491	1.1	164
RC cast in situ (avg. as in TOTEM)	436	–	41	25	14	13	0.7	–	0.7	–

9.1 Environmental data for CLT

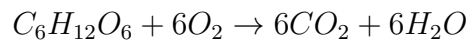
For the CLT floor systems, the environmental impact is determined from the timber volume associated with each structurally valid panel configuration. The quantities of timber are obtained directly from the structural sizing, based on the selected layer configuration and total panel thickness. The corresponding embodied carbon is then calculated by combining these quantities with the adopted emission factors for CLT.

Unlike mineral construction materials, timber is a bio-based material and is therefore associated not only with production-related emissions, but also with biogenic carbon storage. During tree growth, carbon dioxide is absorbed from the atmosphere through photosynthesis and part of this carbon remains stored in the wood biomass. This is the reason why timber products are often reported with both a fossil GWP component and a biogenic GWP component.

The carbon storage mechanism in timber can be illustrated through two simplified reactions. The first equation represents photosynthesis, through which trees absorb carbon dioxide from the atmosphere and store carbon in their biomass:



The second equation represents combustion, through which the carbon stored in wood may be released again to the atmosphere:



These simplified equations illustrate that carbon absorbed during tree growth may later be released again, depending on the end-of-life scenario of the timber product. The end-of-life treatment of CLT is therefore particularly important when interpreting its environmental performance. If the timber element is incinerated at the end of its service life, the biogenic carbon stored during tree growth is released back into the atmosphere as CO_2 . During combustion, the stored carbon combines with oxygen from the air, which explains why the mass of CO_2 released is higher than the mass of carbon initially stored in the wood.

As a result, the temporary carbon storage benefit obtained during the product stage may be partly or fully compensated by a biogenic carbon emission at the end-of-life stage if the wood is burned. By contrast, if the timber element is reused, recycled, or kept in long-term storage, the release of this biogenic carbon can be delayed. This may improve the climate performance of the material over the considered time horizon, although the benefit remains dependent on the adopted accounting method and the actual end-of-life scenario.

For this reason, the environmental advantage of CLT depends not only on the amount of timber used and its A1–A3 production impact, but also on the assumptions made regarding biogenic carbon and end-of-life treatment. In the present study, end-of-life scenarios are not explicitly modelled, since the comparison is limited to the product stage A1–A3. For this reason, the comparative environmental assessment is based on the fossil GWP contribution only. The biogenic carbon contribution is discussed separately, but it is not included in the main comparative indicator, in order to avoid interpreting temporary carbon storage as a permanent carbon removal.

Trees may therefore be considered as temporary carbon sinks, since they absorb and store carbon in their biomass during growth. However, the amount of stored carbon and the resulting long-term climate benefit depend on several factors, including forest management, harvesting age, soil conditions, climate and end-of-life treatment. These broader aspects

are not modelled explicitly in the present study. Instead, within the adopted cradle-to-gate boundary, the environmental assessment of CLT is based on the product-stage fossil impact of the timber panels. This approach allows the comparison with reinforced concrete to remain conservative and avoids relying on uncertain assumptions regarding the future release, reuse, recycling, or storage of biogenic carbon.

9.2 Environmental data for reinforced concrete

For the reinforced concrete slabs, the environmental assessment includes both the concrete volume and the reinforcement steel. Although concrete is mainly composed of aggregates, sand and water, its embodied carbon is largely governed by the cement content, due to the emissions associated with cement production and clinkerisation. The contribution of reinforcement steel is also included, since it can represent a significant share of the total carbon footprint of reinforced concrete elements.

The influence of cement content is illustrated in Figure 7, which shows that cement represents only a limited fraction of the concrete mass but dominates its A1–A3 carbon footprint.

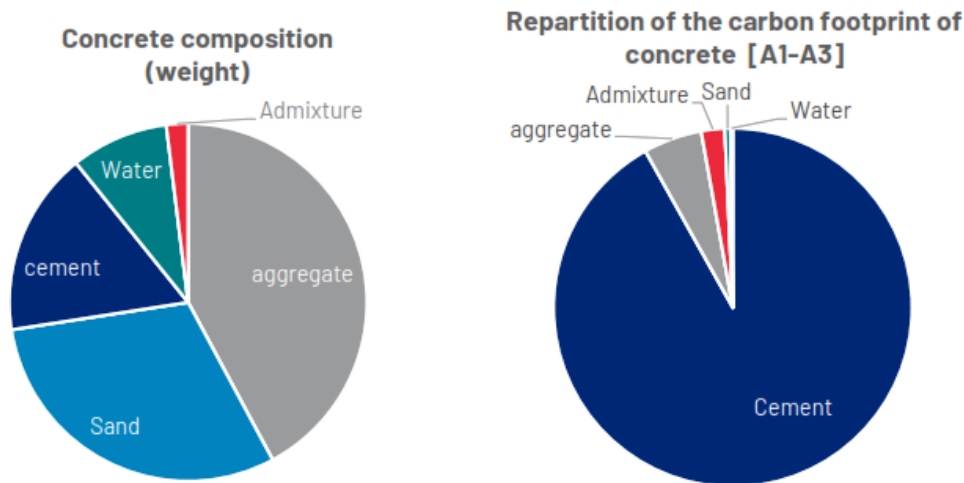


Figure 7: Comparison between the mass composition of concrete and the repartition of its A1–A3 carbon footprint, showing the dominant contribution of cement. Source: BESIX.

In this study, different concrete strength classes and cement types are considered in order to account for their influence on the environmental performance of reinforced concrete slabs. Lower-clinker cements, such as CEM III/A and CEM III/B, generally lead to lower embodied carbon than traditional Portland cement CEM I, while higher concrete strength classes usually require higher cement contents and therefore lead to higher product-stage emissions.

The environmental input values used for concrete and reinforcement steel are based on data provided by Buildwise and are used directly in the comparative calculations.

9.3 Calculation approach

For each structurally valid floor configuration, the embodied carbon is calculated from the material quantities obtained from the structural design and the corresponding A1–A3 emission factors. The assessment is carried out separately for CLT floor systems and reinforced concrete slabs.

In the present study, the calculations are performed on a floor strip of width $B = 1$ m. As a result, the environmental impacts are directly obtained per square metre of floor area.

For the CLT floor systems, the embodied carbon is calculated from the timber volume. Since the environmental input data for CLT distinguish between fossil and biogenic contributions, both components are assessed separately in this thesis. The corresponding expressions may be written as:

$$\begin{aligned} CO_{2e,CLT}^{fossil} &= X_{CLT}^{fossil} h_{CLT} \quad [\text{kgCO}_2\text{e/m}^2] \\ CO_{2e,CLT}^{biogenic} &= X_{CLT}^{biogenic} h_{CLT} \quad [\text{kgCO}_2\text{e/m}^2] \end{aligned}$$

where:

- X_{CLT}^{fossil} : fossil emission factor adopted for CLT [$\text{kgCO}_2\text{e/m}^3$]
- $X_{CLT}^{biogenic}$: biogenic emission factor adopted for CLT [$\text{kgCO}_2\text{e/m}^3$]
- h_{CLT} : total thickness of the CLT panel [m]

The main CLT indicator used in the comparative assessment is the fossil GWP:

$$CO_{2e,CLT}^{main} = CO_{2e,CLT}^{fossil}$$

The biogenic contribution is not included in the main comparison, but it is calculated and discussed separately because it strongly depends on the end-of-life scenario. When the temporary carbon storage effect is considered at the product stage, the following indicative value can be obtained:

$$CO_{2e,CLT}^{A1-A3,total} = CO_{2e,CLT}^{fossil} + CO_{2e,CLT}^{biogenic}$$

However, if the timber is burned or fully oxidised at the end of life, the biogenic carbon stored during the product stage is released again in the end-of-life modules. Therefore, the biogenic

contribution must be interpreted as temporary carbon storage rather than as a permanent carbon removal.

For reinforced concrete slabs, the embodied carbon associated with the concrete is written as:

$$CO_{2e,c} = X_c h_c \quad [\text{kgCO}_2\text{e/m}^2]$$

where:

- X_c : emission factor adopted for concrete [$\text{kgCO}_2\text{e/m}^3$]
- h_c : thickness of the concrete slab [m]

Since reinforced concrete slabs also include steel reinforcement, the total embodied carbon of the reinforced concrete solution is obtained by adding the steel contribution:

$$CO_{2e,RC} = X_c h_c + X_s m'_s \quad [\text{kgCO}_2\text{e/m}^2]$$

where:

- X_s : emission factor adopted for reinforcing steel [$\text{kgCO}_2\text{e/kg}$]
- m'_s : mass of reinforcing steel per unit floor area [kg/m^2]

10 Economic assessment

The economic assessment carried out in this thesis aims to compare the material cost of the investigated floor systems on a consistent basis, using the quantities obtained from the structural design calculations. Construction and labour related costs are not explicitly evaluated in this study, as they depend strongly on project-specific conditions such as site organisation, contractor practices and local market factors. They are therefore beyond the scope of the present comparison, although it is acknowledged that they can significantly influence the overall competitiveness of a structural solution.

This distinction is particularly relevant when comparing CLT floor systems with cast in-situ reinforced concrete slabs. CLT is delivered to site as a prefabricated element, which can reduce assembly time and simplify on-site operations. By contrast, cast in-situ concrete requires more extensive site work, including formwork, reinforcement placement, concreting and a hardening period, which has a direct influence on labour and execution costs. These differences are not captured by the material-cost comparison adopted here and should be kept in mind when interpreting the results.

10.1 CLT floor systems

For the CLT floor systems, the cost assessment is based on supplier prices collected for different layer thicknesses and timber strength classes. In order to obtain a consistent input for the study, the supplier data were averaged for each thickness category and adjusted according to the timber strength class.

The resulting CLT material costs adopted in the study are summarised in Table 15. These values are expressed in (€/m²) and correspond to the panel material itself.

Table 15: Approximate average CLT material costs adopted in the study as a function of layer thickness and timber strength class, based on the average of prices collected from several manufacturers

Layer thickness [mm]	C14 [€/m ²]	C16 [€/m ²]	C24 [€/m ²]	C30 [€/m ²]
20	~26	~27	~28	~31
30	~35	~36	~37	~41
40	~44	~45	~47	~52

10.2 Reinforced concrete slabs

For the reinforced concrete slabs, the material cost is decomposed into two contributions: the cost of the concrete itself and the cost of the reinforcement steel. Each component is associated with a unit cost expressed per unit volume for concrete (€/m³) and per unit mass for steel (€/kg), in line with common construction-market practice.

The unit costs adopted in the study are based on cost information representative of the Belgian construction market, obtained from internal BESIX data. For each concrete strength class, several cement compositions are considered (CEM I, CEM III/A, CEM III/B and CEM V/A) in order to account for the influence of cement type on the cost. For the reinforcement, two options are considered: a standard rebar with high recycled content and a low-carbon alternative (XCarb[®] recycled and renewably produced reinforcing steel from ArcelorMittal).

The unit costs adopted in the study are summarised in Table 16. The detailed supplier-level data are not reproduced here for confidentiality reasons.

Table 16: Approximate unit costs adopted for reinforced concrete slab components, excluding execution costs

Component	Configuration	Unit cost
Concrete C25/30	CEM I	~135 €/m ³
Concrete C25/30	CEM III	~129 €/m ³
Concrete C25/30	CEM V/A	~134 €/m ³
Concrete C30/37	CEM I	~140 €/m ³
Concrete C30/37	CEM III/A	~134 €/m ³
Concrete C30/37	CEM V/A	~139 €/m ³
Concrete C35/45	CEM I	~143 €/m ³
Concrete C35/45	CEM III/A	~137 €/m ³
Concrete C35/45	CEM III/B	~147 €/m ³
Concrete C35/45	CEM V/A	~142 €/m ³
Reinforcement	Standard rebar (80% recycled)	~0.70 €/kg
Reinforcement	XCarb [®] low-carbon rebar	~0.80 €/kg

Note: The values correspond to material unit costs only. They exclude execution-related costs such as formwork, reinforcement placing, concrete pouring, pumping, labour, site equipment and other indirect construction costs.

For each structurally valid reinforced concrete slab configuration, the material cost per square metre of floor area is obtained by combining the concrete contribution and the steel contribution:

$$C_{RC} = c_c h_c + c_s m'_s \quad [\text{€/m}^2]$$

where:

- C_{RC} : material cost of the reinforced concrete slab per unit area [€/m²]
- c_c : unit cost of the selected concrete [€/m³]
- h_c : thickness of the concrete slab [m]
- c_s : unit cost of the selected reinforcement steel [€/kg]
- m'_s : mass of reinforcement steel per unit floor area [kg/m²]

11 Results and discussion

This section presents and discusses the results obtained from the parametric workflow developed in the previous sections. The objective is to analyse the structural feasibility, environmental performance and economic performance of the investigated floor systems under equivalent design conditions.

The results are first analysed for the CLT floor systems alone, in order to identify the influence of span, loading conditions, panel configuration and fire resistance requirements. The CLT results are then compared with the reinforced concrete slab results in order to determine the design situations in which CLT constitutes a relevant alternative and those in which reinforced concrete remains more appropriate.

11.1 Overview of the analysed configurations

The parametric study generated a database of floor configurations by varying the span, permanent load, variable load, material class and structural configuration. For each configuration, the relevant ultimate and serviceability limit state verifications were evaluated. Only the configurations satisfying all required utilisation criteria were retained for the environmental and economic comparison.

Table 17: Overview of the main parameters considered in the parametric study.

Parameter	Values considered
Span L	3.0 to 10.0 m, with a step of 0.5 m
Permanent load G_k	0.0 to 6.0 kN/m ² , with a step of 0.5 kN/m ²
Variable load Q_k	1 to 15 kN/m ² , with a step of 1 kN/m ²
Number of CLT layers	3, 5, 7
Layer thicknesses	20, 30, 40 mm
Timber strength classes	C14, C16, C24, C30
Fire resistance classes	No fire, R30, R60, R90
Concrete strength classes	C16/20, C20/25, C25/30, C30/37, C35/45
Cement types	CEM I, CEM II, CEM III/A, CEM III/B, CEM V/A
Reinforcement steel types	Generic reinforcing steel, XCarb recycled reinforcing steel

11.2 Structural performance

The structural performance is first analysed through the span-load domain of the valid CLT configurations. This makes it possible to identify the range of applications in which CLT

panels remain structurally feasible before considering environmental and economic aspects.

11.2.1 Structural feasibility of CLT floor systems

The structural feasibility of the CLT floor systems is assessed by considering only the configurations for which all utilisation criteria remain lower than unity. For each span and panel thickness, the maximum admissible unfactored applied load is extracted from the valid database. In this context, the unfactored applied load is defined as the sum of the characteristic permanent load and the characteristic variable load, excluding the self-weight of the CLT panel itself:

$$q_{\text{unfactored}} = G_k + Q_k \quad (6)$$

This representation allows the different CLT configurations to be compared on the basis of their effective load-carrying capacity. Figure 8 shows the resulting application domain for CLT panels made of C24 timber without any specific fire resistance requirement.

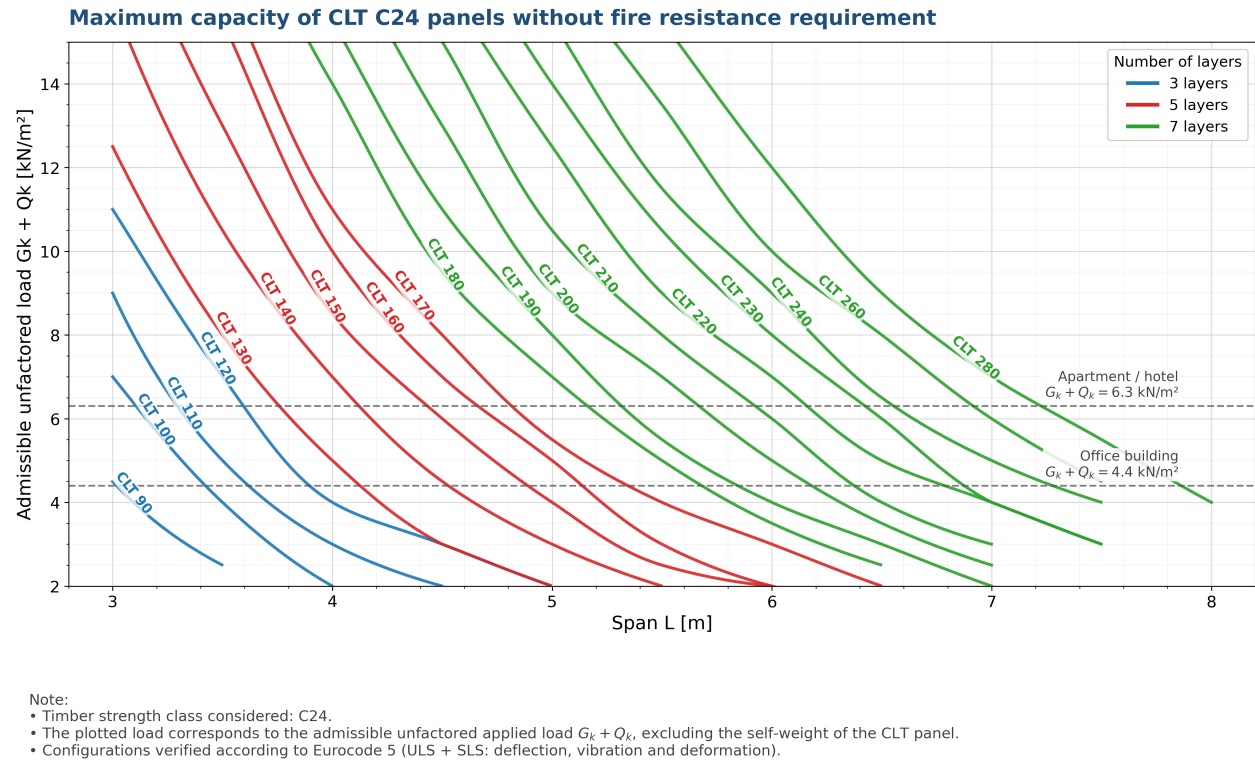


Figure 8: Maximum admissible useful load as a function of span for CLT C24 floor panels without specific fire resistance requirement.

Overall, the results indicate that CLT floor panels are structurally more suitable for short to medium spans. For the office reference load, several CLT configurations remain feasible over a relatively broad span range, although the required panel thickness increases progressively with span. For the apartment/hotel reference load, the feasible domain is more restricted and thicker configurations are required earlier. The three-layer configurations appear to have a very limited application domain, as they are only relevant for short spans and relatively low load levels. This shows that the relevance of CLT floors depends strongly on both the span and the adopted permanent and variable load assumptions.

11.2.2 Governing utilisation criteria

After defining the structural application domain of the CLT floor panels, the governing utilisation criterion was identified for the configurations located on the capacity envelope. For each CLT thickness and span, these configurations correspond to the maximum admissible useful load and therefore represent the boundary of the feasible domain.

For each configuration, the governing criterion is defined as the check with the highest utilisation ratio:

$$UC_{\max} = \max_i (UC_i) \quad (7)$$

where UC_i is the utilisation ratio of each individual verification. The considered checks include bending, shear, rolling shear, short-term deformation, long-term deformation, fundamental frequency and point-load deflection.

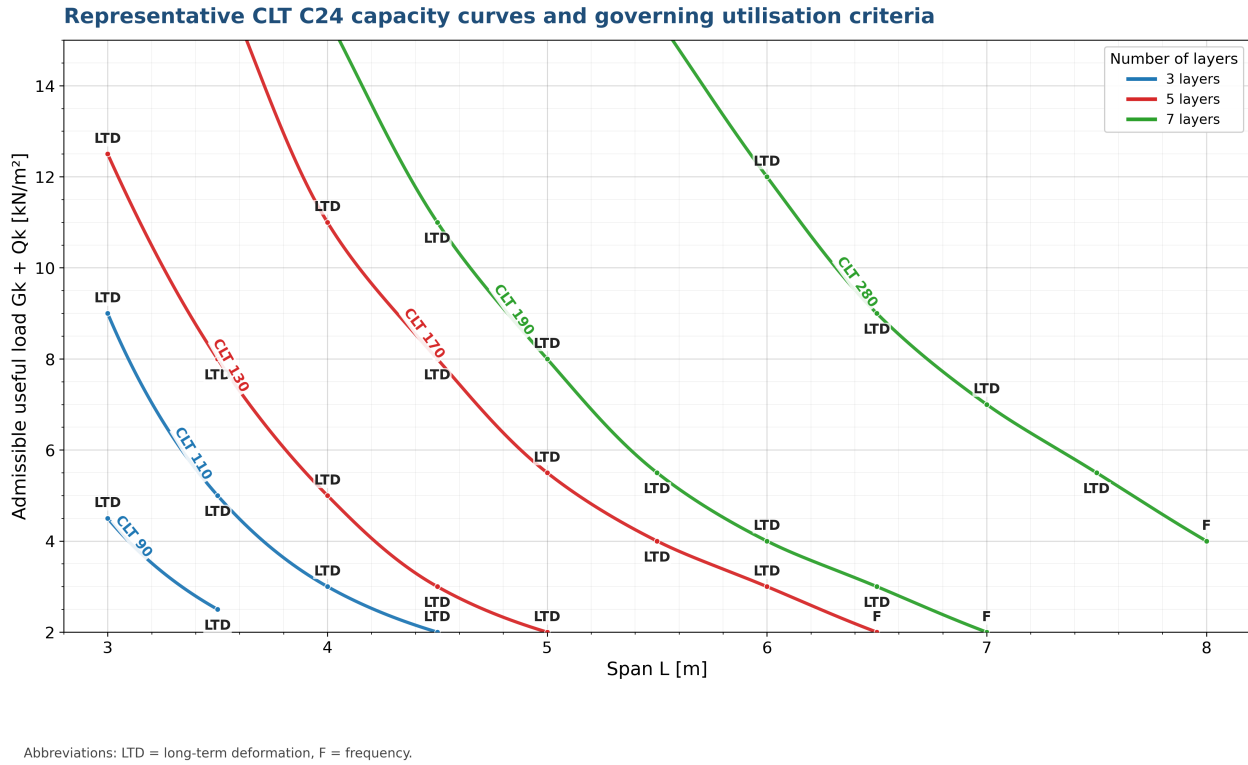


Figure 9: Representative CLT C24 capacity curves with governing utilisation criteria indicated at the envelope points.

Figure 9 shows that long-term deformation is the dominant governing criterion over most of the representative capacity envelope. This is particularly clear for the short- and medium-span configurations, where the maximum admissible useful load is generally controlled by the long-term deflection requirement rather than by ultimate resistance.

For the longest spans of the selected configurations, the governing criterion progressively shifts towards the fundamental frequency check. This indicates that increasing the panel thickness or the number of layers extends the feasible span range, but does not necessarily remove serviceability limitations. In long-span applications, dynamic comfort can become as restrictive as, or more restrictive than, deformation.

The resistance-related checks remain less critical for the selected envelope points. Bending and shear utilisation ratios stay below the serviceability-related criteria, while rolling shear reaches moderate values in some cases but does not govern the representative configurations shown in Figure 9. The structural limitation of CLT floor panels should therefore not be interpreted only as a strength problem. For the investigated C24 panels without specific fire resistance requirement, the boundary of the feasible domain is mainly controlled by deformation and vibration criteria.

To complement the graphical interpretation, Table 18 reports the utilisation ratios for selected envelope configurations. The table allows the governing criterion to be compared with the other checks and shows whether the governing criterion is clearly dominant or close to another verification.

Table 18: Representative unity checks for selected CLT C24 envelope configurations, expressed relative to the limit value.

Configuration	Span [m]	$G_k + Q_k$ [kN/m ²]	Bending	Shear	Rolling shear	Short-term def.	Long-term def.	Frequency	Point-load def.	Governing
CLT 90 L3	3.5	2.5	0.36	0.05	0.28	0.80	0.96	0.49	0.74	Long-term def.
CLT 110 L3	4.5	2.0	0.35	0.05	0.27	0.77	0.88	0.66	0.84	Long-term def.
CLT 130 L5	5.0	2.0	0.38	0.04	0.24	0.76	0.87	0.73	0.79	Long-term def.
CLT 170 L5	6.5	2.0	0.41	0.05	0.26	0.80	0.94	0.95	0.79	Frequency
CLT 190 L7	7.0	2.0	0.40	0.05	0.29	0.75	0.89	0.99	0.71	Frequency
CLT 280 L7	8.0	4.0	0.51	0.07	0.40	0.79	0.91	0.98	0.41	Frequency

The numerical values in Table 18 confirm the graphical observation. For the shorter and intermediate representative configurations, long-term deformation gives the highest utilisation ratio and therefore controls the admissible useful load. For larger spans, however, the frequency utilisation ratio progressively increases and becomes close to the long-term deformation ratio. In the selected long-span configurations, it eventually becomes the governing criterion.

This result shows that increasing the panel thickness or the number of layers can extend the feasible span range, but it does not necessarily remove serviceability limitations. Although longer spans may be possible from a resistance point of view, the natural frequency of the floor decreases as the span increases and dynamic comfort can become decisive. The full set of envelope-point utilisation ratios for the selected representative curves is provided in Appendix A.

11.2.3 Influence of fire resistance requirements

Each configuration retained as valid in normal conditions (ULS + SLS) is re-verified under three fire scenarios — R30, R60 and R90 — following the reduced cross-section method of EN 1995-1-2 (Section 8). The fire verification covers only the ultimate strength checks (bending, longitudinal shear and rolling shear) on the residual cross-section, since the accidental design situation addresses ultimate resistance only.

Figure 10 reproduces the application domain of Figure 8 for the four scenarios. The panels are visually almost indistinguishable. The only clearly observable contraction occurs for the CLT 90 mm curve under R90, whose longest spans disappear from the feasible domain. This is consistent with the reduced cross-section method, since $d_{ef} = 65.5$ mm leaves only about

24.5 mm of residual section to resist the accidental loading. All configurations of CLT 120 mm and above remain almost entirely unaffected.

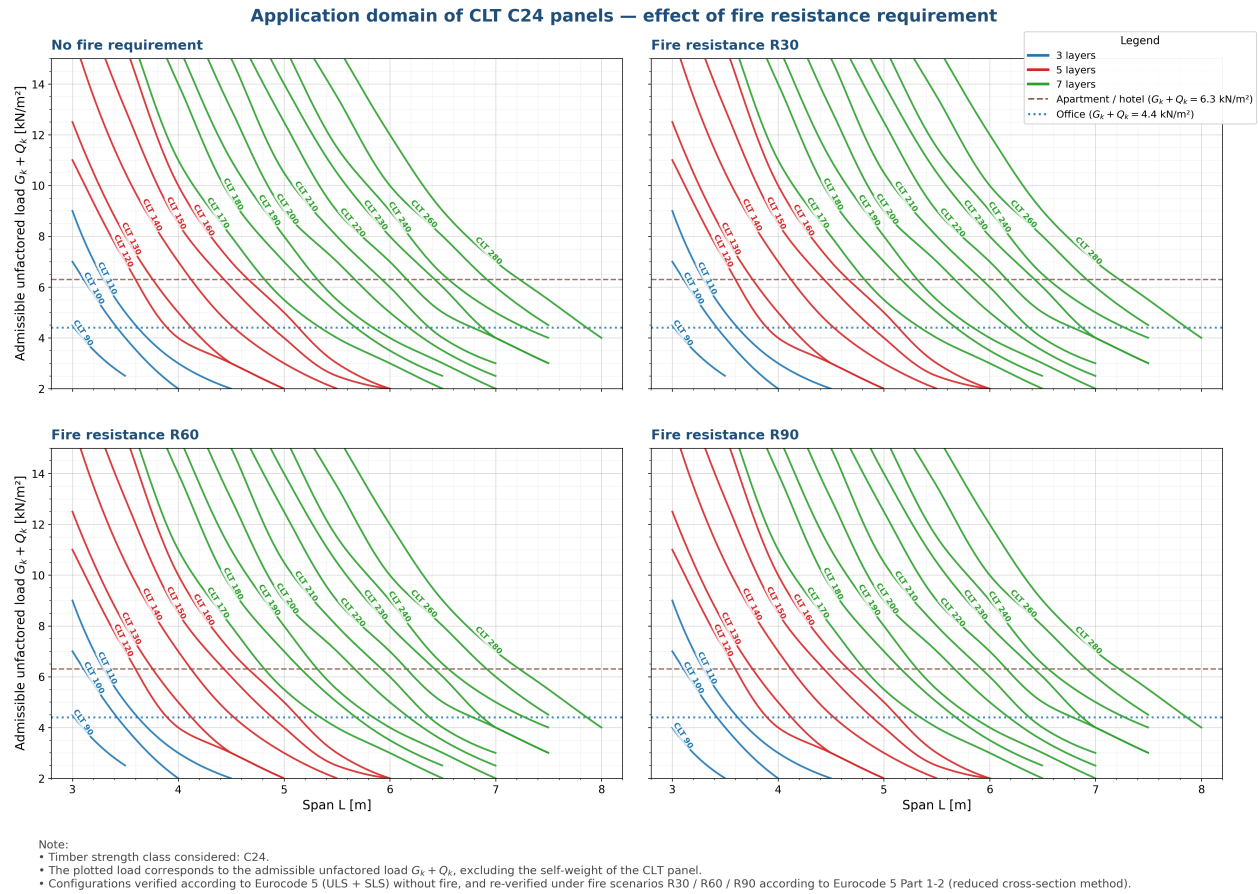


Figure 10: Application domain of CLT C24 floor panels for the four fire scenarios (No fire, R30, R60, R90).

Table 19 quantifies this observation by reporting, for each fire class, the share of CLT C24 configurations valid in normal conditions that also satisfy the fire verification.

Table 19: Share of structurally valid CLT C24 configurations that also satisfy the fire resistance verification.

Fire scenario	Passing	Total valid	Survival rate	Failures
R30	65 844	65 846	99.997 %	2
R60	65 830	65 846	99.976 %	16
R90	65 748	65 846	99.851 %	98

Even under the most demanding R90 scenario, more than 99.8 % of the valid configurations remain admissible. This high survival rate is explained by two combined effects. First, as

shown in Section 11.2.2, the structural design of CLT floor panels is consistently governed by serviceability criteria, while the bending, longitudinal shear and rolling shear utilisations typically remain below 0.5. This latent over-resistance constitutes a substantial reserve that absorbs the cross-section reduction induced by charring. Second, the accidental load combination ($q_{Ed,fi} = G_k + 0.3 \cdot Q_k$) is significantly less demanding than the fundamental ULS combination ($q_{Ed} = 1.35 \cdot G_k + 1.5 \cdot Q_k$), with a reduction of more than 50 % for typical office loading.

This confirms that CLT panels exhibit a particularly favourable behaviour under fire exposure. The progressive and predictable charring of timber, combined with the insulating effect of the char layer protecting the residual cross-section, allows CLT floors to retain a significant load-bearing capacity even under prolonged fire exposure. As a result, fire resistance generally does not constitute a binding design constraint for CLT floor panels in the building typologies considered in this study.

11.3 Environmental performance

The environmental results are presented for the structurally valid CLT configurations. Since the fossil GWP of CLT is directly proportional to the timber volume, the environmental performance is mainly governed by the total panel thickness required to satisfy the structural criteria. This subsection therefore focuses on how the required panel thickness affects the fossil GWP of the valid CLT solutions.

Figure 11 shows the fossil GWP of representative valid CLT configurations for selected office building and apartment/hotel cases. For a given span and building type, the fossil GWP increases linearly with the total CLT thickness. The figure therefore mainly illustrates the direct effect of panel thickness on fossil GWP.

Fossil GWP as a function of CLT thickness for selected design cases

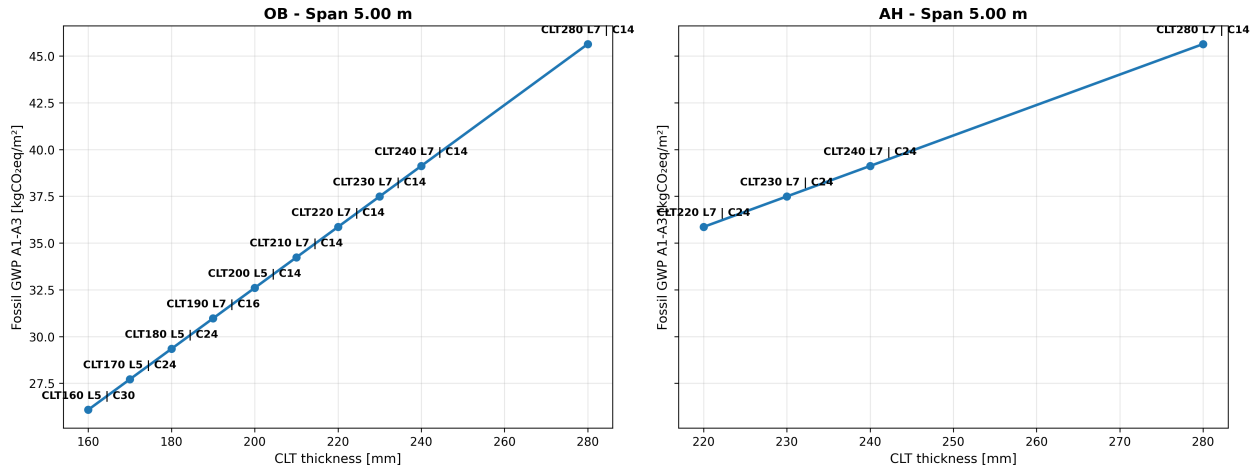


Figure 11: Fossil GWP as a function of CLT thickness for selected valid CLT configurations.

The graph also illustrates that the timber strength class does not directly affect the fossil GWP calculation, since the emission factor is applied per unit volume of CLT. However, the strength class can influence the structural validity of a configuration. In other words, the environmental value associated with a given thickness remains the same, but the set of configurations that can be used for a given span and loading condition depends on the structural checks.

To evaluate the environmental impact from a design perspective, the configuration with the lowest fossil GWP was selected for each span and building type. The resulting minimum values are shown in Figure 12.

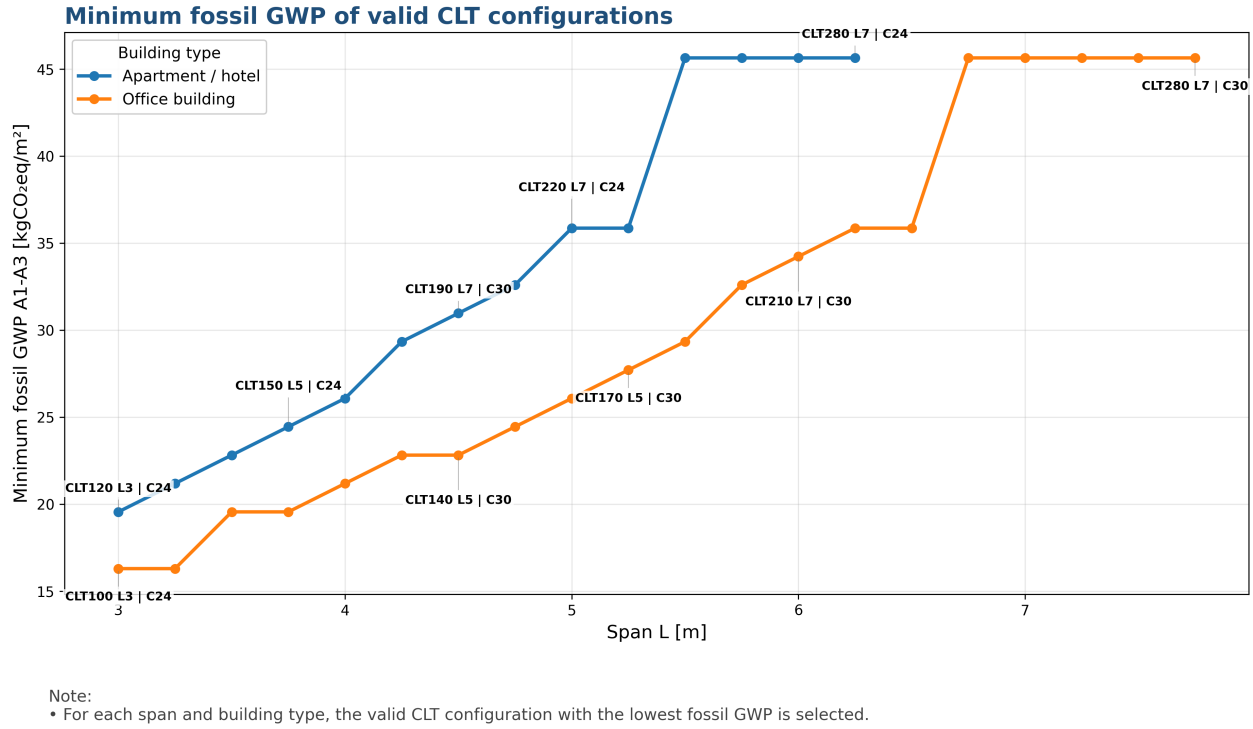


Figure 12: Minimum fossil GWP of valid CLT configurations as a function of span for the office building and apartment/hotel cases.

The apartment/hotel case generally leads to higher fossil GWP values than the office building case. This is due to the higher reference loading assumptions, which require thicker valid panels for the same span. The difference between the two curves therefore reflects the influence of the structural load case rather than a difference in the environmental factor used for the material.

The step-like shape of the curves corresponds to changes in the minimum valid CLT configuration. When a given panel thickness is no longer sufficient to satisfy the structural criteria, the next valid thickness becomes necessary, leading to a sudden increase in fossil GWP. This confirms that, for CLT floor systems, the environmental performance must be interpreted together with the structural feasibility results.

Overall, the lowest fossil GWP is obtained for the thinnest structurally valid CLT configuration. The environmental optimisation of CLT floors is therefore closely linked to the structural design: reducing the panel thickness reduces the fossil GWP, but only if the configuration remains valid for the considered span, loading condition and serviceability requirements.

11.4 Economic performance

The economic assessment focuses on the material cost of structurally valid CLT floor configurations and on the way this cost interacts with the embodied carbon results presented in Section 11.3. As established in Chapter 10, only material costs are considered, since labour and execution-related costs depend on project-specific conditions that fall outside the scope of this comparative study.

11.4.1 Material cost

For each structurally valid CLT configuration, the material cost per unit floor area is obtained by summing the cost contributions of each individual layer:

$$C_{\text{CLT}} = \sum_{i=1}^n c_i(t_i, \text{wood class})$$

where c_i is the unit cost, in €/m², of layer i for the considered layer thickness and timber strength class, taken from Table 15. Since the unit cost depends both on the layer thickness and on the wood class, two configurations with identical total panel thickness can lead to different material costs depending on their layup and on the selected timber strength class.

To evaluate the cost performance from a design perspective, the configuration with the lowest material cost was selected for each panel thickness and span. The resulting cost-efficient frontier is presented in Figure 13 for two representative office spans, $L = 4$ m and $L = 5$ m.

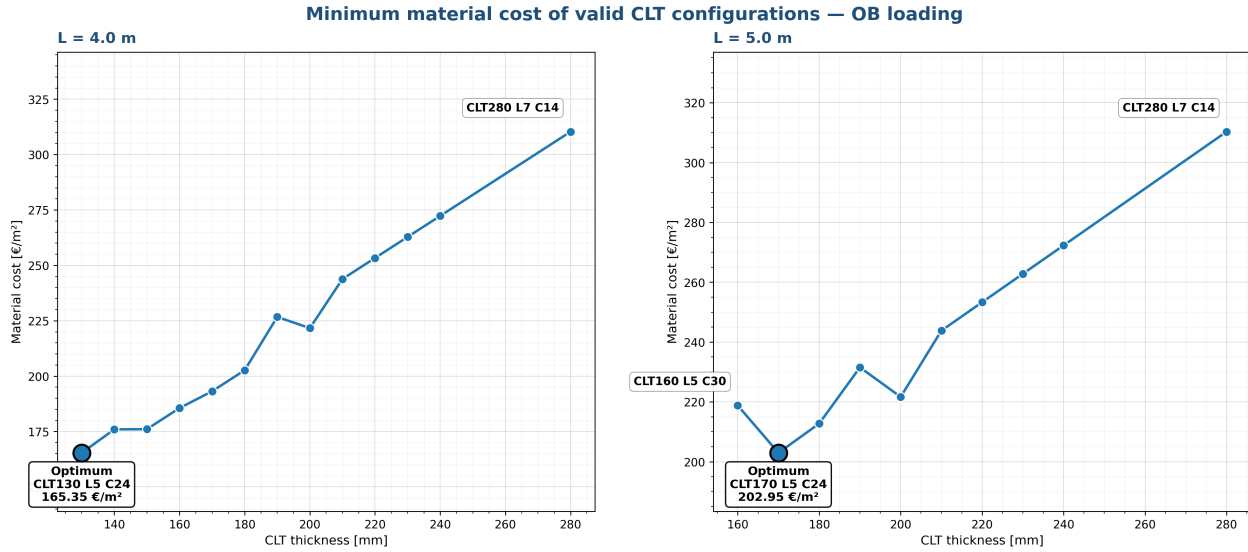


Figure 13: Minimum material cost of valid CLT configurations as a function of panel thickness, for office building loading and two representative spans.

The cost curves are not strictly monotonic. Although the material cost generally increases with panel thickness, local minima can be observed at intermediate thicknesses. These dips correspond to configurations where the increase in total thickness is compensated by a more economical layup or timber strength class. As a result, a slightly thicker configuration may sometimes be less expensive than a thinner alternative requiring a less favourable material combination.

However, selecting the cheapest valid configuration ignores its environmental impact. A configuration that minimises material cost may simultaneously lead to a higher embodied carbon footprint, particularly when thicker panels in lower-strength wood classes are favoured. The cost–carbon trade-off must therefore be examined explicitly, which motivates the multi-criteria analysis presented in the following subsection.

11.4.2 Cost–carbon trade-off

The structural validity, environmental and economic results obtained in the previous sections show that no single configuration is universally optimal. A configuration may minimise material cost, fossil GWP or both, depending on the considered span and loading conditions. In order to support early-stage design decisions, a single indicator combining both criteria is therefore introduced.

For each span and building type combination, the cost and fossil GWP values of the struc-

turally valid configurations are first normalised between 0 and 1:

$$\tilde{C}_i = \frac{C_i - C_{\min}}{C_{\max} - C_{\min}} \quad \tilde{G}_i = \frac{G_i - G_{\min}}{G_{\max} - G_{\min}}$$

where C_i and G_i are respectively the material cost and the fossil GWP of configuration i . The minimum and maximum values are taken over all valid configurations sharing the same span and building type.

A compromise score is then defined as the Euclidean distance between the normalised performance of configuration i and the ideal point $(\tilde{C}, \tilde{G}) = (0, 0)$, corresponding to the minimum-cost and minimum-GWP combination:

$$S_i = \sqrt{\tilde{C}_i^2 + \tilde{G}_i^2}$$

In the results presented in this thesis, equal weighting is adopted between cost and fossil GWP in order to provide a neutral comparison between the two criteria. The Euclidean formulation is preferred over a simple ranking approach, as it directly measures the distance from the ideal point in the normalised cost–GWP plane.

The configuration minimising S_i is identified as the compromise optimum for the considered span and building type combination. By construction, this configuration represents a balanced solution between the economic and environmental objectives for the adopted weighting assumptions, rather than a solution optimised for only one criterion.

Figures 14 and 15 present, for two representative office spans, the minimum cost, the minimum fossil GWP and the minimum compromise score as a function of CLT thickness. For each thickness, only the configuration that minimises the considered criterion is retained.

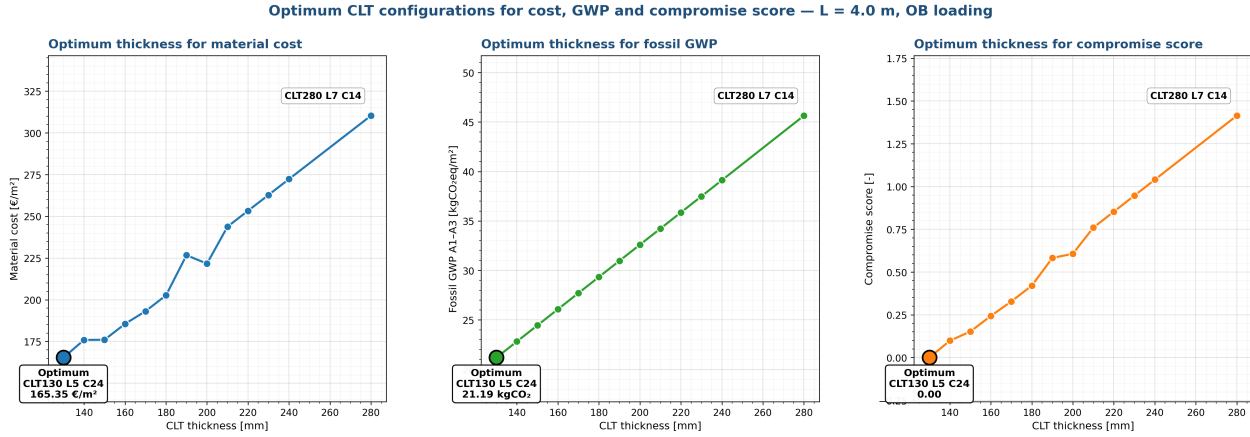


Figure 14: Optimum CLT configurations for material cost, fossil GWP and compromise score as a function of panel thickness ($L = 4$ m, office building loading).

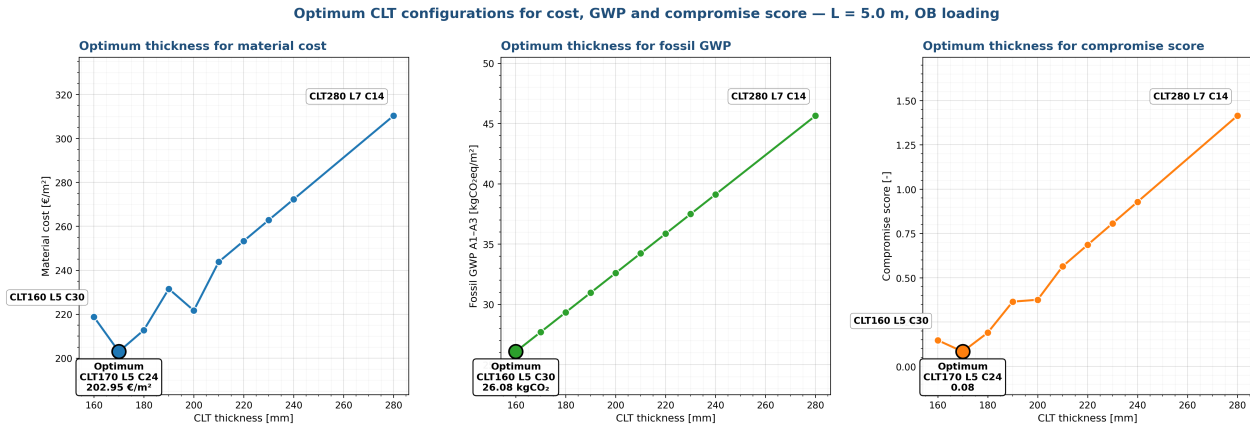


Figure 15: Optimum CLT configurations for material cost, fossil GWP and compromise score as a function of panel thickness ($L = 5$ m, office building loading).

Several observations can be drawn from these figures. The cost curve confirms the non-monotonic behaviour already discussed in Section 11.4.1, with local minima reflecting changes in the cheapest valid layout. By contrast, the fossil GWP curve is strictly linear. Since the same emission factor of is adopted for all CLT strength classes, the embodied carbon depends only on the total panel volume. Consequently, the minimum-GWP configuration always corresponds to the thinnest structurally valid panel, regardless of the wood class.

The compromise curve combines these two effects and reveals an intermediate optimum that does not necessarily coincide with the minimum-cost or the minimum-GWP configuration. For both investigated spans, the compromise optimum is located at a moderate panel thickness, where the cost penalty associated with thinner higher-strength panels is balanced by the

lower embodied carbon achieved through reduced timber volume. This shows that the design solution which best balances both criteria is generally not the cheapest, nor the lightest, but a configuration that performs reasonably well on both dimensions simultaneously.

To support the practical use of this multi-criteria approach, a Power BI decision-support tool was developed within the BESIX Engineering Department's parametric workflow. The tool allows the user to filter the validated configuration database by building type, span, structural system and design parameters and to visualise the corresponding cost, fossil GWP, mass and compromise score. For each selected design situation, the dashboard directly identifies the optimal configuration according to the chosen criterion, such as minimum material cost, minimum fossil GWP or minimum compromise score. In the results presented in this thesis, equal weights are assigned to material cost and fossil GWP in the compromise score. However, the Power BI tool also allows the user to adjust these weights depending on the relative importance given to cost or environmental performance.

11.5 Comparison with reinforced concrete floor systems

After analysing the CLT floor systems independently, the results are compared with reinforced concrete floor systems in order to identify the situations in which CLT can constitute a relevant alternative. The comparison is carried out from two complementary perspectives. First, the structural capacity of CLT panels is compared with reference precast hollow-core slabs. Then, reinforced concrete slabs and CLT panels are compared in terms of fossil GWP, material cost and compromise score for representative office building design cases.

The objective of this comparison is not to determine a universally superior floor system. Instead, it aims to identify the design situations in which each solution becomes more relevant, depending on span, load level and project priorities.

11.5.1 Structural comparison

The structural comparison is first performed by comparing the load-span domain of CLT panels with reference precast concrete hollow-core slabs. Figure 16 compares the maximum admissible useful load of selected CLT C24 panels designed for R60 fire resistance with Ergon hollow-core slab curves. For consistency, the useful load is expressed as the load applied in addition to the self-weight of the structural floor element.

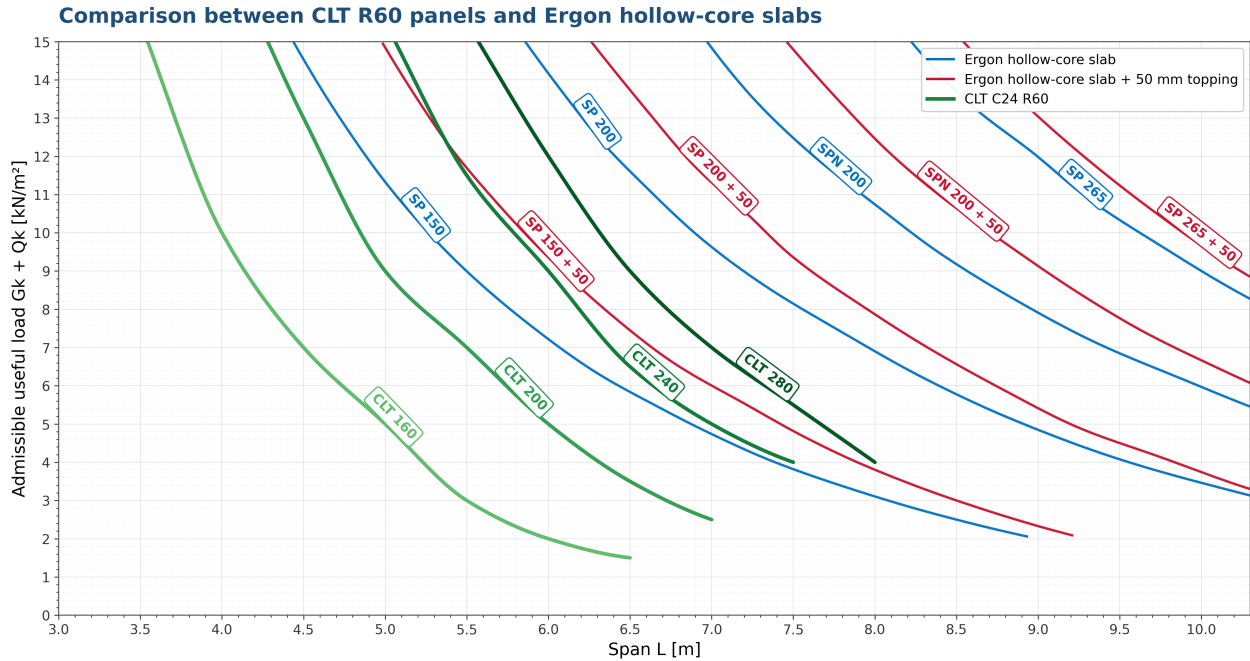


Figure 16: Comparison between CLT C24 R60 panels and Ergon hollow-core slabs in terms of admissible useful load as a function of span.

The comparison shows that the structural domain of CLT panels remains significantly more limited than that of the hollow-core slab systems. Even when relatively thick CLT panels are considered, the CLT curves mainly overlap with the lower range of the Ergon hollow-core slab solutions. In particular, the thickest CLT configurations approach only the capacity domain of the thinner hollow-core slabs, while the deeper hollow-core sections remain clearly more efficient for larger spans and higher useful loads.

This observation is important because it shows that CLT cannot be considered as a direct structural substitute for reinforced concrete hollow-core slabs over the full range of applications. The relevance of CLT is mostly limited to the lower part of the load-span domain, where spans and useful loads remain moderate. When the span increases, the required CLT thickness becomes significant and the available structural margin decreases.

The Ergon hollow-core slabs therefore remain structurally more advantageous for longer spans and higher load levels. Their higher stiffness and load-carrying capacity allow them to cover a wider range of applications with comparatively thinner structural depths. Consequently, the choice of CLT in this comparison can only be justified within a restricted structural domain and must be assessed together with the environmental and economic results. In particular, even when CLT is structurally feasible, the required panel thickness may lead to a significantly higher material cost, which can limit its practical competitiveness compared

with reinforced concrete alternatives.

11.5.2 Environmental and economic comparison

The comparison is then extended to the environmental and economic performance of CLT panels and in-situ reinforced concrete slab solutions. The structurally valid configurations are compared in terms of fossil GWP, material cost and compromise score. The compromise score combines both criteria after normalisation, so that configurations can be evaluated not only according to their minimum cost or minimum carbon footprint, but also according to their balanced performance.

Figures 17, 18 and 19 present the optimisation results for office building loading and spans of 4 m, 5 m and 6 m. For each span, the first graph shows the minimum material cost as a function of thickness, the second graph shows the minimum fossil GWP and the third graph shows the compromise score.

CLT vs reinforced concrete — optimum configurations for L = 4 m (Office building loading)

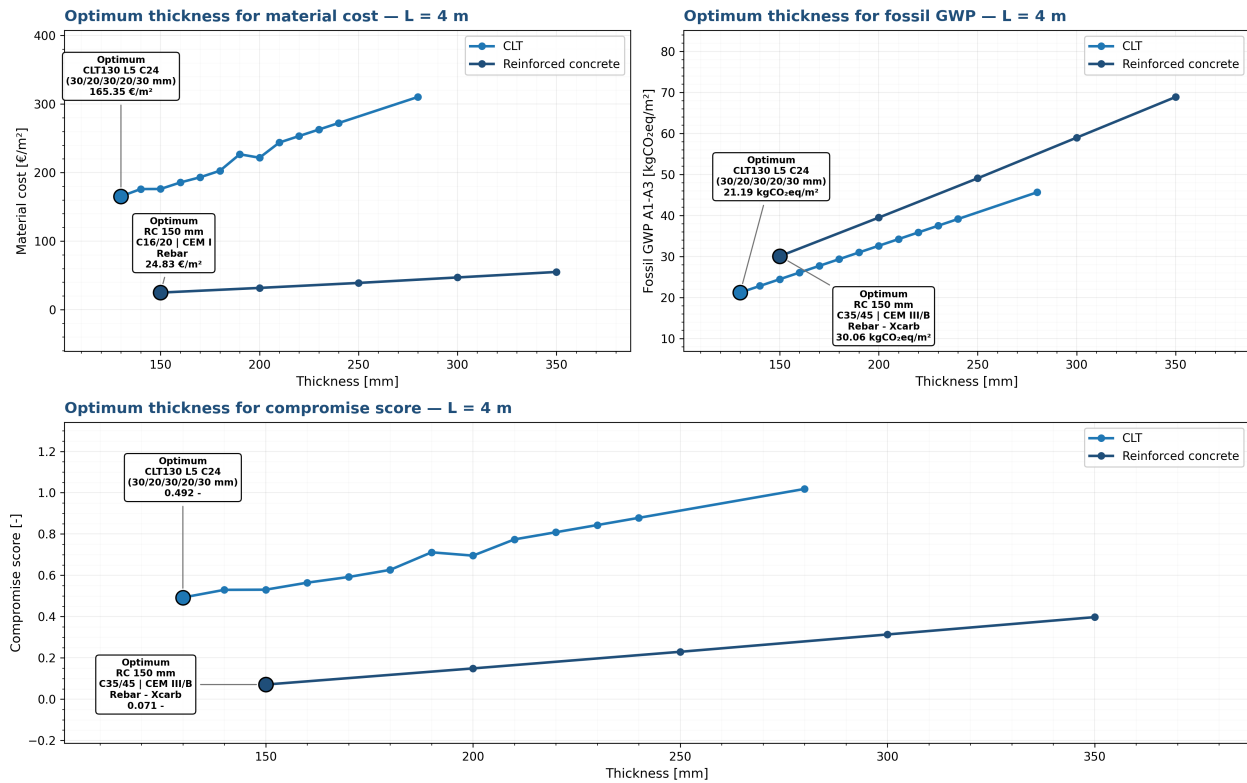


Figure 17: Optimum CLT and reinforced concrete configurations for a 4 m span under office building loading.

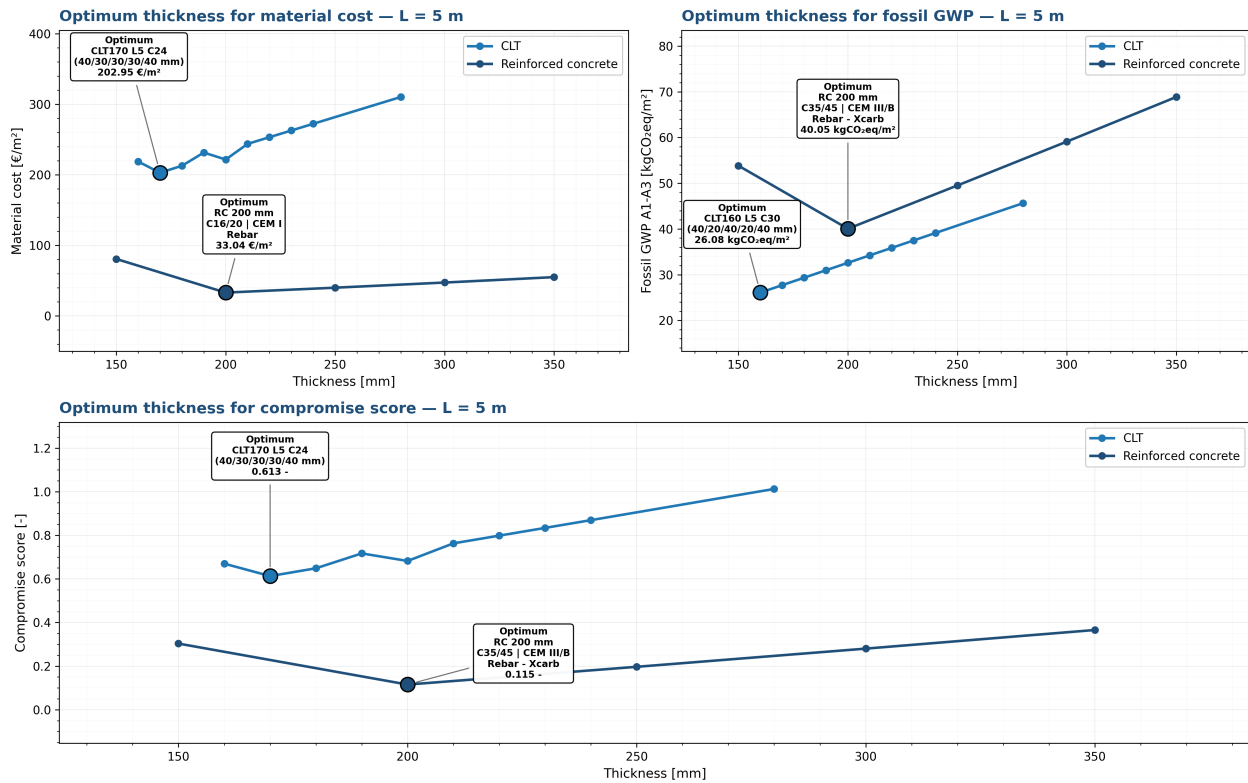
CLT vs reinforced concrete — optimum configurations for $L = 5$ m (Office building loading)

Figure 18: Optimum CLT and reinforced concrete configurations for a 5 m span under office building loading.

CLT vs reinforced concrete — optimum configurations for L = 6 m (Office building loading)

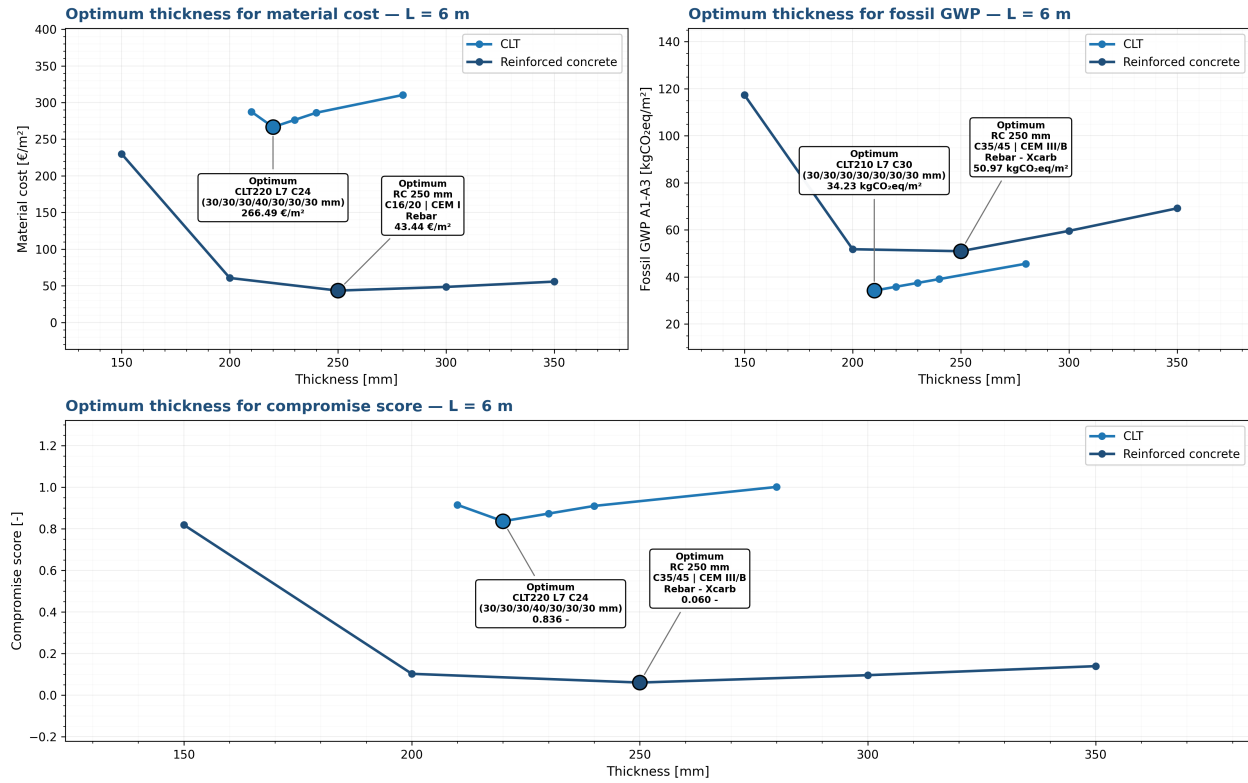


Figure 19: Optimum CLT and reinforced concrete configurations for a 6 m span under office building loading.

The results show a clear contrast between the two systems. From a fossil GWP point of view, CLT performs better than the in-situ reinforced concrete alternatives for the representative office spans considered. This is visible in the GWP graphs, where the minimum-GWP CLT configurations remain below the corresponding reinforced concrete solutions. For example, for the 5 m span, the best CLT solution reaches approximately 26 kgCO₂eq/m², compared with about 40 kgCO₂eq/m² for the best reinforced concrete solution. This confirms the environmental advantage of CLT when the comparison is limited to fossil GWP.

However, the opposite conclusion is obtained from an economic point of view. The reinforced concrete solutions are significantly less expensive than the CLT alternatives. For the same 5 m span, the minimum material cost is approximately 33 €/m² for reinforced concrete, compared with about 203 €/m² for CLT. Therefore, although CLT is more favourable in terms of fossil GWP, it is economically much less competitive in the investigated cases.

The shape of the reinforced concrete curves also requires some interpretation. Unlike CLT, where the fossil GWP increases almost directly with thickness due to the fixed emission

factor per cubic metre of timber, the reinforced concrete results are influenced by both concrete volume and reinforcement quantity. Increasing the slab thickness increases the amount of concrete, but it can also reduce the required reinforcement. As a result, the reinforced concrete curves are not always strictly increasing and an optimum can appear at an intermediate thickness. This optimum corresponds to the balance between the additional concrete volume and the reduction in reinforcement demand.

The compromise score highlights the consequence of this cost–carbon trade-off. Although CLT gives the lowest fossil GWP, reinforced concrete obtains the lowest compromise score for the investigated office spans when cost and fossil GWP are weighted equally. This is mainly because the economic advantage of reinforced concrete is much larger than its environmental disadvantage in the selected cases.

The comparison therefore shows that CLT is environmentally attractive but economically penalised. In the present dataset, the decision to use CLT cannot be justified by material cost alone, since reinforced concrete is clearly more competitive on that criterion. Its relevance is instead linked to projects where reducing fossil GWP is a priority and where the additional material cost can be accepted. Conversely, when economic performance, stiffness and long-span efficiency are dominant, in-situ reinforced concrete remains the more favourable solution for the investigated office floor cases.

11.6 Application domains and design recommendations

The results of the parametric study show that the relevance of CLT floor systems depends strongly on the design context. CLT should not be considered as a universal replacement for reinforced concrete slabs but rather as a targeted alternative for specific span, load and project-priority conditions.

From a structural point of view, CLT is most suitable for short- to medium-span applications where the required unfactored applied loads remain moderate. In this range, the structural requirements can generally be satisfied with reasonable panel thicknesses and the environmental benefit of CLT remains significant. This is particularly relevant for projects where reducing fossil GWP is a major design objective and where the use of a lightweight and prefabricated system provides additional advantages, such as reduced self-weight, rapid installation and dry construction.

However, the applicability of CLT decreases when spans or imposed loads increase. Longer spans require thicker panels and more demanding layups in order to satisfy bending, deflection and vibration requirements. The fire resistance verification does not drastically modify the overall feasibility domain for the selected configurations, although it remains an important

design constraint that must be checked. A more critical limitation is related to acoustic performance. As shown in the acoustic assessment, bare CLT panels do not satisfy the expected acoustic requirements by increasing the structural panel thickness alone. Additional build-up layers, such as resilient layers, screeds, suspended ceilings or acoustic insulation, are therefore required. These layers would increase the total floor cost, mass and possibly embodied carbon of the CLT solution, whereas reinforced concrete slabs generally benefit from their higher mass and are less penalised by this aspect. Therefore, although CLT remains advantageous from a fossil GWP perspective, its practical competitiveness must be assessed together with the additional measures required for acoustic performance.

The comparison with Ergon hollow-core slabs also shows that even the thickest CLT panels considered in this study mainly compete with the lower range of hollow-core slab solutions. This confirms that CLT is mainly relevant in the lower part of the load-span domain. For longer spans and higher unfactored applied loads, concrete-based floor systems remain structurally more efficient because of their higher stiffness, load-carrying capacity and wider application range.

From an economic point of view, reinforced concrete remains clearly more competitive in the cases investigated. The material cost of the reinforced concrete slabs is significantly lower than that of the CLT alternatives. This difference would probably become even more pronounced if the additional acoustic build-up required for CLT floors were included in the cost assessment. Therefore, the decision to use CLT cannot be justified by material cost alone. It is mainly relevant for projects where carbon reduction, reduced self-weight, prefabrication or construction speed are given priority over direct material cost.

Based on these results, the following design recommendations can be formulated. CLT should be considered primarily for short- and medium-span floor systems where moderate loads are applied and where fossil GWP reduction is an important project objective. It is less suitable when the design is governed by long spans, high loads, strict vibration requirements, acoustic performance or low-cost optimisation. Reinforced concrete remains the more appropriate solution when material cost, stiffness, acoustic robustness, fire robustness and long-span efficiency are the dominant design criteria.

The results also highlight the importance of using a multi-criteria decision-support approach. The most suitable solution cannot be identified from a single criterion alone. A system that performs well in terms of fossil GWP may be less favourable in terms of cost, while a cheaper system may have a higher environmental impact. For this reason, the Power BI dashboard developed in this thesis provides a useful practical tool for early-stage design. It allows the user to filter the validated database by building type, span, structural system and design parameters and to visualise the corresponding material cost, fossil GWP, mass and

compromise score.

This type of comparison is also increasingly relevant in the context of emerging environmental regulations for buildings. Several European countries are progressively introducing maximum environmental impact thresholds for new buildings. For example, in France, the RE2020 regulation defines a construction-stage carbon indicator, $I_{c_{\text{construction}}}$, expressed in $\text{kgCO}_2\text{eq}/\text{m}^2$ of reference floor area over a 50-year study period. For permits filed from 2025, the maximum average values are approximately $530 \text{ kgCO}_2\text{eq}/\text{m}^2$ for single-family houses, $650 \text{ kgCO}_2\text{eq}/\text{m}^2$ for collective housing and $810 \text{ kgCO}_2\text{eq}/\text{m}^2$ for office buildings. Further reductions are planned in later regulatory steps, for example for collective housing. These values are whole-building limits and are modulated depending on project-specific parameters such as building type, surface, climate zone, location and foundation conditions.

Another example is the Dutch MPG method, used in the Netherlands to assess the environmental performance of new buildings. Unlike RE2020, the MPG indicator is not directly expressed in $\text{kgCO}_2\text{eq}/\text{m}^2$. It aggregates several environmental impact categories, including climate change, into a single monetised environmental cost, expressed in $\text{€}/\text{m}^2/\text{year}$. The current limit values are $0.8 \text{ €}/\text{m}^2/\text{year}$ for dwellings and $1.0 \text{ €}/\text{m}^2/\text{year}$ for office buildings larger than 100 m^2 . Therefore, RE2020 can be interpreted as a direct carbon-cap example, whereas MPG represents a broader environmental-cost cap in which carbon is only one weighted component.

These regulatory examples should not be directly compared with the numerical results of this thesis. The RE2020 and MPG limits are whole-building assessment indicators, whereas the present study focuses on floor-system indicators and mainly on the A1–A3 product stage. For example, the floor-system fossil GWP values obtained in this thesis only represent one structural component of the building, while regulatory thresholds include a broader scope of materials, trades and life-cycle modules. Nevertheless, these frameworks illustrate the direction in which building design is evolving: embodied carbon and environmental performance are becoming explicit design constraints. This reinforces the relevance of early-stage tools capable of comparing structural systems in terms of fossil GWP, cost and performance.

In this context, the selection of a floor system is not only a structural problem, but also an environmental, economic and performance-based decision. In the present thesis, the tool is applied to CLT panels and in-situ reinforced concrete slabs. However, the same framework could be extended to other floor systems, such as steel–concrete composite floors, precast concrete slabs or hybrid timber–concrete solutions. The workflow developed in this study can therefore be seen as a first step towards a broader floor-system selection tool, capable of supporting real design decisions in engineering projects and tenders.

12 Summary of the main findings

The main findings of the results and discussion chapter can be summarised as follows.

First, the structural feasibility of CLT floor systems is strongly governed by span length, loading level and serviceability requirements. As the span increases, the number of valid configurations decreases and thicker panels are required. Deflection and vibration criteria become particularly important because CLT floors are relatively lightweight and deformable compared with reinforced concrete systems.

Second, fire resistance remains an important design verification for CLT floor systems, but in the investigated results it does not drastically change the overall feasibility domain compared with the other structural and serviceability requirements. The residual cross-section must still be checked for the required fire class, but the results suggest that span, stiffness, vibration and load level have a more direct influence on the selection of valid configurations.

Third, acoustic performance represents a major practical limitation for CLT floors. The acoustic assessment showed that increasing the bare CLT panel thickness is not sufficient to satisfy the expected acoustic requirements. In practice, additional layers such as resilient systems, screeds, insulation or suspended ceilings are required. This means that the final CLT floor build-up would be heavier and more expensive than the structural panel alone. This point is important because the economic comparison presented in this thesis is based on the structural floor element and does not fully include the additional cost of the acoustic build-up.

Fourth, the fossil GWP of CLT is directly related to the amount of timber used per square metre. As panel thickness increases, the fossil GWP of the CLT solution also increases. Nevertheless, in the investigated office cases, CLT remains more favourable than the in-situ reinforced concrete alternatives from a fossil GWP point of view.

Fifth, the economic comparison shows the opposite trend. Reinforced concrete slabs are significantly less expensive than the CLT alternatives in terms of material cost. This cost difference is large enough to strongly influence the compromise score when cost and fossil GWP are weighted equally. Consequently, reinforced concrete remains the more favourable solution from a balanced cost–carbon perspective in the investigated cases.

Sixth, the comparison with reinforced concrete floor systems shows that CLT is not a direct substitute for all concrete solutions. Structurally, CLT is most relevant in the lower part of the load-span domain, while hollow-core slabs and reinforced concrete systems remain more efficient for longer spans and higher loads. Environmentally, CLT is advantageous, but economically it remains penalised by its higher material cost and by the additional build-up

required to satisfy acoustic performance.

Finally, the Power BI decision-support tool developed in this thesis proved necessary to interpret the large amount of parametric data generated by the workflow. It provides a practical way to compare structurally valid configurations according to cost, fossil GWP, mass and compromise score. This type of tool is particularly relevant in a context where environmental performance is increasingly regulated, as illustrated by frameworks such as RE2020 in France and MPG in the Netherlands. Although the results of this thesis are not direct whole-building regulatory compliance values, the workflow helps identify floor-system solutions that may contribute to reducing embodied carbon at an early design stage. Although it was applied here to CLT and in-situ reinforced concrete slabs, the same approach could be extended to additional floor systems in future work.

Overall, the study shows that CLT should be considered as a targeted low-carbon alternative rather than as a universal replacement for reinforced concrete. Its use is most justified when the span-load domain remains moderate and when carbon reduction is prioritised over material cost. Reinforced concrete remains more competitive when cost, stiffness, acoustic robustness and long-span efficiency dominate the design.

References

- Adviesbureau Lünig (2025a). *Kantoorgebouw Well House – Constructieplan PLG-06*. Drawing number WH_TO-LUN-T-PLG-06; project code 2401597; confidential project drawing.
- (2025b). *Kantoorgebouw Well House – Constructieplan PLG-21*. Drawing number WH_TO-LUN-T-PLG-21; project code 2401597; confidential project drawing.
- (Mar. 28, 2025c). *Kantoorgebouw Well House – Deel H: Elementberekening hout- en staalconstructies*. Tech. rep. 2401597. Technical design report; project document; confidential. Adviesbureau Lünig.
- (Mar. 28, 2025d). *Kantoorgebouw Well House – Principe details*. Drawing number WH_TO-LUN-T-DET-00; project code 2401597; confidential project drawing.
- Allan, K. and A. R. Phillips (2021). “Comparative Cradle-to-Grave Life Cycle Assessment of Low and Mid-Rise Mass Timber Buildings with Equivalent Structural Steel Alternatives”. In: *Sustainability* 13.6, p. 3401. DOI: [10.3390/su13063401](https://doi.org/10.3390/su13063401).
- Andersen, C. E. et al. (2022). “Comparative life cycle assessment of cross laminated timber building and concrete building with special focus on biogenic carbon”. In: *Energy and Buildings* 254, p. 111604. DOI: [10.1016/j.enbuild.2021.111604](https://doi.org/10.1016/j.enbuild.2021.111604).
- BESIX (2026). *Internal cost data for CLT floor systems and reinforced concrete slabs*. Internal company data provided to the author for the purpose of this thesis; confidential.
- Bois de structure – Classes de résistance* (2003). Belgian implementation: NBN EN 338:2003. CEN.
- Buildwise and TOTEM (2025). *Environmental data for construction materials in the Belgian TOTEM framework*. Buildwise environmental database and TOTEM material data used for Belgian construction materials.
- Carlson, Youri and Eloïse Denis (Feb. 23, 2026). *Understanding Construction Materials Carbon Emissions and Applying Sustainable Solutions Throughout Our Project*. BESIX BDA II Sustainability training presentation; internal company document.
- Cazemier, D. (2017). “Comparing Cross-Laminated Timber with Concrete and Steel Construction from a Developer Perspective”. Master’s thesis. MA thesis. Delft University of Technology.
- Chen, Z. et al. (2020). “Comparative Life-Cycle Assessment of a High-Rise Mass Timber Building with an Equivalent Reinforced Concrete Alternative Using the Athena Impact Estimator for Buildings”. In: *Sustainability* 12.11, p. 4708. DOI: [10.3390/su12114708](https://doi.org/10.3390/su12114708).
- CLT (2021). *CLT 2021 – Liste de prix*. Price list for CLT elements.
- Cole, R. J. (1999). “Building environmental assessment methods: Clarifying intentions”. In: *Building Research & Information* 27.4–5, pp. 230–246. DOI: [10.1080/096132199369354](https://doi.org/10.1080/096132199369354).

- Dagenais, C. and E. Karacabeyli (2012). *CLT Handbook (US Edition) – Chapter 8: Fire*. Tech. rep. FPInnovations and US Forest Products Laboratory.
- De Geetere, Lieven and Arne Dijckmans (2020). “Recent Advancements in Belgian Building Acoustical Standards”. In: Belgian Building Research Institute.
- Demissie, Girum (Apr. 18, 2024). *Understanding Analytical Methods of CLT: Shear Analogy, Gamma, Extended Gamma, and Timoshenko Beam Theory Methods*. Online article. SPEC Toolbox. URL: <https://spectoolbox.com/blog/understanding-analytical-methods-of-clt-shear-analogy-gamma-extended-gamma-and-timoshenko-beam-theory-methods>.
- Di Bella, Antonino and Milica Mitrovic (2020). “Acoustic Characteristics of Cross-Laminated Timber Systems”. In: *Sustainability* 12.14, p. 5612. DOI: [10.3390/su12145612](https://doi.org/10.3390/su12145612).
- Dijckmans, Arne and Lieven De Geetere (July 2020). *Overzicht van de akoestische normen voor woongebouwen in België volgens NBN S 01-400-1*. Normen-Antenne Akoestiek, version 2.0. Wetenschappelijk en Technisch Centrum voor het Bouwbedrijf.
- Drewniok, Michal P. (2020). *Relationships between Building Structural Parameters and Embodied Carbon. Part 1: Reinforced Concrete Floors Solutions*. Tech. rep. ENG-TR.013. EPSRC Impact Acceleration Account Postdoctoral Placement Scheme; ISSN 2633-6839. University of Cambridge.
- Duan, Z., Q. Huang, and Q. Zhang (2022). “Comparative life cycle assessment of a reinforced concrete residential building with equivalent cross laminated timber alternatives in China”. In: *Journal of Building Engineering* 62, p. 105357. DOI: [10.1016/j.jobe.2022.105357](https://doi.org/10.1016/j.jobe.2022.105357).
- Eurocode 1: Actions sur les structures – Partie 1-1: Actions générales – Poids volumiques, poids propres, charges d’exploitation des bâtiments* (2002). French implementation: NF EN 1991-1-1:2003. CEN.
- Eurocode 5: Conception et calcul des structures bois – Partie 2: Ponts* (2004). Belgian implementation: NBN EN 1995-2:2005. CEN.
- Eurocode 5: Conception et calcul des structures en bois – Partie 1-1: Généralités – Règles communes et règles pour les bâtiments* (2004). Belgian implementation: NBN EN 1995-1-1:2005, including AC:2006. CEN.
- Eurocode 5: Conception et calcul des structures en bois – Partie 1-1: Généralités – Règles communes et règles pour les bâtiments – Annexe nationale belge* (2008). Belgian National Annex to NBN EN 1995-1-1:2005. NBN.
- Eurocode 5: Conception et calcul des structures en bois – Partie 1-2: Généralités – Calcul des structures au feu* (2004). Belgian implementation: NBN EN 1995-1-2:2005, including AC:2006 and AC:2009. CEN.

- Eurocode 5: Conception et calcul des structures en bois – Partie 1-2: Règles générales – Calcul du comportement au feu – Annexe nationale belge* (2008). Belgian National Annex to NBN EN 1995-1-2:2005. NBN.
- Eurocode 5: Conception et calcul des structures en bois – Partie 2: Ponts – Annexe nationale belge* (2008). Belgian National Annex to NBN EN 1995-2:2005. NBN.
- Eurocode 5: Design of timber structures – Part 1-1: General – Common rules and rules for buildings* (2004). Including amendments and national annex where applicable. CEN.
- Eurocodes structuraux – Eurocodes: Bases de calcul des structures* (2002). Belgian implementation: NBN EN 1990:2002. CEN.
- Frangi, A. et al. (2014). “Fire Tests on Loaded Cross-laminated Timber Wall and Floor Elements”. In: *Fire Safety Science - Proceedings of the Eleventh International Symposium*, pp. 626–639. DOI: [10.3801/IAFSS.FSS.11-626](https://doi.org/10.3801/IAFSS.FSS.11-626).
- Gallagher, Simon (n.d.). *Formation Utilisations et Calculs CLT*. Training material. Nordic Structures.
- Gustavsson, L., K. Pingoud, and R. Sathre (2006). “Carbon dioxide balance of wood substitution: Comparing concrete- and wood-framed buildings”. In: *Mitigation and Adaptation Strategies for Global Change* 11.3, pp. 667–691. DOI: [10.1007/s11027-006-7207-1](https://doi.org/10.1007/s11027-006-7207-1).
- Hassan, O. A. B. and U. A. Girhammar (2013). “Assessment of Footfall-Induced Vibrations in Timber and Lightweight Composite Floors”. In: *International Journal of Structural Stability and Dynamics* 13.2, p. 1350015. DOI: [10.1142/S0219455413500156](https://doi.org/10.1142/S0219455413500156).
- Hassan, O. A. B. and C. Johansson (2018). “Glued laminated timber and steel beams: A comparative study of structural design, economic and environmental consequences”. In: *Journal of Engineering, Design and Technology* 16.3, pp. 398–417. DOI: [10.1108/JEDT-12-2017-0130](https://doi.org/10.1108/JEDT-12-2017-0130).
- Hill, C. A. S. and J. Dibdiakova (2016). “The environmental impact of wood compared to other building materials”. In: *International Wood Products Journal* 7.4, pp. 215–219. DOI: [10.1080/20426445.2016.1191604](https://doi.org/10.1080/20426445.2016.1191604).
- Jayalath, A. et al. (2020). “Life cycle performance of Cross Laminated Timber mid-rise residential buildings in Australia”. In: *Energy and Buildings* 223, p. 110091. DOI: [10.1016/j.enbuild.2020.110091](https://doi.org/10.1016/j.enbuild.2020.110091).
- Klein Goldewijk, L. (2025). “Comparative LCA and Cost Assessment of Cross-Laminated Timber, Ordinary Portland Cement Concrete and Geopolymer Concrete in Dutch Housing”. Master's thesis. MA thesis. Delft University of Technology. URL: https://repository.tudelft.nl/file/File_e58200dc-4eed-4df4-9b92-58d09ce75f7d.
- KLH Massivholz GmbH (July 2021). *Cross-Laminated Timber*. Technical brochure. KLH Massivholz GmbH.
- Laminated Timber Solutions (2019). *Concevoir en CLT: Manuel technique 2019*. Technical manual. URL: <https://www.laminatedtimbersolutions.be>.

- Liang, S. et al. (2020). “Comparative Life-Cycle Assessment of a Mass Timber Building and Concrete Alternative”. In: *Wood and Fiber Science* 52.2, pp. 217–229. DOI: [10.22382/wfs-2020-019](https://doi.org/10.22382/wfs-2020-019).
- Mass Timber Technologies (Aug. 2023). *Cross-laminated Timber & Glue-laminated Timber Design Guide*. 2nd ed. Design guide. Mass Timber Technologies.
- Ministère de la Transition écologique (2025a). *Guide RE2020: Réglementation environnementale des bâtiments neufs*. Official guide to the French RE2020 regulation. Ministère de la Transition écologique. URL: https://rt-re-batiment.developpement-durable.gouv.fr/IMG/pdf/guide_re_2020_16mai2025.pdf.
- (2025b). *Réglementation environnementale RE2020*. URL: <https://www.ecologie.gouv.fr/politiques-publiques/reglementation-environnementale-re2020>.
- Nationale Milieudatabase (2025a). *Environmental Performance of Construction Works*. URL: <https://milieudatabase.nl/en/environmental-performance/>.
- (2025b). *FAQ: Environmental performance calculation*. Explanation of the MPG environmental performance calculation method. URL: <https://milieudatabase.nl/en/faq/faq-environmental-performance-calculation/>.
- OpenAI (2026). *ChatGPT*. Artificial intelligence tool used for assistance with Python code development, graph generation, debugging and the structuring of selected sections of the thesis. All outputs were reviewed, adapted and validated by the author. URL: <https://chat.openai.com/>.
- Parry-Jones, Joel (Mar. 2018). *CLT Acoustic Performance*. Technical Design Guide 44. WoodSolutions Technical Design Guide. Forest and Wood Products Australia. ISBN: 978-1-925213-44-7.
- Petersen, A. K. and B. Solberg (2002). “Greenhouse gas emissions, life-cycle inventory and cost-efficiency of using laminated wood instead of steel construction: Case beams at Gardermoen Airport”. In: *Environmental Science & Policy* 5.2, pp. 169–182. DOI: [10.1016/S1462-9011\(01\)00044-2](https://doi.org/10.1016/S1462-9011(01)00044-2).
- Pierobon, F. et al. (2019). “Environmental benefits of using hybrid CLT structure in midrise non-residential construction: An LCA based comparative case study in the U.S. Pacific Northwest”. In: *Journal of Building Engineering* 26, p. 100862. DOI: [10.1016/j.jobe.2019.100862](https://doi.org/10.1016/j.jobe.2019.100862).
- RE Bâtiment (2025). *Seuils RE2020 2025: carbone ACV, Ic construction et Ic énergie*. Summary of the 2025 RE2020 carbon thresholds for Ic construction. URL: <https://re-batiment.fr/reglementaire/seuils-re2020-2025-carbone-acv-ic-construction-et-ic-energie/>.
- Renaux, Julie (2020). *Recommandations relatives à l’acoustique*. Formation Bâtiment Durable: Ventilation, conception et régulation, Printemps 2020.

- Rijksdienst voor Ondernemend Nederland (2026). *Milieuprestatie gebouwen (MPG)*. Official Dutch government page on MPG limit values in the Building Works Living Environment Decree. URL: <https://www.rvo.nl/onderwerpen/wetten-en-regels-gebouwen/milieuprestatie-gebouwen-mpg>.
- Rooij, N. H. van (Sept. 11, 2023). “Assessment of Steel-CLT Composite Floor Systems: Advancing Material-Efficient and Environmentally Friendly Construction”. Master’s thesis. MA thesis. Delft University of Technology.
- Ryberg, M. W. et al. (2021). “Comparative life cycle assessment of four buildings in Greenland”. In: *Building and Environment* 204, p. 108130. DOI: [10.1016/j.buildenv.2021.108130](https://doi.org/10.1016/j.buildenv.2021.108130).
- Sandin, G. (2015). “Life cycle assessment in the development of forest products”. PhD thesis. Chalmers University of Technology. URL: <https://publications.lib.chalmers.se/records/fulltext/214302/214302.pdf>.
- Sathre, R. and J. O’Connor (2010). “Meta-analysis of greenhouse gas displacement factors of wood product substitution”. In: *Environmental Science & Policy* 13.2, pp. 104–114. DOI: [10.1016/j.envsci.2009.12.005](https://doi.org/10.1016/j.envsci.2009.12.005).
- Schaeffer, N. J. I. (2025). “Design and Numerical Analysis of Line- and Point-Supported CLT Floor Systems: Static and Dynamic Performance of Panel-to-Panel Connections”. Master’s thesis. MA thesis. Delft University of Technology.
- Södra (Oct. 1, 2024). *Panel Structure Cross-laminated Timber*. CLT panel structure data sheet. Södra. URL: <https://www.sodra.com/buildingsystems>.
- Stabilame (Dec. 16, 2020). *B-EPD Environmental Product Declaration: Glued Cross Laminated Timber*. Tech. rep. B-EPD n° 2000102_002_EN. Environmental Product Declaration according to EN 15804+A2, NBN/DTD B08-001 and ISO 14025; valid until 16.12.2025. Federal Public Service of Health, Food Chain Safety and Environment.
- Stora Enso (June 2020a). *Soundproofing for CLT by Stora Enso*. Technical fact sheet.
- (June 2020b). *Soundproofing for CLT by Stora Enso*. Swedish version.
- (n.d.). *CLT by Stora Enso: Technical Brochure*. Technical brochure.
- Structures en bois – Bois lamellé croisé – Exigences* (2021). Belgian implementation: NBN EN 16351:2021. CEN.
- Studiengemeinschaft Holzleimbau e.V. and Überwachungsgemeinschaft Konstruktionsvollholz e.V. (Sept. 3, 2018). *Umweltproduktdeklaration nach ISO 14025 und EN 15804 für Duobalken® und Triobalken® (Balkenschicht-Holz)*. Tech. rep. EPD-SHL-20180026-IBG1-DE. Environmental Product Declaration; valid until 02.09.2023. Institut Bauen und Umwelt e.V.
- Theurl Austrian Premium Timber (Mar. 28, 2025). *Products*. Product catalogue including CLTPLUS technical specifications. Theurl Austrian Premium Timber.

- Tokede, O. O. et al. (2022). “Harmonising life cycle sustainability thinking in material substitution for buildings”. In: *Journal of Cleaner Production* 365, p. 132832. DOI: [10.1016/j.jclepro.2022.132832](https://doi.org/10.1016/j.jclepro.2022.132832).
- Ultratec (n.d.). *I-FIT Joist MD: Poutrelles ajourées ajustables*. Product brochure.
- UNEP and GlobalABC (2025). *Global Status Report for Buildings and Construction 2024/2025*. Nairobi: United Nations Environment Programme. URL: <https://www.unep.org/resources/report/global-status-report-buildings-and-construction-20242025>.
- WIEHAG Timber Construction GmbH (Apr. 5, 2024). *Environmental Product Declaration: Glued Laminated Timber*. Tech. rep. EPD-WIG-20240079-IBB1-EN. Environmental Product Declaration according to ISO 14025 and EN 15804+A2; valid until 04.04.2029. Institut Bauen und Umwelt e.V.
- XLam (Apr. 2020). *Australia & New Zealand Acoustic Design Guide*. XLam Acoustic Design Guide V2.
- XLAM Dolomiti (n.d.). *Technical Informative Brochure*. Technical brochure; includes surface quality, specifications, customisation, jointing and machining of XLAM panels. XLAM Dolomiti.

A Envelope-point utilisation ratios for representative CLT curves

This appendix provides the full set of utilisation ratios for the envelope points of the representative CLT C24 curves discussed in Section 11.2.2. Each row corresponds to one envelope point used to define the maximum admissible useful load for a given CLT thickness and span.

Table 20: Full set of envelope-point utilisation ratios for the selected representative CLT C24 curves.

Configuration	Span [m]	$G_k + Q_k$ [kN/m ²]	Bending	Shear	Rolling shear	Short-term def.	Long-term def.	Frequency	Point-load def.	Governing
CLT 90 L3	3.0	4.5	0.43	0.07	0.40	0.87	0.99	0.37	0.48	LTD
CLT 90 L3	3.5	2.5	0.36	0.05	0.28	0.80	0.96	0.49	0.74	LTD
CLT 110 L3	3.0	9.0	0.55	0.11	0.64	0.93	0.99	0.30	0.26	LTD
CLT 110 L3	3.5	5.0	0.44	0.08	0.44	0.83	0.90	0.40	0.41	LTD
CLT 110 L3	4.0	3.0	0.38	0.06	0.33	0.77	0.86	0.52	0.60	LTD
CLT 110 L3	4.5	2.0	0.35	0.05	0.27	0.77	0.88	0.66	0.84	LTD
CLT 130 L5	3.0	12.5	0.61	0.12	0.65	0.91	0.99	0.28	0.19	LTD
CLT 130 L5	3.5	8.0	0.56	0.09	0.50	0.91	0.99	0.37	0.29	LTD
CLT 130 L5	4.0	5.0	0.48	0.07	0.38	0.87	0.95	0.48	0.42	LTD
CLT 130 L5	4.5	3.0	0.41	0.05	0.29	0.78	0.87	0.60	0.58	LTD
CLT 130 L5	5.0	2.0	0.38	0.04	0.24	0.76	0.87	0.73	0.79	LTD
CLT 170 L5	3.0	21.0	0.58	0.15	0.81	0.76	0.91	0.22	0.09	LTD
CLT 170 L5	3.5	16.5	0.64	0.14	0.77	0.90	1.00	0.29	0.14	LTD
CLT 170 L5	4.0	11.0	0.58	0.11	0.61	0.88	0.94	0.38	0.20	LTD
CLT 170 L5	4.5	8.0	0.56	0.09	0.52	0.90	0.98	0.47	0.28	LTD
CLT 170 L5	5.0	5.5	0.50	0.08	0.42	0.86	0.99	0.57	0.37	LTD
CLT 170 L5	5.5	4.0	0.47	0.07	0.36	0.86	0.96	0.69	0.49	LTD
CLT 170 L5	6.0	3.0	0.46	0.06	0.32	0.87	0.99	0.82	0.62	LTD
CLT 170 L5	6.5	2.0	0.41	0.05	0.26	0.80	0.94	0.95	0.79	F
CLT 190 L5	3.0	21.0	0.49	0.13	0.71	0.62	0.74	0.21	0.08	LTD
CLT 190 L7	3.5	20.0	0.61	0.15	0.88	0.82	0.97	0.27	0.11	LTD
CLT 190 L7	4.0	15.5	0.64	0.14	0.81	0.91	0.99	0.34	0.15	LTD
CLT 190 L7	4.5	11.0	0.60	0.12	0.67	0.91	0.98	0.43	0.21	LTD
CLT 190 L7	5.0	8.0	0.56	0.10	0.57	0.91	0.99	0.52	0.27	LTD
CLT 190 L7	5.5	5.5	0.50	0.08	0.46	0.85	0.97	0.63	0.36	LTD
CLT 190 L5	6.0	4.0	0.49	0.06	0.35	0.87	0.98	0.76	0.48	LTD
CLT 190 L5	6.5	3.0	0.47	0.06	0.31	0.86	0.99	0.89	0.61	LTD
CLT 190 L7	7.0	2.0	0.40	0.05	0.29	0.75	0.89	0.99	0.71	F
CLT 280 L7	3.0	21.0	0.27	0.10	0.56	0.27	0.32	0.17	0.03	RS
CLT 280 L7	3.5	21.0	0.36	0.11	0.65	0.38	0.46	0.22	0.05	RS
CLT 280 L7	4.0	21.0	0.47	0.13	0.74	0.53	0.64	0.27	0.06	RS
CLT 280 L7	4.5	21.0	0.60	0.15	0.83	0.71	0.85	0.34	0.09	LTD
CLT 280 L7	5.0	19.0	0.68	0.15	0.85	0.85	0.99	0.40	0.11	LTD
CLT 280 L7	5.5	15.5	0.70	0.14	0.80	0.90	0.99	0.48	0.14	LTD
CLT 280 L7	6.0	12.0	0.67	0.12	0.70	0.90	0.98	0.57	0.18	LTD
CLT 280 L7	6.5	9.0	0.62	0.10	0.59	0.87	0.96	0.66	0.23	LTD
CLT 280 L7	7.0	7.0	0.59	0.09	0.53	0.86	0.96	0.76	0.28	LTD
CLT 280 L7	7.5	5.5	0.56	0.08	0.47	0.85	0.99	0.86	0.34	LTD
CLT 280 L7	8.0	4.0	0.51	0.07	0.40	0.79	0.91	0.98	0.41	F

B Hand Calculation Note: Design of CLT Floor Systems

B.1 Worked Example: 7-Layer CLT Floor Panel

B.1.1 Problem Definition

Geometry, support conditions and use category

Simply supported CLT floor structure of span

$$L = 5.5 \text{ m}$$

and strip width

$$b_t = 1.0 \text{ m.}$$

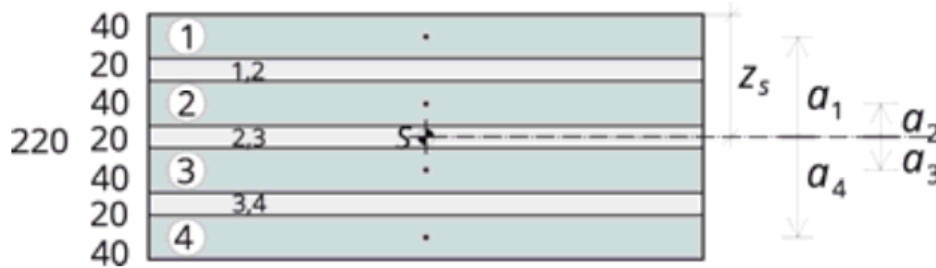


Figure 20: Designation of longitudinal layers, neutral axis position and distances a_i for the 7-layer CLT cross-section

The floor structure consists of a 7-layer CLT panel with total thickness

$$h_{\text{CLT}} = 220 \text{ mm}$$

and the following lay-up (from bottom to top):

$$40 \text{ L} - 20 \text{ T} - 40 \text{ L} - 20 \text{ T} - 40 \text{ L} - 20 \text{ T} - 40 \text{ L},$$

where L denotes layers with fibres parallel to the span (longitudinal) and T denotes layers with fibres perpendicular to the span (transverse).

All layers are made of boards in strength class C24. Service class is taken as 1.

Material data and design strengths

For C24 timber, the following characteristic material values are adopted:

$$\begin{aligned} E_{0,\text{mean}} &= 11,000 \text{ N/mm}^2, \\ E_{0,0.05} &= 7,400 \text{ N/mm}^2, \\ G_0 &\approx 690 \text{ N/mm}^2, \\ G_{\text{rolling shear}} &\approx 50 \text{ N/mm}^2. \end{aligned}$$

Characteristic strengths for CLT panels composed entirely of C24 boards are:

$$\begin{aligned} f_{m,k} &= 24 \text{ MPa}, \\ f_{v,k} &= 4 \text{ MPa}, \\ f_{v,90,k} &= 0.7 \text{ MPa} \quad (\text{rolling shear strength}). \end{aligned}$$

For Service Class 1 and medium-term loading (imposed load as leading action), the following factors apply:

$$k_{mod} = 0.8, \quad \gamma_M = 1.25.$$

The corresponding design strengths become:

Design bending strength

$$f_{m,d} = \frac{k_{mod}}{\gamma_M} f_{m,k} = \frac{0.8}{1.25} \times 24 = 15.36 \text{ MPa}.$$

Design shear strength (parallel to grain)

$$f_{v,d} = \frac{k_{mod}}{\gamma_M} f_{v,k} = \frac{0.8}{1.25} \times 4 = 2.56 \text{ MPa}.$$

Design rolling shear strength

$$f_{v,90,d} = \frac{k_{mod}}{\gamma_M} f_{v,90,k} = \frac{0.8}{1.25} \times 0.7 = 0.448 \text{ MPa} \approx 0.45 \text{ MPa}.$$

Rolling shear failure governs the transverse layers of the CLT panel, which are subjected

to significant shear deformation in bending; this check will be performed later in the ULS verification.

B.1.2 Loads and Design Combinations

Permanent and variable loads

The following characteristic line loads are assumed for a strip of width $b_t = 1.0$ m:

- self-weight of CLT panel (including finishes):

$$g_k = 1.1 \text{ kN/m},$$

- live load:

$$q_k = 2.0 \text{ kN/m}.$$

ULS and SLS design values

For the fundamental Ultimate Limit State (ULS) combination, the design line load acting on the strip is obtained from:

$$q_{d,\text{ULS}} = \gamma_G g_k + \gamma_Q q_k,$$

with partial factors, for example,

$$\gamma_G = 1.35, \quad \gamma_Q = 1.50.$$

This yields:

$$q_{d,\text{ULS}} = 1.35 \times 1.1 + 1.50 \times 2.0 = 1.485 + 3.00 = 4.485 \text{ kN/m} \approx 4.49 \text{ kN/m}.$$

B.1.3 Position of the Centre of Gravity

Only the longitudinal layers (fibres parallel to the span) contribute to bending stiffness in the main direction, so the position of the neutral axis is computed using these four layers.

The centre of gravity is obtained from:

$$z_s = \frac{\sum_{i=1}^n \frac{E_i}{E_c} b t_i o_i}{\sum_{i=1}^n \frac{E_i}{E_c} b t_i}$$

where: - E_i = modulus of elasticity of layer i (parallel to grain), - $E_c = E_{\text{ref}}$ = reference modulus (taken equal to E_0 since all longitudinal layers are C24), - b = strip width, - t_i = layer thickness, - o_i = distance from the bottom reference fibre to the centroid of layer i .

For the four longitudinal layers:

$$b = 100 \text{ cm}, \quad t_i = 4 \text{ cm}, \quad A_i = b t_i = 400 \text{ cm}^2, \quad \frac{E_i}{E_c} = 1.$$

Distances from the bottom to the centroid of each longitudinal layer:

$$o_1 = 2 \text{ cm}, \quad o_2 = 8 \text{ cm}, \quad o_3 = 14 \text{ cm}, \quad o_4 = 20 \text{ cm}.$$

i	b [cm]	$\frac{E_i}{E_c}$ [–]	t_i [cm]	A_i [cm ²]	$A_i o_i$ [cm ³]
1	100	1.000	4	400	800
2	100	1.000	4	400	3,200
3	100	1.000	4	400	5,600
4	100	1.000	4	400	8,000
Sum	–	–	–	1,600	17,600

$$z_s = \frac{17,600}{1,600} = 11.0 \text{ cm} = 110 \text{ mm}.$$

B.1.4 Moment of Inertia

The rigid-section moment of inertia of the longitudinal layers is:

$$I_{\text{net}} = \sum_{i=1}^n \frac{E_i}{E_c} \frac{b t_i^3}{12} + \sum_{i=1}^n \frac{E_i}{E_c} b t_i a_i^2$$

where t_i = thickness of layer i , $a_i = o_i - z_s$ = distance from the neutral axis, $E_c = E_{\text{ref}}$.

i	$\frac{E_i}{E_c} A_i$ [cm ²]	a_i [cm]	$I_{\text{intrinsic}}$ [cm ⁴]	$\frac{E_i}{E_c} A_i a_i^2$ [cm ⁴]
1	400	−9	533.33	32,400
2	400	−3	533.33	3,600
3	400	3	533.33	3,600
4	400	9	533.33	32,400
Sum	1,600	−	2,133.33	72,000

$$I_{\text{net}} = 2,133.33 + 72,000 = 74,133 \text{ cm}^4.$$

B.1.5 Section Modulus

The moment of resistance for bending about the x -axis is given by:

$$W_{x,\text{net}} = \frac{I_{x,\text{net}}}{\max\{|z_o|, |z_u|\}},$$

where:

- z_s is the distance from the neutral axis to the centroid,
- z_o and z_u are the distances from the neutral axis to the outer (top and bottom) fibres.

For a symmetric CLT panel, the neutral axis lies at mid-depth, therefore:

$$z_o = z_u = z_s = 11 \text{ cm}.$$

The section modulus becomes:

$$W_{x,\text{net}} = \frac{I_{\text{net}}}{z_s} = \frac{74,133}{11} = 6,739 \text{ cm}^3.$$

B.1.6 Static Moments

Rolling shear static moment

$$S_{R,x,\text{net}} = \sum_{i=1}^{m_L} \frac{E_{x,i}}{E_{\text{ref}}} b_{x,i} t_i |a_i|$$

For the longitudinal layers above and below the neutral axis:

$$S_{R,x,\text{net}} = A_1|a_1| + A_2|a_2|$$

$$S_{R,x,\text{net}} = 400 \cdot 9 + 400 \cdot 3 = 4,800 \text{ cm}^3.$$

Static moment for longitudinal layer shear

General expression when the neutral axis lies inside the longitudinal layer k_L :

$$S_{x,\text{net}} = \sum_{i=1}^{k_L} \frac{E_{x,i}}{E_{\text{ref}}} b_{x,i} t_i a_i + b_{x,k_L} \left(\frac{t_{k_L}}{2} - a_{k_L} \right)^2 \frac{1}{2}$$

If the neutral axis does not lie inside a longitudinal layer:

$$S_{x,\text{net}} = \sum_{i=1}^{k_L} \frac{E_{x,i}}{E_{\text{ref}}} b_{x,i} t_i a_i$$

In this panel, the neutral axis is at mid-depth (11 cm), which lies within a transverse layer, therefore:

$$S_{x,\text{net}} = S_{R,x,\text{net}} = 4,800 \text{ cm}^3.$$

B.1.7 Application of the Extended Gamma Method

For cross-sections with four or more longitudinal layers, the simplified Eurocode Gamma method is no longer applicable, as it provides closed-form expressions only for panels with two or three longitudinal layers (i.e. 3- or 5-layer CLT). Since the present 7-layer panel contains **four longitudinal layers**, the *extended Gamma method* must be used. The γ_i coefficients are obtained by solving a linear system:

$$[V] \gamma = s,$$

Input values

The relevant geometric and material quantities for the longitudinal layers are summarised in the table below (indices i, j refer to adjacent longitudinal layers).

i	j	$\frac{E_i}{E_c}$ [-]	$t_{i/j}$ [mm]	$\frac{E_i}{E_c} A_i$ [mm ²]	a_i [mm]	$G_{j,k}$ [N/mm]	$C_{j,k}$ [N/mm ²]	$\Delta a_{j,k}$	$\frac{\pi^2 \cdot E \cdot A_i}{\ell_{ef}^2}$
1	–	1	40	40.000	-90	–	–	–	143,56
–	1,2	0	20	–	–	50	2.500	60	–
2	–	1	40	40.000	-30	–	–	–	143,56
–	2,3	0	20	–	–	50	2.500	60	–
3	–	1	40	40.000	30	–	–	–	143,56
–	3,4	0	20	–	–	50	2.500	60	–
4	–	1	40	40.000	90	–	–	–	143,56

The serviceability reference length used in the Gamma method is:

$$\ell_{ef} = 5.5 \text{ m.}$$

Coefficient matrix

The extended Gamma method produces the following 4×4 coefficient matrix:

$$[V] = \begin{bmatrix} C_{12} + \frac{\pi^2 E_1 A_1}{\ell_{ef}^2} & -C_{12} \cdot a_2 & 0 & 0 \\ -C_{12} \cdot a_1 & C_{12} + C_{23} + \frac{\pi^2 E_2 A_2}{\ell_{ef}^2} & -C_{23} \cdot a_3 & 0 \\ 0 & -C_{23} \cdot a_2 & C_{23} + C_{34} + \frac{\pi^2 E_3 A_3}{\ell_{ef}^2} & -C_{34} \cdot a_4 \\ 0 & 0 & -C_{34} \cdot a_3 & C_{34} + \frac{\pi^2 E_4 A_4}{\ell_{ef}^2} \end{bmatrix}.$$

Substituting the numerical values (units N/mm):

$$[V] = \begin{bmatrix} -237.920 & 75.000 & 0 & 0 \\ 225.000 & -154.307 & -75.000 & 0 \\ 0 & 75.000 & 154.307 & -225.000 \\ 0 & 0 & -75.000 & 237.920 \end{bmatrix}.$$

Right-hand side vector

The RHS vector s is:

$$s = \begin{bmatrix} -C_{1,2} a_{1,2} \\ -C_{2,3} a_{2,3} + C_{1,2} a_{1,2} \\ -C_{3,4} a_{3,4} + C_{2,3} a_{2,3} \\ C_{3,4} a_{3,4} \end{bmatrix}.$$

With the numerical values:

$$s = \begin{bmatrix} -150.000 \\ 0 \\ 0 \\ 150.000 \end{bmatrix}.$$

Solution of the system

The gamma values follow from:

$$\gamma = [V]^{-1} s.$$

Solving the system yields:

$$\gamma_1 = 0.9128,$$

$$\gamma_2 = 0.8957,$$

$$\gamma_3 = 0.8957,$$

$$\gamma_4 = 0.9128.$$

These γ_i coefficients will be used in the computation of the effective bending stiffness $(EI)_{\text{eff}}$ and shear stiffness $(GA)_{\text{eff}}$ of the 7-layer CLT panel.

B.1.8 Effective Moment of Inertia

The effective bending stiffness for a CLT section with more than three longitudinal layers is computed using the extended Gamma method. The effective second moment of area is given by:

$$I_{\text{ef}} = \sum_{i=1}^n \frac{b t_i^3}{12} + \sum_{i=1}^n \gamma_i \frac{E_i}{E_c} b t_i a_i^2,$$

where only the longitudinal layers contribute to the second summation.

$$I_{\text{ef}} = 2,133.33 + 65,598.48 = 67,732 \text{ cm}^4$$

B.1.9 Ultimate Limit State Bending and Shear Checks

Moment

Design moment for a single-span beam of length $L = 5.5$ m under uniform design load $q_{d,ULS} = 4.49$ kN/m:

$$M_d = \frac{q_{d,ULS} L^2}{8} = \frac{4.49 \cdot 5.5^2}{8} = 17.0 \text{ kNm.}$$

Design bending stress:

$$\sigma_d = \frac{M_d}{W_{x,net}} = \frac{16.96 \cdot 10^3}{6.739 \cdot 10^3} = 2.5 \text{ MPa} < f_{m,d} = 15.4 \text{ MPa.}$$

Shear force

Design shear force (simply supported beam with uniform load):

$$V_d = 0.5 q_{d,ULS} L = 0.5 \cdot 4.49 \cdot 5.5 = 12.3 \text{ kN.}$$

Shear stress parallel to grain:

$$\tau_d = \frac{V_d S_{x,net}}{I_{x,net} b_x} = \frac{12.33 \cdot 10^3 \cdot 4,800 \cdot 10^3}{74,133 \cdot 10^4 \cdot 1,000} \approx 0.08 \text{ MPa} < f_{v,d} = 2.6 \text{ MPa.}$$

Rolling shear stress in the transverse layers:

$$\tau_{Rv,d} = \frac{S_{R,x,net} V_d}{I_{x,net} b_x} = \frac{4,800 \cdot 10^3 \cdot 12.33 \cdot 10^3}{74,133 \cdot 10^4 \cdot 1,000} \approx 0.08 \text{ MPa} < f_{v,90,d} = 0.45 \text{ MPa.}$$

Both bending and shear (including rolling shear) satisfy the ULS requirements for the 7-layer CLT panel.

B.1.10 Deformations (Serviceability Limit State)

Allowable deflection for $L/300$:

$$\frac{L}{300} = \frac{5.5 \text{ m}}{300} = 18.3 \text{ mm.}$$

Characteristic deflection due to permanent load

$$w_{g,k} = \frac{5 g_k L^4}{384 E_{0,\text{mean}} I_{x,\text{ef}}} = \frac{5 \cdot 1.1 \cdot 5,500^4}{384 \cdot 11,000 \cdot 6.77 \cdot 10^8} = 1.76 \text{ mm.}$$

Characteristic deflection due to variable load

$$w_{q,k} = \frac{5 q_k L^4}{384 E_{0,\text{mean}} I_{x,\text{ef}}} = \frac{5 \cdot 2.0 \cdot 5,500^4}{384 \cdot 11,000 \cdot 6.77 \cdot 10^8} = 3.20 \text{ mm.}$$

Short-term deformation of characteristic load

$$w_{\text{inst}} = w_{g,k} + w_{q,k} = 1.76 + 3.20 = 4.96 \text{ mm} < 18.3 \text{ mm} \Rightarrow \text{OK.}$$

Final deformation including creep (quasi-permanent combination)

For Service Class 1, the deformation modification factor is taken as

$$k_{\text{def}} = 0.85,$$

and for office-type loading a quasi-permanent factor

$$\psi_2 = 0.3$$

is adopted.

$$w_{\text{fin},g} = w_{g,k} (1 + k_{\text{def}}) = 1.76 \cdot (1 + 0.85) = 3.25 \text{ mm,}$$

$$w_{\text{fin},q} = w_{q,k} (1 + \psi_2 k_{\text{def}}) = 3.20 \cdot (1 + 0.3 \cdot 0.85) = 4.01 \text{ mm.}$$

$$w_{\text{fin}} = w_{\text{fin},g} + w_{\text{fin},q} = 3.25 + 4.01 = 7.27 \text{ mm} < 18.3 \text{ mm} \Rightarrow \text{OK.}$$

B.1.11 Vibrations

Lowest fundamental frequency

The lowest fundamental frequency f_1 of the floor strip is calculated as:

$$f_1 = \frac{\pi}{2L^2} \sqrt{\frac{(EI)_L}{m}} = \frac{\pi}{2 \cdot 5.5^2} \sqrt{\frac{11.000 \times 10^6 \cdot 6.7732 \times 10^{-5}}{110}} = 13.5 \text{ Hz} > 8 \text{ Hz} \Rightarrow \text{OK.}$$

Point-load stiffness check

Control of stiffness for a point load $F = 1 \text{ kN}$ at midspan:

$$w = \frac{FL^3}{48(EI)_L} = \frac{1 \cdot 10^3 \cdot 5.5^3}{48 \cdot 11.000 \times 10^6 \cdot 6.7732 \times 10^{-5}} = 0.47 \text{ mm} < 2 \text{ mm} \Rightarrow \text{OK.}$$

Impulse velocity response

The maximum allowed velocity response is computed as:

$$v_{\max} = b^{(f_1^{0.025}-1)} = 100^{(13.5^{0.025}-1)} = 0.047.$$

The floor width used in the dynamic check is taken as:

$$B = 4.5 \text{ m.}$$

The number of first-order modes with frequencies up to 40 Hz is then estimated using:

$$n_{40} = \left\{ \left[\left(\frac{40}{f_1} \right)^2 - 1 \right] \left(\frac{B}{L} \right)^4 \left(\frac{(EI)_L}{(EI)_B} \right) \right\}^{0.25} = 2.05.$$

The corresponding impulse velocity response becomes:

$$v = \frac{4(0.4 + 0.6 n_{40})}{mBL + 200} = \frac{4(0.4 + 0.6 \cdot 2.05)}{110 \cdot 4.5 \cdot 5.5 + 200} = 0.002 < v_{\max} = 0.045 \Rightarrow \text{OK.}$$

The floor therefore satisfies all vibration criteria: minimum fundamental frequency, point-load stiffness and maximum velocity response.

B.1.12 Environmental Assessment – Life Cycle Assessment (A1–A3)

In addition to structural and serviceability verifications, the environmental performance of the CLT floor system is assessed through a Life Cycle Assessment (LCA). The assessment focuses on the product stage, corresponding to modules A1–A3 according to EN 15804, which include raw material supply, transport to manufacturing and manufacturing processes.

The analysis is performed for the 7-layer CLT panel considered in the hand calculation example. The total volume of CLT required for the floor is:

$$V_{\text{CLT}} = 1.21 \text{ m}^3.$$

The Global Warming Potential (GWP) values are taken from Buildwise environmental data for cross-laminated timber and are separated into fossil and biogenic contributions.

B.1.12.1 Environmental data per unit volume

For CLT, the following values are adopted:

$$\begin{aligned} \text{GWP}_{\text{fossil}} &= 163 \text{ kgCO}_2\text{eq/m}^3, \\ \text{GWP}_{\text{biogenic}} &= -653 \text{ kgCO}_2\text{eq/m}^3. \end{aligned}$$

B.1.12.2 A1–A3 impact of the floor system

The total GWP contributions for the CLT floor are obtained by multiplying the unit values by the panel volume:

$$\begin{aligned} \text{GWP}_{\text{fossil,A1–A3}} &= 163 \times 1.21 = 197.2 \text{ kgCO}_2\text{eq}, \\ \text{GWP}_{\text{biogenic,A1–A3}} &= -653 \times 1.21 = -790.1 \text{ kgCO}_2\text{eq}. \end{aligned}$$

The resulting total Global Warming Potential for modules A1–A3 is therefore:

$$\text{GWP}_{\text{A1–A3}} = -592.9 \text{ kgCO}_2\text{eq}.$$

B.1.13 Cost Assessment

In addition to the structural and environmental checks, a simplified material cost assessment is carried out for the selected 7-layer CLT floor panel. The objective is to remain consistent with the economic assessment adopted in the thesis, where only the material cost of the floor system is considered.

The considered panel is made of C24 timber and has the following lay-up:

$$40/20/40/20/40/20/40 \text{ mm.}$$

Based on the adopted CLT material cost table, the unit costs for C24 timber are 27.67 €/m² for a 20 mm layer and 46.67 €/m² for a 40 mm layer.

Since the panel contains four 40 mm layers and three 20 mm layers, the material cost per square metre is:

$$C_{\text{CLT},m^2} = 4 \times 46.67 + 3 \times 27.67 = 269.69 \text{ €/m}^2.$$

The floor area considered in the worked example is:

$$A = 5.5 \text{ m}^2.$$

The total CLT material cost is therefore:

$$C_{\text{CLT,tot}} = A \cdot C_{\text{CLT},m^2} = 5.5 \times 269.69 = 1483.30 \text{ €}.$$

Table 21: Cost assessment for the representative 7-layer CLT floor panel

Cost Assessment		
Quantity	Symbol	Value
Floor area	A	5.5 m ²
CLT cost	C_{CLT,m^2}	269.69 €/m ²
Total CLT cost	$C_{\text{CLT,tot}}$	1483.30 €

It should be noted that this value corresponds to the material cost of the CLT panel only. It does not include transport, lifting, installation, connections, acoustic build-up, floor finishes or other execution-related costs. It is therefore used as a simplified material-cost indicator, consistent with the comparative approach adopted in the main body of the thesis.

UNIVERSITÉ CATHOLIQUE DE LOUVAIN
École polytechnique de Louvain

Rue Archimède, 1 bte L6.11.01, 1348 Louvain-la-Neuve, Belgique | www.uclouvain.be/epl