



**Politécnico
Castelo Branco**

Escola Superior
de Tecnologia

Modular Cross-Laminated Timber Construction

Design and Analysis of a Lightweight System for Educational Extensions and Rapid Housing

Daniel Martínez Pérez

Orientadores

Doutor Luís Filipe de Carvalho Jorge

This Dissertation, entitled “Modular Cross-Laminated Timber Construction: Design and Analysis of a Lightweight System for Educational Extensions and Rapid Housing”, is submitted to the School of Engineering of the Polytechnic Institute of Castelo Branco. The work was carried out under the scientific supervision of Dr. Jorge of the Polytechnic Institute of Castelo Branco.

January 2026

Composição do júri

Presidente do júri

Doutora Maria Constança Simões Rigueiro

Professor Coordenador, Instituto Politécnico de Castelo Branco

Vogais

Doutor Afonso Carlos Bonina de Mesquita

Professor-Adjunto Convidado, Instituto Politécnico de Castelo Branco

Doutor Luís Filipe de Carvalho Jorge

Professor-Adjunto, Instituto Politécnico de Castelo Branco

Abstract

The urgent need to expand educational facilities rapidly and sustainably, while minimising disruption to their daily operation, has exposed the limitations of conventional construction systems based on reinforced concrete. At the same time, recent natural disasters in Spain, such as the La Palma volcanic eruption and recurrent severe storm events, have revealed the lack of dignified, efficient and technically robust solutions for rapid housing provision. These two apparently distinct challenges share common technical requirements: speed of execution, lightweight construction, high environmental performance, industrialised production and adequate levels of comfort, safety and durability.

In this context, mass timber construction—and specifically Cross-Laminated Timber (CLT)—emerges as a strategic alternative capable of addressing both educational building extensions and rapid post-disaster housing. CLT is a high-performance engineered wood product that combines low self-weight, high structural stiffness and excellent prefabrication potential. Its plate-based structural behaviour allows walls and floors to act as load-bearing diaphragms, enabling mid-rise construction and vertical extensions on existing buildings without the need for structural reinforcement.

This project develops a three-dimensional modular construction system based on CLT panels combined with a carefully designed multilayer building envelope. The proposed system addresses the main technical challenges associated with timber construction, including moisture sensitivity, interstitial condensation, acoustic performance and fire safety. Hygrothermal control is achieved through an optimised arrangement of insulation, vapour control layers and ventilated cavities, while acoustic and fire performance are ensured by multilayer solutions that comply with current regulatory requirements.

The modular CLT system is conceived as a flexible and transferable solution. The same structural and envelope configuration can be used either as an educational classroom module or as a rapid housing unit, with only minor adaptations to the internal layout and services. This dual-use capability enhances the system's value for public administrations, allowing it to be deployed efficiently in both planned educational interventions and emergency scenarios.

Comparative analyses with reinforced concrete and metallic modular systems demonstrate that CLT offers significant advantages in terms of construction speed, self-weight, environmental impact and interior comfort. The study concludes that industrialised modular construction using CLT constitutes a technically viable, sustainable and socially responsible solution for contemporary educational infrastructure expansion and resilient housing provision in Spain.

Keywords

Cross-Laminated Timber (CLT), mass timber construction, modular construction, industrialised building systems, prefabricated three-dimensional modules, educational building extensions, non-disruptive construction, rapid housing solutions, post-disaster housing, mid-rise timber buildings, lightweight structural systems, multilayer building envelope, hygrothermal performance, moisture control, acoustic performance, fire resistance of timber structures, sustainable construction, low-carbon building materials, off-site manufacturing, circular construction.

Index

CHAPTER 1. SUMMARY AND GENERAL INTRODUCTION	1
1.1. Summary.....	1
1.2. General Introduction	1
1.3. Problem Statement	2
1.4. Jusfication of the Study	3
1.5. Hypothesis	3
1.6. Objetives	3
1.7. Methodology	3
1.8. Scope and Limitations.....	3
1.9. Structure of the Document	4
CHAPTER 2. CONTEXT AND THEORETICAL FRAMEWORK: THE NEED FOR A NEW WAY OF BUILDING	5
2.1. Introduction	5
2.2. The Need for Rapid Educational Expansions.....	5
2.3. Industrialisation of Construction as a Paradigm Shift.....	6
2.4. Modular Construcion: Concept and Potential.....	6
2.5. Timber as a Sustainable Material and Its Strategic Return	6
2.6. CLT as a Contemporary Structural Technology	7
2.7. The Role of Regulations	7
2.8. Housing Emergencies: La Palma and DANA Events as Evidence of Need	7
2.9. Transferability of the Modular CLT System	7
2.10. Chapter Conclusion	7
CHAPTER 3. HISTORICAL EVOLUTION OF TIMBER CONSTRUCTION	8
3.1. Introduction	8
3.2. Primitive Timber Architectures	8
3.3. Traditional European Timber Framing Systems.....	9
3.4. The Industrial Revolution and the Decline of Timber Construction	10
3.5. The North American Timber Frame and the Rise of Light Construction	11
3.6. The Emergence of Engineered Timber Products	12
3.7. The Birth of Cross-Laminated Timber (CLT).....	12

3.8. Contemporary Timber Architecture and Mid-Rise Construction.....	13
3.9. Timber Construction in the Context of Sustainability	13
3.10. Chapter Conclusion	13
CHAPTER 4. TECHNICAL CHALLENGES OF CROSS-LAMINATED TIMBER (CLT).....	14
4.1. Introduction	14
4.2. Hygroscopic Behaviour and Dimensional Stability.....	14
4.3. Condensation Risks and Hygrothermal Control	15
4.4. Fire Behaviour of CLT Structures	16
4.5. Acoustic Performance and Sound Transmission	17
4.6. Structural Behaviour and Load Transfer	17
4.7. Durability and Long-Term Performance.....	18
4.8. Multilayer Envelope as a Technical Response	18
4.9. Regulatory Compliance and Technical Validation.....	18
4.10. Chapter Conclusion	18
CHAPTER 5. INDUSTRIALISED STRUCTURAL TIMBER PRODUCTS AND COMPARISON WITH TRADITIONAL SYSTEMS.....	19
5.1. Introduction: Mass timber as a contemporary industrial revolution	19
5.2. Cross-Laminated Timber (CLT): concept, manufacturing process, properties and structural behaviour	20
5.3. Glued Laminated Timber (GLT): linear reinforcement, stiffness and structural continuity.....	22
5.4. Laminated Veneer Lumber (LVL): extreme homogeneity and precision for concentrated stresses.....	22
5.5. Synergies between CLT, GLT and LVL in three-dimensional modules.	23
5.6. In-depth comparison between CLT and reinforced concrete	23
5.7. Comparative table: CLT vs. reinforced concrete.....	25
5.8. In-depth comparison between CLT and metallic systems.....	25
5.9. Comparative table: CLT vs. metallic systems	26
5.10. Chapter conclusion	27
CHAPTER 6. STRUCTURAL SYSTEMS FOR MID-RISE CONSTRUCTION WITH CLT: AN IN-DEPTH ANALYSIS	28
6.1. Structural logic of CLT: stiffness, lightness and plate behaviour.....	29
6.2. Load-bearing walls as the primary structural system in CLT buildings .	29
6.3. CLT floor slabs as rigid diaphragms	30

6.4. GLT frames and linear elements: extending structural capacity.....	30
6.5. Global stability and bracing of the building.....	31
6.6. Hybrid systems combining CLT, steel and concrete	31
6.7. Seismic behaviour: the remarkable ductility of CLT	31
6.8. Building on existing structures: technical feasibility and advantages of CLT	32
6.9. The three-dimensional module as the optimal structural unit.....	32
6.10. Chapter conclusion	32
CHAPTER 7. CRITICAL TECHNICAL CHALLENGES IN CLT BUILDINGS AND THEIR RESOLUTION THROUGH A MULTILAYER MODULAR SYSTEM	34
7.1. Moisture and vapour diffusion: the most critical challenge	35
7.2. Interstitial condensation: an invisible but highly destructive enemy	36
7.3. Acoustics: CLT lightness and the need for multilayer design	36
7.4. Fire safety: technical analysis and multilayer solutions	37
7.5. Integration of building services without compromising the structural panel	37
7.6. Joints between modules and system airtightness	38
7.7. Chapter conclusion	38
CHAPTER 8. DESIGN OF THE PROPOSED CONSTRUCTION SYSTEM: MULTILAYER ENVELOPE, CLT PANEL AND HYGROTHERMAL, ACOUSTIC AND FIRE-SAFETY SOLUTIONS	39
8.1. Introduction: towards an integrated construction system	39
8.2. General concept of the multilayer envelope	40
8.3. Detailed composition of the envelope	40
8.3.1. Internal layer: finish, service cavity and acoustic conditioning	41
8.3.2. Structural CLT panel	42
8.3.3. Intelligent vapour control layer	42
8.3.4. Continuous external insulation	42
8.3.5. Water-tight and vapour-permeable external membrane.....	43
8.3.6. External substructure and final finish	43
8.4. Hygrothermal behaviour of the proposed system.....	43
8.5. Fire protection	43
8.6. Acoustic insulation	44
8.7. Service cavity and building services	44

8.8. Insulation, stability and energy efficiency in educational modules	44
8.9. Application to rapid post-emergency housing	45
8.10. Comparison with traditional alternatives	45
8.11. Chapter conclusion	45
CHAPTER 9. MANUFACTURING, TRANSPORT AND ASSEMBLY PROCESS OF CLT MODULES	46
9.1. Introduction	46
9.2. Industrial manufacturing of CLT panels	46
9.3. Prefabrication of the three-dimensional module.....	47
9.4. Factory quality control.....	49
9.5. Logistics and transport.....	49
9.6. On-site assembly: speed, precision and minimal disruption	49
9.7. Advantages over traditional construction	51
9.8. Modular systems in housing emergencies	51
9.9. Durability, cost and maintenance	52
9.10. Chapter conclusion	52
CHAPTER 10. MODELLING, GEOMETRY AND MODULAR CONFIGURATION OF THE PROPOSED SYSTEM	53
10.1. Introduction	53
10.2. The module as a spatial and structural unit	53
10.3. Determination of the number of modules and programme compliance	54
10.4. Plan layout: functional coherence and spatial continuity.....	54
10.5. Structural integration on the existing building	55
10.6. Modulation, repetition and dimensional precision	55
10.7. Typological flexibility: from classroom to rapid housing	56
10.8. Circulation, accessibility and safety	56
10.9. Relationship between geometry and hygrothermal–acoustic performance.....	56
10.10. Architectural integration with the existing building	57
10.11. Chapter conclusion	57
CHAPTER 11. GRAPHICAL DOCUMENTATION AND TECHNICAL REPRESENTATION OF THE CLT MODULAR SYSTEM	58
11.1. Introduction	58
11.2. The operational value of drawings in an industrialised modular system	59

11.3. Representation of the overall system: plans, elevations and sections	60
11.4. Representation of the standard module: space, structure and envelope	60
11.5. Detailed representation of the multilayer envelope	61
11.6. Module joints: structural, thermal and acoustic continuity	62
11.7. Graphical documentation of integrated building services	63
11.8. Layout and assembly drawings: from factory to school roof	63
11.9. Global coherence between representation, fabrication and built reality	63
11.10. Chapter conclusion	64
CHAPTER 12. ADVANCED CONSTRUCTION ANALYSIS: JOINTS, EDGE DETAILS AND RESOLUTION OF CRITICAL NODES IN CLT MODULAR SYSTEMS	64
12.1. Introduction	64
12.2. The logic of joints in modular construction	64
12.3. Vertical joints between modules	65
12.4. Horizontal joints between modules	66
12.5. Connections between the module and the existing structure	67
12.6. Roof-edge details and climatic protection	68
12.7. Window and façade opening details	68
12.8. Service penetrations and transition points	69
12.9. Global system behaviour resulting from correct detail resolution	69
12.10. Chapter conclusion	70
CHAPTER 13. TECHNICAL AND REGULATORY ASSESSMENT OF THE CLT MODULAR SYSTEM	70
CHAPTER 14. FINAL CONCLUSIONS	73
CHAPTER 15. FUTURE RESEARCH LINES	74
CHAPTER 16. EXTERNAL SOURCES	76
16.1 Books and technical manuals	76
16.1.2 Scientific articles	76
16.1.3 Relevant standards and regulations	76
16.1.4 International reports and guidelines	76
16.2 Image resources	76

Image Index

Figure 3.1— Evolution of timber structural systems: Traditional timber framing systems in medieval Europe, characterised by load-bearing wooden frames combined with infill materials such as masonry or adobe.....	9
Figure 3.2— Evolution of timber structural systems: Half-timbered construction (Fachwerk) as developed in Central Europe, illustrating the structural role of the timber skeleton and its long-term durability.	10
Figure 3.3— Evolution of timber structural systems: North American balloon frame system, representing the transition towards lightweight, repetitive and industrialised timber construction techniques.....	11
Figure 3.4— Evolution of timber structural systems: Cross-Laminated Timber (CLT) panel configuration, showing the crosswise arrangement of timber layers that provides bidirectional structural capacity and dimensional stability..	12
Figure 4.1— Anisotropic mechanical behaviour of timber, showing the longitudinal, radial and tangential directions of the wood fibres.	14
Figure 4.2— Cross-laminated timber (CLT) panel configuration, illustrating the cross-oriented layers used to improve structural stability and stiffness.	15
Figure 4.3.1— Vapour diffusion through a wall section and potential risk of interstitial condensation depending on the arrangement of the construction layers.	16
Figure 4.4— Charring mechanism of CLT elements under fire exposure and reduction of the effective loadbearing section.	17
Figure 5.1— Main industrialised structural timber products: CLT panels, glulam beams (GLT) and laminated veneer lumber (LVL).	20
Figure 5.2— Three-dimensional modular construction using CLT panels combined with linear timber elements.	21
Figure 5.3— Conceptual comparison between CLT and reinforced concrete structures in terms of weight, construction process and environmental impact. ...	24
Figure 6.1— Three-dimensional CLT structure acting as a rigid structural box, illustrating load-bearing walls, floor diaphragms and global structural stability in mid-rise construction.	28
Figure 7.1— Percentages of errors that caused failures in the Sweden-Finland ELU, based on 127 real cases.	34
Figure 8.1— Multilayer sandwich envelope for CLT modules, showing the internal service cavity, structural CLT panel, intelligent vapour control layer, continuous external insulation and external finish.	39
Figure 8.2.1— Multilayer modular CLT wall design.	41

Figure 9.1 — Industrial manufacturing process of CLT panels, including drying, cross-layer bonding, pressing and CNC machining.....	47
Figure 9.2 — Prefabrication of three-dimensional CLT modules in controlled factory conditions prior to transport.	48
Figure 9.1 — Transport, lifting and on-site installation of CLT modules, enabling rapid assembly with minimal disruption.	50
Figure 10.1 — Conceptual diagram illustrating the geometric organisation and aggregation logic of the modular system, highlighting the repetition of identical units and the spatial flexibility of the configuration, independent of material definition or dimensional constraints.	53
Figure 11.1 — Graphical documentation of the CLT modular system, including plans, sections and construction details enabling industrial fabrication and precise on-site assembly.....	59
Figure 11.2 — Detailed representation of the multilayer CLT envelope and inter-module joints, ensuring structural, thermal and acoustic continuity.	62
Figure 12.1 — Vertical and horizontal joints between CLT modules, illustrating structural connectors, insulation continuity and airtightness strategies.	66
Figure 12.2 — Structural connection between CLT modular extension and existing building, showing load distribution, separation layers and envelope continuity.	67
Figure 13.1 — Overall regulatory performance of the CLT modular system, illustrating structural behaviour, thermal efficiency, acoustic insulation and fire resistance.	71
Figure 14.1 — CLT modular system as a consolidated architectural solution, capable of functioning both as an educational extension and as rapid housing with high technical and spatial quality.	73
Figure 15.1 — Potential future research pathways for CLT modular systems, including energy optimisation through dynamic simulations, integration of renewable energy systems, industrial automation, reconfigurability and applications in emergency and public infrastructure.....	74

Table Index

Table 5.1— Comparison between CLT modular construction and reinforced concrete.....	25
Table 5.2— Comparison between CLT modular construction and metallic systems.	26
Table 9.1— Comparison between CLT modular construction and traditional on-site construction.	51
Table 10.1— Relationship between modular geometry and structural, hygrothermal and acoustic performance.	57
Table 12.1— Critical construction nodes in CLT modular systems and associated performance requirements.	69
Table 13.1— Technical and regulatory assessment of the proposed CLT modular system.....	72

CHAPTER 1. SUMMARY AND GENERAL INTRODUCTION

1.1. Summary

The growing need to expand educational facilities rapidly, sustainably and with minimal interference in their daily operation has driven the search for innovative construction alternatives. Traditional solutions based on concrete and masonry present clear limitations in terms of execution time, environmental impact, disruption during construction works and lack of flexibility. At the same time, recent events such as the volcanic eruption on La Palma or the DANA episodes that have affected different regions of Spain have highlighted the absence of dignified and efficient solutions for the temporary rehousing of displaced families.

In this context, mass structural timber, and particularly Cross-Laminated Timber (CLT), emerges as a strategic material capable of responding simultaneously to these two realities: the modular expansion of educational buildings and the provision of rapid post-emergency housing.

This work develops a modular system based on CLT panels incorporating a multilayer envelope designed according to hygrothermal, acoustic, structural and fire protection criteria. The analysis demonstrates that this type of industrially manufactured module not only allows school extensions to be executed far more quickly than conventional construction, but also provides a remarkable level of comfort and habitability, making it suitable for use as temporary housing after natural disasters.

CLT modules exhibit exceptional thermal performance, competitive acoustic behaviour, a surprisingly high level of fire resistance and a significantly lower environmental impact than metal or concrete-based systems. Their ease of assembly and disassembly, combined with their low weight, makes them an ideal solution for interventions on existing buildings without the need for structural reinforcement.

The study concludes that CLT, when used in prefabricated three-dimensional modules with a properly designed multilayer envelope, constitutes a realistic, viable and technically optimal solution to address urgent educational and housing needs in Spain.

1.2. General Introduction

Construction in Spain and Portugal is facing increasingly complex challenges: urgent needs for the expansion of educational centres, adaptation of buildings to new regulatory requirements, the progressive replacement of low-quality prefabricated classrooms, seasonal demographic pressure and, in parallel, a climatic context that increases the frequency of extreme natural events. Each of these as

pects forces a rethinking of how buildings are constructed and calls into question the suitability of traditional construction systems.

Schools, in particular, represent a singular challenge. They are buildings that must remain operational almost throughout the entire year, and any intervention must minimise disruption, noise and occupation of common spaces. At the same time, they require high-quality solutions that ensure thermal comfort, good acoustic performance, fire safety and long-term durability. Wet construction systems based on concrete are incompatible with these objectives due to their long execution times, the acoustic impact they generate, the need for heavy machinery and the practical impossibility of maintaining school activity during construction works.

While this situation unfolds in the educational sector, similar problems arise in the field of emergency housing. After the La Palma volcanic eruption, hundreds of families were rehoused in metal containers with very poor habitability conditions. This was not an isolated failure, but clear evidence that Spain lacks a rapid, dignified, efficient and sustainable modular system capable of being deployed after a natural disaster.

CLT thus emerges as a bridging material between two worlds: education and emergency housing. Its structural properties allow construction on existing buildings; its thermal performance makes it suitable for habitable dwellings; its light weight facilitates transport and assembly; and its sustainability makes it a key ally in the ecological transition.

This work is based on the hypothesis that a prefabricated CLT module, when properly designed, can be used interchangeably as a classroom or as rapid postemergency housing, provided that the multilayer envelope adequately manages moisture, acoustics and fire protection.

1.3. Problem Statement

The central problem addressed in this project is twofold. First, how to construct a vertical extension on a school building without interrupting its operation, without reinforcing the existing structure and while complying with the strict requirements of an educational environment. Second, how to take advantage of this same modular technology to create rapid housing solutions after natural disasters that offer a level of habitability far superior to the metal containers currently used.

Both situations share similar technical requirements: speed of execution, lightness, thermal efficiency, safety, hygrothermal control and the ability to be industrially prefabricated. The initial premise is that CLT can simultaneously respond to both challenges.

1.4. Justification of the Study

The importance of this study lies in its ability to respond to contemporary debates on sustainability, construction efficiency and social resilience. Industrialised timber construction not only reduces emissions, but also improves indoor well-being, shortens construction times and minimises disruption in sensitive environments such as educational centres. At the same time, it provides a dignified solution for temporary housing, directly impacting the quality of life of displaced populations.

This work offers a rigorous technical analysis that demonstrates why timber should be incorporated into public infrastructure policies.

1.5. Hypothesis

The hypothesis guiding this project states that a three-dimensional module manufactured in CLT and equipped with a properly designed multilayer envelope can simultaneously meet the structural, hygrothermal, acoustic and fire safety requirements necessary for use both as a classroom in an educational centre and as rapid housing after a natural emergency.

1.6. Objectives

The objectives are focused on demonstrating the technical feasibility of the module and analysing its overall performance. The aim is to justify, based on scientific and construction criteria, that timber is a suitable material for both school expansions and the provision of rapid, high-quality housing.

1.7. Methodology

The work is based on a review of technical literature and regulations, comparative analyses, technical studies of CLT behaviour and the examination of real national and international case studies.

1.8. Scope and Limitations

The study focuses on the external envelope, the overall structural behaviour and construction feasibility. It does not include detailed structural calculations of the existing school building, nor advanced hygrothermal simulations.

1.9. Structure of the Document

The document progresses from contextualisation and the historical evolution of timber construction to technical analysis, the specific challenges of CLT and the proposal of a multilayer construction system designed to resolve these issues.

CHAPTER 2. CONTEXT AND THEORETICAL FRAMEWORK: THE NEED FOR A NEW WAY OF BUILDING

2.1. Introduction

The contemporary context of architecture and engineering demands a profound reconsideration of how buildings, public facilities and, in particular, educational centres and post-emergency infrastructures are constructed. This need does not arise solely from environmental criteria—although these are decisive—but also from social, demographic, economic and climatic changes that compel the adoption of more flexible, faster, more sustainable construction models capable of responding to scenarios of uncertainty.

Traditional construction in Spain, dominated by reinforced concrete, presents numerous challenges: slow execution, high levels of interference in school environments, low energy efficiency and a carbon footprint that is no longer sustainable in a world moving towards decarbonised economies. At the same time, events such as the La Palma volcanic eruption or the severe storms that have damaged housing and public facilities have exposed the precariousness of historically used solutions, such as adapted metal containers, which fail to provide dignified living conditions.

Within this context, industrialised modular construction—particularly through CLT panels—positions itself as a powerful alternative capable of delivering rapid, high-quality responses to urgent needs.

2.2. The Need for Rapid Educational Expansions

Every year, educational centres in Spain face fluctuations in enrolment, programme expansions, new regulatory requirements and spatial needs derived from social and pedagogical changes. Schools are living buildings that must constantly adapt. However, traditional construction systems do not offer the flexibility required to accommodate these transformations.

Prolonged construction works, the use of heavy machinery and the continuous presence of workers are incompatible with a functioning school. For this reason, a construction system is required that allows expansions to be carried out without disrupting educational activity. Modular construction, especially using CLT, makes it possible to manufacture the extension in a factory environment and transport it to the school for installation within a matter of days, avoiding the negative impacts characteristic of wet construction processes.

2.3. Industrialisation of Construction as a Paradigm Shift

The industrialisation of construction aims to transfer to the building sector the advances that have transformed other industries such as automotive or aeronautics. Precision, repeatability, efficiency and quality control—hallmarks of industrial processes—increase reliability and significantly reduce the margin for error.

Instead of constructing the building on site, as occurs with concrete-based systems, industrialised construction allows entire components or modules to be manufactured in controlled environments, free from climatic variability and the improvisation typical of traditional construction sites. This results in architecture that is more sustainable, more accurate and considerably faster to deliver.

CLT fits perfectly within this philosophy: it is a material that can be machined with millimetric precision, allowing complete panels to be fabricated with exact openings and enabling seamless integration into three-dimensional modules.

2.4. Modular Construction: Concept and Potential

Modular construction is not merely the assembly of “boxes”. It is a process that transforms the building into a high-quality industrial product. In this model, modules are fully manufactured in a factory environment, including structure, envelope, installations and finishes, and subsequently assembled on site as if they were components of a complex and precise mechanism.

This approach offers clear advantages: extremely reduced construction times, millimetric dimensional precision, minimisation of errors, minimal impact on school environments, significant reduction of noise, dust and waste.

CLT modules, in addition, provide a level of comfort far superior to that of metal modular solutions, offering better thermal, acoustic and environmental performance.

2.5. Timber as a Sustainable Material and Its Strategic Return

Timber has regained prominence in contemporary engineering not only for its aesthetic value, but also for its central role in the ecological transition. It stores carbon during its growth, requires relatively little energy to process and contributes positively to the emotional well-being of users.

In schools, this quality is particularly relevant: the indoor environment directly affects concentration, psychological well-being and stress levels. Numerous studies indicate that timber reduces heart rate, improves thermal perception and creates spatially welcoming environments.

2.6. CLT as a Contemporary Structural Technology

CLT represents the technological culmination of timber construction. Its bidirectional strength, dimensional stability, precise machining and excellent structural performance make it suitable for mid-rise buildings, extensions on existing structures and three-dimensional modular systems.

Its behaviour under fire exposure, its flexibility under seismic loads and its low density position it as an exceptionally safe material.

2.7. The Role of Regulations

The Spanish Building Technical Code (CTE), together with Eurocode 5, provides a sufficiently robust framework for designing timber buildings with high levels of safety. Acoustic, thermal and fire protection requirements can be met without difficulty through an appropriate multilayer construction system, demonstrating that timber is no longer an experimental material but a fully regulated and technically validated option.

2.8. Housing Emergencies: La Palma and DANA Events as Evidence of Need

The La Palma volcanic eruption marked a turning point in the management of housing emergencies in Spain. Thousands of families lost their homes within a matter of days, and many were rehoused in hotels or adapted metal containers with very limited habitability. These events revealed a structural deficiency: the lack of rapid, dignified, sustainable and truly habitable housing solutions.

CLT modules offer an opportunity to transform this paradigm by providing living spaces that are efficient, healthy and rapidly deployable.

2.9. Transferability of the Modular CLT System

The modular system proposed in this project can operate in a dual manner: as a classroom or as rapid housing. The structure and envelope remain unchanged; only the interior layout and equipment differ. This flexibility makes the module a valuable resource for public administrations that require fast, reliable and scalable solutions.

2.10. Chapter Conclusion

The analysis of the contemporary context demonstrates that modular construction using CLT is not a passing trend, but a strategic necessity. It simultaneously addresses educational, environmental and social challenges. It has

the capacity to transform how schools are expanded and how housing emergencies are addressed, offering rapid, safe and dignified solutions.

CHAPTER 3. HISTORICAL EVOLUTION OF TIMBER CONSTRUCTION

3.1. Introduction

Timber has been one of the earliest construction materials used by humankind. Its availability, workability and favourable mechanical properties have made it a fundamental structural resource across different cultures and historical periods. Despite this long tradition, the use of timber as a primary structural material experienced a significant decline during the twentieth century due to the widespread adoption of reinforced concrete and steel, which came to be associated with durability, progress and industrial modernity.

However, in recent decades, timber has undergone a profound technological transformation. This evolution has repositioned it as a competitive, highperformance structural material capable of meeting contemporary regulatory, structural and environmental requirements. Understanding this historical trajectory is essential in order to contextualise the emergence of engineered wood products such as Cross-Laminated Timber (CLT).

3.2. Primitive Timber Architectures

The earliest forms of timber construction were directly linked to the natural environment and the structural logic of available materials. Primitive shelters, huts and early dwellings relied on timber frameworks combined with earth, stone or vegetal fibres. These constructions were based on empirical knowledge of load transfer, using vertical elements for compression and horizontal members for spanning.

Although rudimentary, these systems already demonstrated fundamental structural principles that remain valid today: load distribution, triangulation, redundancy and adaptability. Timber allowed rapid construction, repair and modification, qualities that were essential for early human settlements.

Timber construction has evolved through different structural typologies depending on available materials, technology, and cultural context. Figure 3.1 illustrates a traditional European timber framing system and its basic load-bearing logic, which serves as a reference to understand later engineered timber developments.



Figure 3.1— Evolution of timber structural systems: Traditional timber framing systems in medieval Europe, characterised by load-bearing wooden frames combined with infill materials such as masonry or adobe.

3.3. Traditional European Timber Framing Systems

Throughout the Middle Ages and into the early modern period, timber framing systems became increasingly sophisticated in Europe. Techniques such as half-timbered construction (Fachwerk in Germany, colombage in France or entramado in Spain) combined timber skeletons with infill materials such as masonry or adobe.

These structures exhibited remarkable durability and structural efficiency, many of them remaining in service for several centuries. Their longevity demonstrates that timber, when properly designed and protected, is not an inherently temporary or fragile material. Instead, its perceived fragility was largely a consequence of poor detailing, lack of maintenance or exposure to moisture.

Traditional half-timbered systems illustrate the structural role of a timber skeleton combined with infill materials. Figure 3.2 shows a representative Fachwerk configuration, which helps explain durability and structural logic in early timber construction.



Figure 3.2– Evolution of timber structural systems: Half-timbered construction (Fachwerk) as developed in Central Europe, illustrating the structural role of the timber skeleton and its long-term durability.

3.4. The Industrial Revolution and the Decline of Timber Construction

The Industrial Revolution marked a turning point in construction history. The mass production of steel and the later development of reinforced concrete fundamentally altered building practices. These materials enabled longer spans, taller buildings and greater standardisation, while timber came to be associated with pre-industrial construction.

In urban contexts, fire risk and the desire for permanent, monumental architecture further contributed to the displacement of timber by mineral-based materials. As a result, timber construction was progressively relegated to rural or secondary applications.

Lightweight framing was a key step towards industrialised timber construction. Figure 3.3 illustrates the balloon frame system, which is relevant to understand repetitive modular logic and the transition to prefabrication.



Figure 3.3— Evolution of timber structural systems: North American balloon frame system, representing the transition towards lightweight, repetitive and industrialised timber construction techniques.

3.5. The North American Timber Frame and the Rise of Light Construction

In parallel with European developments, North America experienced a distinct evolution in timber construction. The balloon frame and later the platform frame emerged as lightweight systems that allowed rapid and economical housing construction. These techniques relied on repetitive small-section elements and industrially produced components, anticipating many principles of modern prefabrication.

Although these systems prioritised speed and economy over mass and inertia, they played a crucial role in demonstrating the scalability and industrial potential of timber construction.

Engineered timber products improve stability by reorienting wood layers. Figure 3.4 shows a CLT panel configuration with crosswise layers, clarifying why CLT provides bidirectional structural capacity.

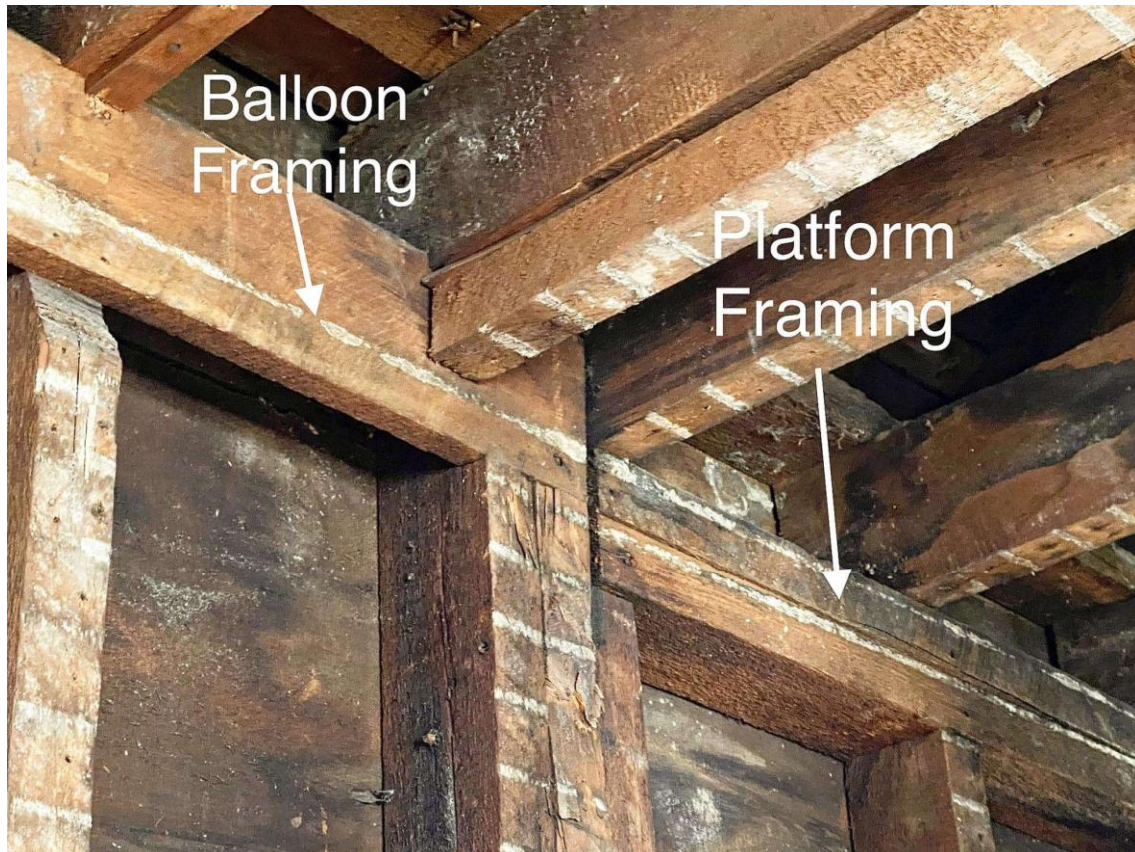


Figure 3.4— Evolution of timber structural systems: Cross-Laminated Timber (CLT) panel configuration, showing the crosswise arrangement of timber layers that provides bidirectional structural capacity and dimensional stability..

3.6. The Emergence of Engineered Timber Products

The late twentieth century saw the emergence of engineered timber products designed to overcome the limitations of solid wood. Glued laminated timber (glulam), laminated veneer lumber (LVL) and oriented strand board (OSB) allowed for greater structural capacity, dimensional stability and material efficiency.

These products marked the transition from traditional carpentry-based construction to an engineering-driven approach, in which timber elements could be calculated, optimised and standardised with the same level of precision as steel or concrete components.

3.7. The Birth of Cross-Laminated Timber (CLT)

Cross-Laminated Timber represents the culmination of this technological evolution. Developed initially in Central Europe, CLT consists of layers of timber boards bonded together with alternating grain orientation. This configuration provides bidirectional strength, high dimensional stability and excellent loadbearing capacity.

CLT enables timber to function as a plate or panel element, rather than solely as linear members. This characteristic fundamentally changes the structural logic of timber buildings, allowing walls and floors to act as diaphragms and load-bearing surfaces.

3.8. Contemporary Timber Architecture and Mid-Rise Construction

The development of CLT has enabled the construction of multi-storey timber buildings that were previously inconceivable. Advances in fire engineering, seismic design and acoustic performance have allowed timber structures to comply with increasingly stringent regulations.

As a result, timber has re-entered the architectural and engineering mainstream, not as a nostalgic or experimental material, but as a technically validated and future-oriented solution.

3.9. Timber Construction in the Context of Sustainability

Beyond its structural capabilities, timber has gained prominence due to its environmental performance. As a renewable material that stores carbon throughout its service life, timber plays a key role in reducing the embodied emissions of buildings.

This environmental dimension has been decisive in the resurgence of timber construction, particularly in public buildings, where sustainability objectives are increasingly embedded in procurement policies.

3.10. Chapter Conclusion

The historical evolution of timber construction demonstrates that the current resurgence of timber is not a novelty, but rather a technologically advanced continuation of a long-established tradition. Cross-Laminated Timber represents a synthesis of empirical knowledge and modern engineering, positioning timber as a structural material fully capable of addressing contemporary construction challenges.

CHAPTER 4. TECHNICAL CHALLENGES OF CROSS-LAMINATED TIMBER (CLT)

4.1. Introduction

Despite its structural and environmental advantages, Cross-Laminated Timber (CLT) presents a series of technical challenges that must be carefully addressed in order to guarantee its correct performance throughout the service life of the building. These challenges are not inherent weaknesses of the material, but rather aspects that require specific design strategies and an appropriate understanding of timber behaviour.

The main technical issues associated with CLT construction are related to moisture sensitivity, hygroscopic movement, condensation risks, acoustic transmission, fire behaviour and long-term durability. The correct resolution of these aspects is essential to ensure that CLT buildings meet regulatory requirements and provide adequate comfort and safety levels.

4.2. Hygroscopic Behaviour and Dimensional Stability

Timber is a hygroscopic material, meaning that it exchanges moisture with the surrounding environment depending on ambient temperature and relative humidity. This characteristic causes dimensional variations in timber elements, particularly in directions perpendicular to the grain.

Timber behaves as an anisotropic material, with properties that vary by direction. Figure 4.1 illustrates the longitudinal, radial, and tangential axes, which is essential to interpret strength and stiffness in design.

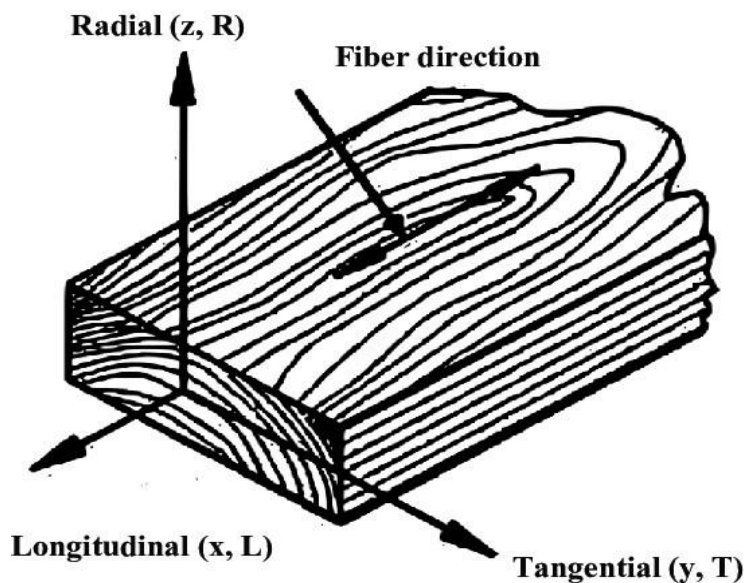


Figure 4.1— Anisotropic mechanical behaviour of timber, showing the longitudinal, radial and tangential directions of the wood fibres.

In CLT panels, the crosswise arrangement of layers significantly reduces global dimensional changes compared to solid timber. However, local movements may still occur, especially at joints, connections and interfaces between different materials. These movements must be anticipated during the design phase in order to avoid cracking, deformation or loss of airtightness.

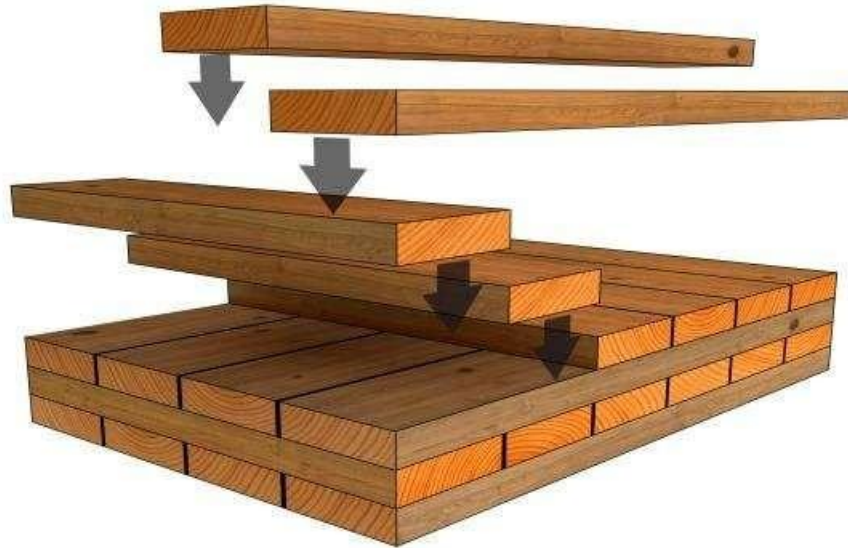


Figure 4.2– Cross-laminated timber (CLT) panel configuration, illustrating the cross-oriented layers used to improve structural stability and stiffness.

Proper detailing, the use of vapour control layers and the selection of compatible materials are fundamental strategies to control hygroscopic behaviour in CLT construction.

4.3. Condensation Risks and Hygrothermal Control

One of the most critical aspects of CLT buildings is the management of interstitial condensation within the building envelope. Timber is particularly sensitive to prolonged exposure to high moisture levels, which can lead to biological degradation, mould growth and a reduction in mechanical performance.

To mitigate these risks, the envelope must be designed following strict hygrothermal criteria. This includes the correct placement of vapour barriers or vapour control membranes, ensuring sufficient thermal insulation and allowing controlled vapour diffusion towards the exterior.

Unlike traditional masonry walls, CLT assemblies require a precise balance between airtightness and vapour permeability. The use of multilayer wall systems

allows these requirements to be met by separating structural, thermal and protective functions.

Moisture transfer through multilayer walls is critical to prevent interstitial condensation. Figure 4.3.1 explains vapour diffusion through a wall section, supporting the discussion of layer sequencing and condensation risk.

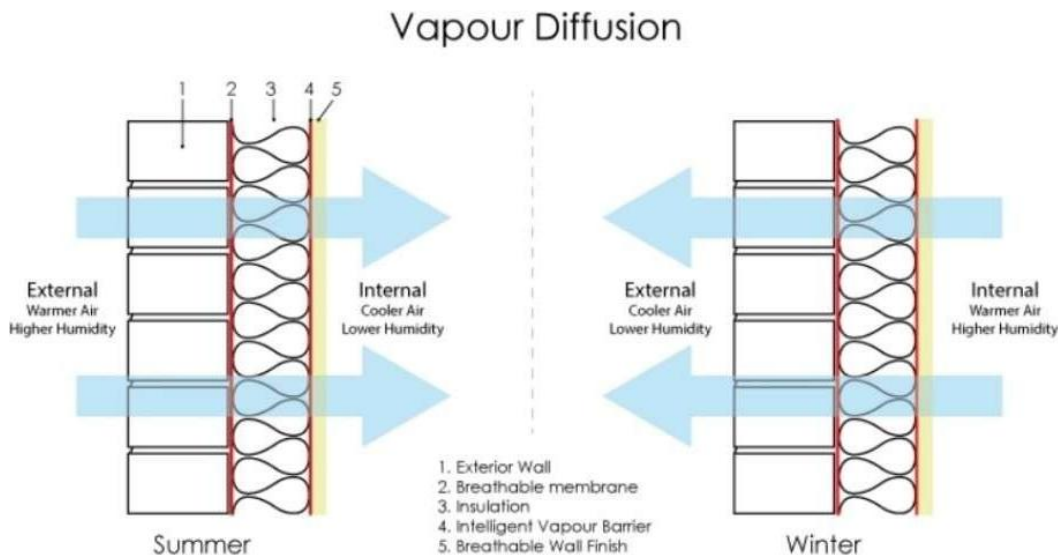


Figure 4.3.1– Vapour diffusion through a wall section and potential risk of interstitial condensation depending on the arrangement of the construction layers.

4.4. Fire Behaviour of CLT Structures

Fire safety is often perceived as a major concern in timber buildings. However, extensive experimental research has demonstrated that massive timber elements such as CLT exhibit predictable and reliable behaviour under fire exposure.

When exposed to fire, CLT panels form a charred layer on their surface, which acts as an insulating barrier that slows down heat penetration and protects the inner structural core. This phenomenon allows CLT elements to maintain their loadbearing capacity for a significant period of time.

Fire resistance in CLT buildings is achieved through a combination of sufficient panel thickness, controlled charring rates, protective linings and compliance with fire engineering principles. As a result, CLT structures can meet or exceed the fire resistance requirements established by building regulations.

4.5. Acoustic Performance and Sound Transmission

Acoustic performance represents another technical challenge in CLT construction, particularly in educational buildings where noise control is essential for learning environments. Due to their low mass compared to concrete, bare CLT panels may exhibit reduced airborne sound insulation.

This limitation is effectively addressed through the use of multilayer assemblies incorporating resilient layers, suspended ceilings, floating floors and additional mass. Proper acoustic detailing ensures that CLT buildings can achieve acoustic performance levels comparable to or better than traditional construction systems.

Acoustic comfort is a key requirement in educational buildings and must be addressed in CLT solutions. Figure 4.4 summarises the implications of exposed CLT surfaces, linking material choices to acoustic performance.

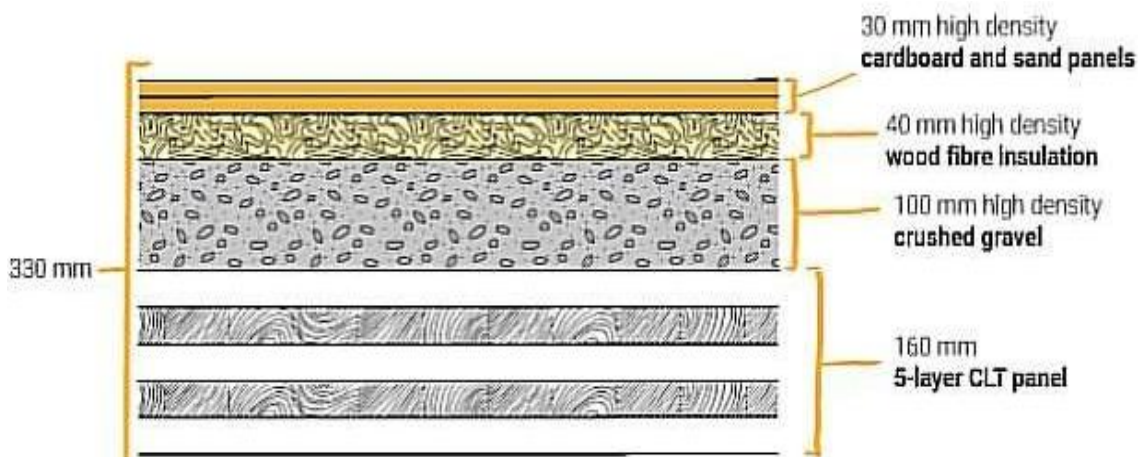


Figure 4.4– Charring mechanism of CLT elements under fire exposure and reduction of the effective loadbearing section.

4.6. Structural Behaviour and Load Transfer

CLT fundamentally alters the structural logic of timber buildings. Instead of relying on linear elements such as beams and columns, CLT buildings behave as platebased systems in which walls and floors act as load-bearing diaphragms.

This behaviour provides high global stiffness, good seismic performance and efficient load distribution. However, it also requires careful design of connections, which play a critical role in transferring loads between panels and ensuring overall structural integrity.

Connections must be designed to accommodate both mechanical loads and dimensional movements, while maintaining robustness and ease of assembly.

Long-term durability in CLT construction depends on controlling moisture at design and execution stages

4.7. Durability and Long-Term Performance

The long-term durability of CLT buildings depends largely on proper design, detailing and maintenance. Timber elements must be protected from direct exposure to moisture, ultraviolet radiation and biological agents.

By keeping CLT panels within the protected envelope of the building and ensuring adequate ventilation and drainage, their service life can be comparable to that of traditional construction materials. Numerous existing timber buildings with service lives exceeding one hundred years demonstrate the viability of timber as a durable structural solution.

4.8. Multilayer Envelope as a Technical Response

The use of a multilayer envelope is the most effective strategy to address the technical challenges associated with CLT. By separating structural, thermal, acoustic and protective functions into distinct layers, each component can be optimised according to its specific role.

This approach not only enhances performance but also increases design flexibility and facilitates compliance with regulatory requirements. The CLT panel functions primarily as the structural core, while additional layers manage insulation, vapour control, fire protection and external weather resistance.

4.9. Regulatory Compliance and Technical Validation

Current building regulations and Eurocodes provide a comprehensive framework for the design of CLT buildings. When correctly applied, these standards ensure that CLT construction meets all requirements related to structural safety, fire resistance, energy efficiency and occupant comfort.

The increasing number of built CLT projects across Europe serves as empirical validation of the material's technical reliability and regulatory acceptance.

4.10. Chapter Conclusion

The technical challenges associated with CLT construction are well understood and can be effectively managed through appropriate design strategies. Moisture control, fire safety, acoustic performance and durability are not obstacles, but rather design parameters that, when properly addressed, allow CLT to perform at a high level.

This chapter demonstrates that CLT is a mature, reliable and technically robust construction system capable of meeting the demanding requirements of educational buildings and modular housing applications.

CHAPTER 5. INDUSTRIALISED STRUCTURAL TIMBER PRODUCTS AND COMPARISON WITH TRADITIONAL SYSTEMS

5.1. Introduction: Mass timber as a contemporary industrial revolution

Timber construction has undergone a profound transformation over the past three decades. Once perceived primarily as a material associated with vernacular architecture or low-rise lightweight construction, timber has re-emerged as a central driver of construction innovation through the development of industrialised products capable of competing with traditional structural systems based on concrete and steel. This evolution is not solely the result of technological progress, but also of cultural, environmental and regulatory shifts. The urgent need to reduce emissions, accelerate construction processes and improve the sustainability of buildings has positioned mass timber as a defining structural material of the twenty-first century.

Within this new context, three engineered timber products stand out in particular: Cross-Laminated Timber (CLT), Glued Laminated Timber (GLT), and Laminated Veneer Lumber (LVL). Each fulfils distinct yet complementary structural roles. CLT functions primarily as a load-bearing surface element; GLT acts as a linear element with high bending capacity; and LVL provides exceptional homogeneity for situations requiring precise control of deformations or concentrated stresses.

Industrialised timber construction is based on a family of engineered products with different structural roles. Figure 5.1 compares CLT, glulam (GLT), and LVL, clarifying where each product is most suitable.

Modular construction—especially when applied to educational buildings and rapid housing solutions remember that this translation is literal; housing is not “emergency housing” in English academic style—benefits significantly from these materials. Mass timber enables the fabrication of complete three-dimensional modules with a level of industrialisation unattainable by wet construction systems. However, to fully understand this potential, it is essential to analyse the nature of these products, their mechanical behaviour, and their capacity to integrate into hybrid systems or to be compared rigorously with conventional alternatives such as reinforced concrete and lightweight steel structures.

This chapter develops these aspects in depth. It begins with a detailed description of each engineered timber product, continues with a comprehensive

comparison between CLT and reinforced concrete, then presents an equally rigorous comparison between CLT and metallic systems, and concludes with two comparative tables that consolidate the theoretical findings.

Industrialised timber construction is based on a family of engineered products with different structural roles. **Figure 5.1** compares CLT, glulam (GLT), and LVL, clarifying where each product is most suitable.

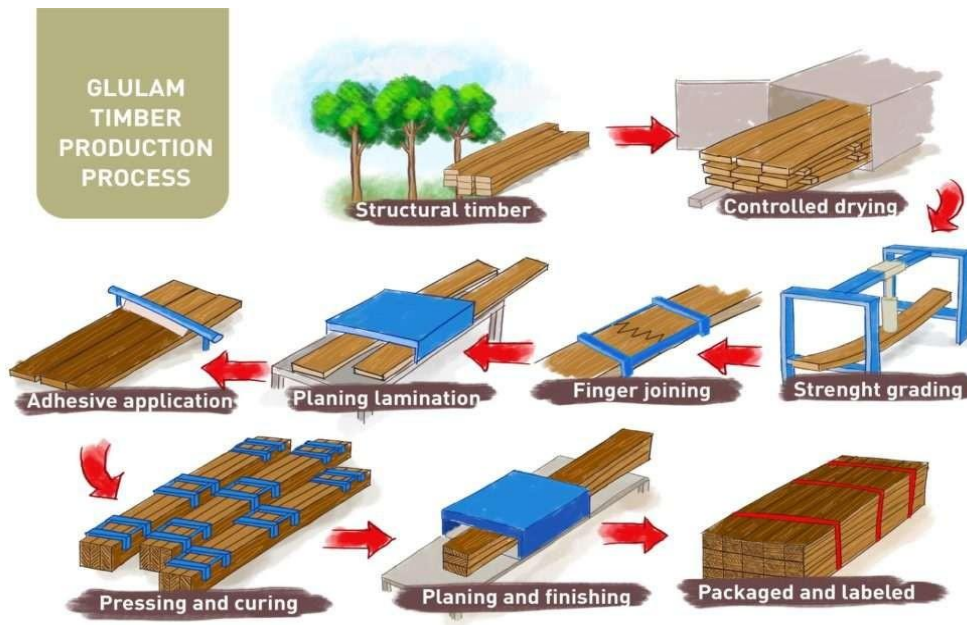


Figure 5.1— Main industrialised structural timber products: CLT panels, glulam beams (GLT) and laminated veneer lumber (LVL).

5.2. Cross-Laminated Timber (CLT): concept, manufacturing process, properties and structural behaviour

Cross-Laminated Timber constitutes the cornerstone of contemporary engineered timber construction. Its structure is based on the superposition of solid timber boards arranged in crosswise layers bonded together using certified structural adhesives. This configuration provides the panel with dimensional stability rarely found in natural materials and enables mechanical performance in two directions, which is essential for plate elements required to resist both vertical and horizontal loads.

The industrial manufacturing process of CLT is characterised by strict quality control at every stage: timber selection, grading and kiln drying; planing to achieve tight tolerances; adhesive application using PUR or MUF systems; controlled

pressing; and CNC machining capable of producing panels with millimetric precision. This precision is essential for modular construction, where geometric accuracy, repeatability and joint quality directly determine the final performance of the building.

CLT exhibits an exceptionally favourable strength-to-weight ratio. It is sti without being heavy, stable without being brittle, and sufficiently lightweight to enable vertical extensions on existing buildings without requiring reinforcement of columns or foundations. Structurally, it behaves as a diaphragm due to its transverse and longitudinal sti ness, facilitating the transfer of horizontal loads in multi-storey buildings or modular assemblies.

From an operational standpoint, CLT is not only efficient but also highly versatile. It can function as a load-bearing wall, floor slab, roof element, partition or bracing component. Its suitability for three-dimensional modular fabrication makes it an ideal material for prefabricated classrooms, post-disaster rapid housing and school extensions executed within limited timeframes.

Volumetric modular construction combines panelised systems with linear elements to create rigid units. Figure 5.2 shows a three-dimensional CLT module concept, supporting the modular approach adopted in this project.

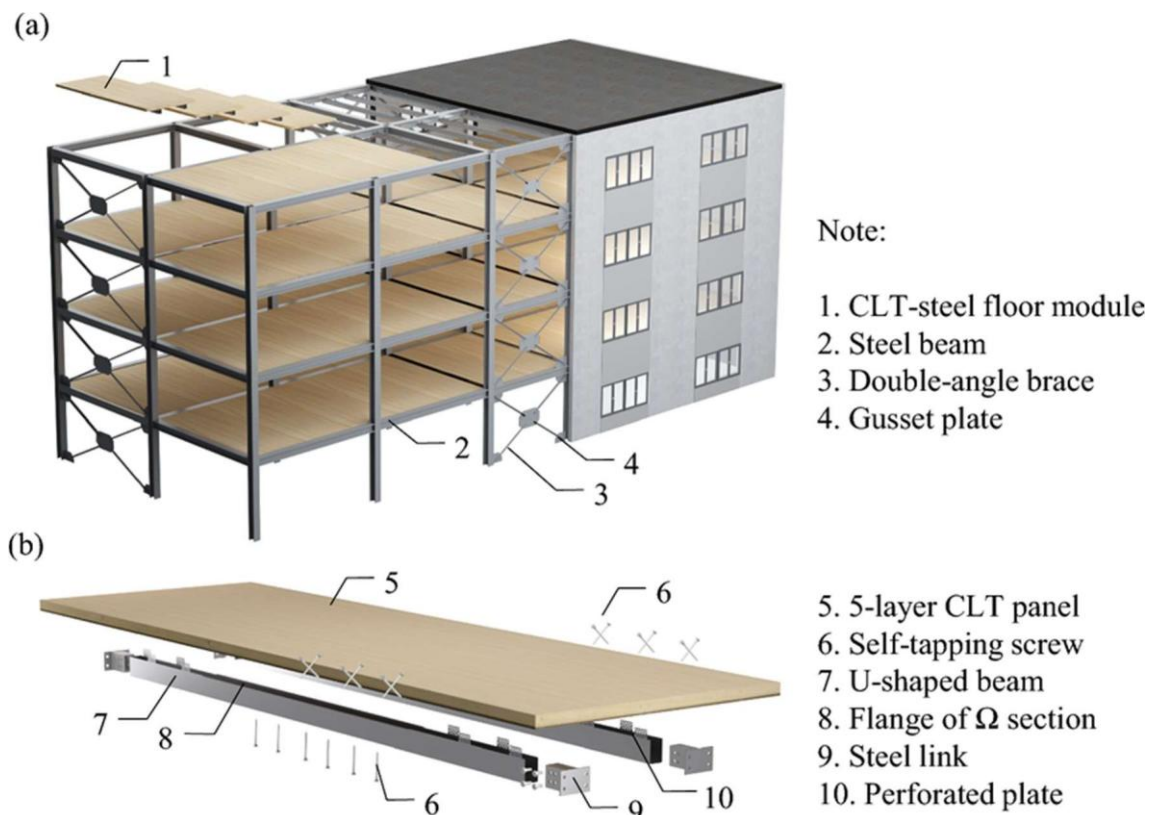


Figure 5.2—Three-dimensional modular construction using CLT panels combined with linear timber elements.

5.3. Glued Laminated Timber (GLT): linear reinforcement, stiffness and structural continuity

GLT—commonly referred to as glulam—constitutes the perfect linear complement to CLT. Unlike CLT, whose layers are cross-oriented, GLT is manufactured by bonding timber boards in the same direction, producing elements of considerable length and high bending resistance. This makes GLT particularly suitable for primary beams, large-span lintels, intermediate columns and other components subjected to significant linear stresses.

Within a modular context, GLT plays strategic roles: reinforcing floor edges, balancing loads in open areas such as corridors or continuous window bands, and acting as a remembrance that this translation is literal; housing is not “emergency housing” in English academic style—benefits significantly from these materials. Mass timber enables the fabrication of complete three-dimensional modules with a level of industrialisation unattainable by wet construction systems. However, to fully understand this potential, it is essential to analyse the nature of these products, their mechanical behaviour, and their capacity to integrate into hybrid systems or to be compared rigorously with conventional alternatives such as reinforced concrete and lightweight steel structures.

This chapter develops these aspects in depth. It begins with a detailed description of each engineered timber product, continues with a comprehensive comparison between CLT and reinforced concrete, then presents an equally rigorous comparison between CLT and metallic systems, and concludes with two comparative tables that consolidate the theoretical findings. The analysis is framed within an academic and critical approach fully aligned with the objectives of this Final Degree Project.

5.4. Laminated Veneer Lumber (LVL): extreme homogeneity and precision for concentrated stresses

Laminated Veneer Lumber (LVL) is manufactured by bonding thin wood veneers oriented in parallel, resulting in a material of exceptional homogeneity that surpasses most structural timber products in terms of strength and dimensional stability. Its behaviour is highly predictable, resistant to moisture-induced variation, and particularly strong in tension and bending.

Within CLT modular systems, LVL is especially suitable for zones where concentrated loads must be transferred: above openings, at wide spans, corners, connections to steel columns, or reinforced roof zones. In these applications, LVL provides additional safety margins and reduces differential deformation.

5.5. Synergies between CLT, GLT and LVL in three-dimensional modules

The true potential of engineered timber emerges when CLT, GLT and LVL are combined. CLT acts as the load-bearing surface, GLT provides linear reinforcement, and LVL ensures precision where stress concentrations occur. Together, they generate structures that are lightweight yet highly resistant, easily transportable and exceptionally well suited to serial production. In the context of prefabricated classrooms and housing modules, this combination constitutes the most efficient structural solution currently available.

5.6. In-depth comparison between CLT and reinforced concrete

The comparison between CLT and reinforced concrete extends far beyond mechanical resistance. Both materials embody fundamentally different ways of building, with significant implications in environmental performance, thermal behaviour, acoustics, construction logistics and social impact. Understanding these differences is essential to justify why school extensions or rapid housing solutions should be executed using mass timber.

Reinforced concrete exhibits high density, providing mass and stability, but at the cost of significantly increased structural loads. A concrete floor can add tens of tonnes to an existing building, placing severe demands on columns and foundations. CLT, approximately five times lighter, allows vertical interventions without structural reinforcement—an advantage of critical importance in educational contexts where construction must be rapid, clean and minimally invasive.

Thermal behaviour also differs markedly. Concrete's high thermal conductivity requires substantial insulation thicknesses to achieve acceptable performance, whereas timber offers inherently favourable thermal properties that, when combined with continuous external insulation, readily achieve high-performance envelopes.

Acoustically, concrete benefits from its mass, but CLT can achieve comparable performance through well-designed multilayer systems. Additionally, timber provides a more comfortable internal acoustic environment by reducing reverberation and imparting a sense of acoustic warmth.

Fire behaviour further distinguishes the materials. Concrete can suffer explosive spalling under high temperatures, leading to sudden loss of capacity, whereas CLT chars in a stable and predictable manner. This predictability explains why many timber buildings achieve fire resistance ratings of EI60 to EI120 without difficulty.

From an environmental perspective, the contrast is stark. Timber stores carbon; concrete emits it. A CLT building can reduce CO₂ emissions by up to 80% compared to a concrete counterpart—an essential consideration in a context where sustainability is no longer optional.

Finally, construction logistics differ radically. Wet concrete construction entails months of noisy, dusty work involving heavy machinery and prolonged site occupation, which is incompatible with school calendars. Modular CLT construction, by contrast, can be completed in days with minimal disruption.

When selecting a structural system, weight and construction process have major implications for time, logistics, and disruption. Figure 5.3 provides a conceptual comparison between CLT and reinforced concrete, supporting the rationale for CLT modules.



CLT vs CMU		
	 Cross-Laminated Timber	 Concrete Masonry Unit
INSTALLATION	Hours	3-4 Weeks
TRADES	One	Multiple
INSPECTIONS	One	Multiple
COMPONENTS	Panelized Design	Thousands
POTENTIAL WEATHER IMPACT	Minimal	Significant

Figure 5.3—Conceptual comparison between CLT and reinforced concrete structures in terms of weight, construction process and environmental impact.

5.7. Comparative table: CLT vs. reinforced concrete

The choice of structural system has a significant impact on construction time, environmental performance, and adaptability. Table 5.7 compares CLT modular construction with reinforced concrete, highlighting the main differences that justify the adoption of CLT in modular extensions.

Table 5.1– Comparison between CLT modular construction and reinforced concrete.

Criteria	CLT	Reinforced concrete
Self-weight	Very low; suitable for extensions	Very high; requires reinforcement
Thermal performance	Excellent; low conductivity	Poor; high insulation demand
Acoustics	Good in multilayer systems	Very good due to mass
Fire behaviour	Stable charring	Sudden loss of resistance
Environmental impact	Very low; carbon storage	Very high
Construction speed	Very fast	Slow
Industrialisation	Optimal	Limited
Reusability	Yes	No

5.8. In-depth comparison between CLT and metallic systems

A complete analysis must also compare CLT with metallic systems commonly used in temporary modular buildings, particularly converted shipping containers or lightweight steel frame systems. While their immediate availability may seem advantageous in emergency contexts, their overall performance is significantly inferior.

Metallic modules exhibit extremely high thermal conductivity, resulting in severe internal temperature fluctuations. Walls become cold in winter and excessively hot in summer, creating uninhabitable environments without intensive mechanical conditioning. The lack of thermal inertia leads to rapid temperature changes that seriously undermine comfort.

Acoustically, metal amplifies vibrations, transmits external noise with little attenuation and causes internal reverberation. Even with added interior layers, the acoustic quality of a container never approaches that of a CLT module.

Fire behaviour is equally problematic: steel loses strength abruptly when heated, leading to sudden deformations or collapse. CLT, by contrast, retains a resistant core through controlled charring.

Environmentally, metallic modules carry a high carbon footprint due to steel production and limited reuse potential. CLT modules can be dismantled, relocated and reintegrated into circular construction systems.

Finally, habitability is decisive. Metal creates hostile environments, whereas timber promotes psychological and emotional well-being—an essential factor in postdisaster housing and educational spaces.

5.9. Comparative table: CLT vs. metallic systems

In addition to concrete systems, metallic modular solutions are often considered for temporary or industrial buildings. Table 5.9 compares CLT modular construction with metallic systems, focusing on comfort, durability, and environmental performance.

Table 5.2– Comparison between CLT modular construction and metallic systems.

Criterion	CLT (mass timber)	Metal (containers / sandwich panels)
Thermal behaviour	Excellent; stable	Very poor; extreme temperatures
Acoustics	Comfortable; well insulated	Very poor; high reverberation
Fire behaviour	Predictable charring	Sudden loss of resistance
Durability	High	Low due to corrosion
Habitability	High	Very low
Environmental impact	Low	High
Reusability	High	Limited

5.10. Chapter conclusion

The analysis presented in this chapter demonstrates that industrialised timber—and CLT in particular—constitutes an exceptionally efficient structural system for modular construction, vertical extensions and rapid housing provision. Comparisons with concrete and metallic systems reveal that CLT not only competes with these materials but significantly outperforms them in key aspects such as construction speed, self-weight, thermal behaviour, sustainability, adaptability and interior comfort.

Mass timber thus emerges as the most technically robust foundation for the prefabricated modules proposed in this Final Degree Project.

CHAPTER 6. STRUCTURAL SYSTEMS FOR MID-RISE CONSTRUCTION WITH CLT: AN IN-DEPTH ANALYSIS

Mass timber construction—and particularly the use of Cross-Laminated Timber (CLT) panels—has transformed the way mid-rise buildings and extensions on existing structures are conceived. For decades, it was assumed that materials capable of supporting multi-storey buildings and ensuring stability under horizontal actions—such as wind or, in certain regions, seismic loads—were limited to reinforced concrete and steel. However, technological advances in CLT have demonstrated that mass timber not only competes with these materials but offers clear advantages in many contexts, especially when design strategies prioritise prefabrication and industrialised processes.

A CLT volumetric module behaves structurally as a rigid box with diaphragms and load-bearing walls. Figure 6.1 illustrates this box action, clarifying load paths and the role of floor and wall panels.



Figure 6.1— Three-dimensional CLT structure acting as a rigid structural box, illustrating load-bearing walls, floor diaphragms and global structural stability in mid-rise construction.

This chapter provides an in-depth examination of the structural systems that enable mid-rise construction using CLT, with particular emphasis on systems suitable for extensions to existing buildings, such as the addition of a new storey to a school using prefabricated three-dimensional modules. From a technical and critical perspective, the chapter analyses the specific characteristics of CLT as a loadbearing material, its role as a structural diaphragm, the importance of load-bearing walls, the function of glulam (GLT) frames, seismic behaviour, and the integration of hybrid systems. All these aspects converge on a fundamental conclusion: CLT is not only viable, but an optimal material for vertical extensions

due to its lightness, stiffness, predictability and compatibility with modular construction.

6.1. Structural logic of CLT: stiffness, lightness and plate behaviour

CLT differs substantially from traditional timber systems. While lightweight timber framing relies on linear members connected in repetitive layouts, CLT consists of solid, continuous panels with cross-oriented layers whose fibre directions provide exceptional stiffness both parallel and perpendicular to the span. This bidirectional stiffness allows the panel to behave similarly to a plate or diaphragm, capable of distributing loads and resisting lateral actions with remarkable stability.

The relative lightness of CLT is, paradoxically, one of its greatest strengths. With a density approximately five times lower than that of concrete, CLT generates significantly reduced vertical loads—an essential factor when intervening in existing buildings. Unlike wet construction systems, which substantially increase demands on columns, beams and foundations, CLT allows the addition of an entire storey without structural strengthening, thereby reducing costs, construction time and disruption.

In the case of three-dimensional modules, CLT panels define walls, floors and roofs with geometric and dimensional continuity. Once assembled, the module behaves not as a collection of components but as a resistant box whose global performance exceeds the sum of its parts. This rigid-box logic enables safe and reliable applications in mid-rise construction.

6.2. Load-bearing walls as the primary structural system in CLT buildings

In most CLT buildings, load-bearing walls constitute the structural core. They carry vertical loads from floors and roofs as well as horizontal actions due to wind, accidental loads or movements of the existing structure. CLT walls perform particularly efficiently in compression parallel to the grain, where timber exhibits high and stable mechanical properties.

Their effectiveness lies in their dual role as vertical plates that provide both load resistance and bracing. This reduces the need for auxiliary structures, simplifies geometry, lowers weight and enhances prefabrication. As panels are CNC-machined in the factory, door and window openings are produced with millimetric precision, eliminating on-site improvisation.

In prefabricated vertical extensions, load-bearing walls are supported on the existing structure through load-distribution elements—typically steel profiles or ring

beams—which ensure uniform load transfer. This avoids localised overloads on columns or beams and allows the extension to be executed without reinforcing the base structure.

6.3. CLT floor slabs as rigid diaphragms

Within CLT structural systems, floor slabs play a critical role as rigid diaphragms that channel horizontal loads towards the walls capable of resisting them. This function is especially relevant in mid-rise buildings and extensions on existing structures, where global stability depends on efficient distribution of lateral actions.

Thanks to its cross-layered configuration, CLT performs highly effectively as a diaphragm. Panel stiffness prevents excessive deformation and ensures that walls act in unison. CLT slabs can also be machined to accommodate service penetrations or module connections without compromising overall resistance, as these interventions are planned during fabrication rather than executed on site.

Another key advantage is the low weight of CLT slabs, which allows complete modules—including walls and roofs—to be lifted without heavy machinery. This facilitates rapid assembly in school environments, minimising noise, disruption and occupation of outdoor areas.

6.4. GLT frames and linear elements: extending structural capacity

Although CLT can resolve most structural demands in mid-rise buildings, it is often complemented by glued laminated timber (GLT) linear elements. GLT is designed to act as beams or columns, offering high resistance to bending and tension, making it an ideal companion to CLT.

Introducing GLT beams or frames at specific locations enables the resolution of large openings—such as continuous horizontal windows or double-leaf doors—and allows increased module spans without excessive deflection. GLT also performs favourably in fire conditions: like CLT, it chars in a controlled manner, maintaining structural stability for extended periods.

The CLT–GLT relationship is therefore complementary. CLT defines load-bearing surfaces and diaphragms, while GLT provides linear support where greater stiffness or longer spans are required. Together, they form an extremely efficient, safe and lightweight structural solution.

6.5. Global stability and bracing of the building

When building in height—even a single additional storey on a school—lateral stability is as critical as vertical resistance. Wind, thermal effects, interaction with the existing structure and timber movements generate stresses that must be transmitted through a coherent bracing system.

In CLT buildings, lateral stability is achieved through the combined action of strategically distributed load-bearing walls, floor diaphragms and a system of metal connectors ensuring load continuity. Well-designed panel connections allow the building to behave as a rigid whole.

In school extensions, bracing is doubly important: while the existing building contributes to lateral resistance, the new storey must be capable of acting independently under horizontal actions. CLT modules are therefore designed as self-contained boxes that, once assembled, create a rigid and stable floor.

The key lies in the connection system: long self-tapping screws, steel plates and high-strength connectors provide both stiffness and ductility. This ductility is a major advantage, as timber accommodates progressive deformation without sudden collapse, enhancing safety under exceptional events.

6.6. Hybrid systems combining CLT, steel and concrete

Although CLT can function as a stand-alone structural material, hybrid systems are often adopted to combine the advantages of different materials—particularly in school extensions.

Steel may be used where concentrated resistance is required, such as point supports on existing beams. Its high strength-to-weight ratio allows for slender and efficient local frames, and it facilitates complex connections between modules while preserving CLT integrity.

Concrete may be employed in stair or lift cores to enhance global stability without relying exclusively on CLT for lateral resistance. However, in vertical extensions on schools, concrete use is generally limited to minor interventions due to its selfweight.

The result is a flexible hybrid system in which timber remains the predominant structural material, with steel and concrete introduced only where strictly necessary.

6.7. Seismic behaviour: the remarkable ductility of CLT

Although seismicity in much of Spain is moderate, seismic engineering remains an international benchmark. One of the most significant findings of recent decades is the excellent seismic performance of CLT.

This behaviour results from several interrelated factors. First, the low self-weight reduces seismic forces. Second, metal connections between panels act as ductile elements dissipating energy through controlled micro-deformations. Third, the

three-dimensional box behaviour of modules resembles reinforced concrete shearwall systems, but with greater flexibility and without cracking.

These characteristics render CLT buildings highly reliable in seismic regions. While this project does not focus on seismic design, understanding these principles reinforces confidence in CLT for vertical school extensions.

6.8. Building on existing structures: technical feasibility and advantages of CLT

The objective of this project—to add a full storey of classrooms to a school—requires demonstrating that CLT is not only feasible but optimal. The main arguments are the drastic reduction in self-weight, uniform load transfer and compatibility with industrialised construction.

The low weight of CLT avoids the need for structural reinforcement, which would be almost unavoidable with concrete. Many schools built decades ago were not designed for additional concrete storeys. CLT modules, being five times lighter, can be supported without deep intervention in columns or foundations.

Furthermore, modules distribute loads through continuous walls and horizontal plates, avoiding excessive point loads. The existing structure benefits from a more uniform and gentle load transfer. Finally, dry assembly minimises disruption, allowing construction during school holidays without noise, dust or prolonged occupation of outdoor spaces.

6.9. The three-dimensional module as the optimal structural unit

The three-dimensional CLT module represents the logical culmination of the analysed systems. Its rigid-box behaviour, industrial manufacturability and compatibility with transport and lifting make it ideal for school extensions and rapid housing.

The module is not merely an assembly of panels; it is a complete unit designed to resist vertical, horizontal and dynamic loads while maintaining structural integrity from factory to final assembly. Its monolithic behaviour and dimensional precision enable fast, safe assembly and predictable performance.

6.10. Chapter conclusion

The analysis confirms that CLT is exceptionally well suited for mid-rise construction and extensions on existing buildings. Its plate behaviour, diaphragm stiffness, efficient load-bearing walls, compatibility with GLT and LVL, ductility under horizontal actions and adaptability to hybrid systems position it among the most relevant structural materials of the twenty-first century.

Within this project, three-dimensional CLT modules constitute the most efficient, sustainable and feasible solution for adding a new storey to a school without compromising the existing structure or disrupting its operation. These same qualities also make CLT an optimal system for post-disaster rapid housing. The following chapter therefore examines the sandwich-type construction system addressing hygrothermal, acoustic and service integration challenges specific to timber buildings.

CHAPTER 7. CRITICAL TECHNICAL CHALLENGES IN CLT BUILDINGS AND THEIR RESOLUTION THROUGH A MULTILAYER MODULAR SYSTEM

CLT construction has proven to be a structural, sustainable and technologically advanced alternative to traditional building systems. However, despite the rapid growth of mass timber buildings across Europe, North America and Asia, the use of CLT panels presents a number of specific challenges that must be addressed with precision—particularly when the objective is to create three-dimensional modules intended to function as classrooms or rapid housing units. Timber is an exceptionally efficient material when properly designed, but it can suffer severe pathologies if its hygrothermal, acoustic, fire-protection or service-integration requirements are neglected.

Defects and execution errors can compromise modular construction performance, especially in envelope continuity and junctions. Figure 7.1 summarises the main error categories observed in real cases, supporting the focus on detailing and quality control.

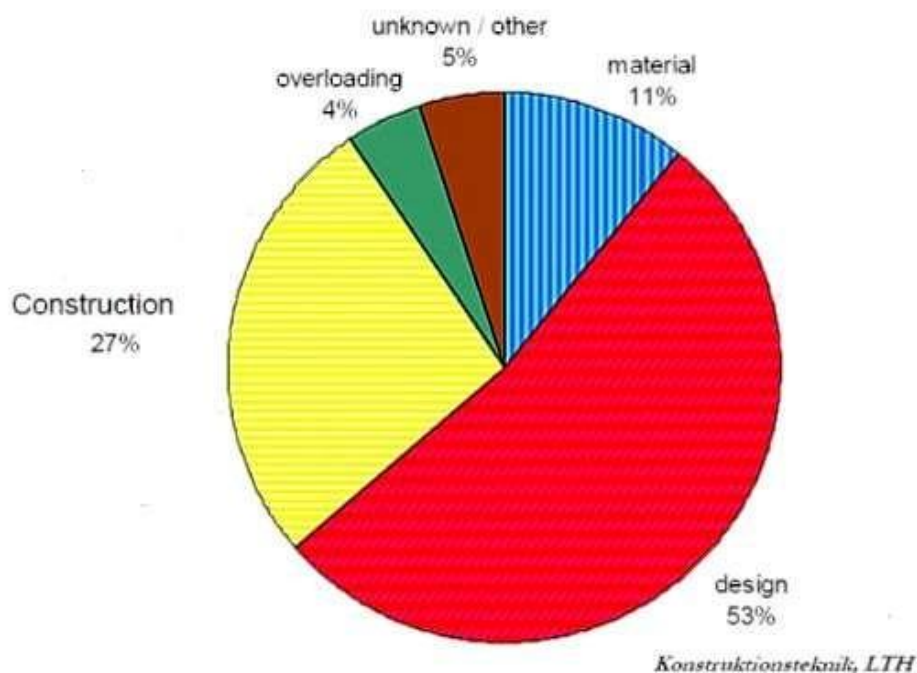


Figure 7.1— Percentages of errors that caused failures in the Sweden-Finland ELU, based on 127 real cases.

The purpose of this chapter is to develop, in a thoroughly argued and non-schematic manner, the main technical problems associated with CLT and to explain how the proposed construction system—a sandwich-type envelope composed of an internal service cavity, a CLT panel, a vapour control layer, continuous external insulation and a rendered (ETICS) or ventilated façade finish—resolves these issues in an integrated way. This holistic approach is essential to ensure the feasibility of a vertical school extension and, at the same time, the habitability of rapid postdisaster housing modules.

7.1. Moisture and vapour diffusion: the most critical challenge

The hygroscopic behaviour of timber is arguably the most decisive factor in its architectural application. Timber is not an inert material; it continuously responds to environmental conditions, attempting to balance its moisture content with that of the surrounding air. This characteristic is beneficial in many respects, as it naturally regulates indoor humidity, improves comfort and contributes to thermal stability. However, it also implies vulnerability to poorly controlled humid environments, particularly when the material is trapped behind impermeable layers or exposed to interstitial condensation.

CLT panels should ideally operate within a moisture content range of 10–14%. When this range is exceeded, physical behaviour changes significantly: timber swells, deforms, loses mechanical strength and may activate xylophagous microorganisms or decay fungi. In modules intended for classrooms or rapid housing, this risk is intensified by the high production of water vapour generated by occupants through breathing, daily activities and heating systems.

Schools represent particularly demanding environments. The simultaneous presence of 20 to 30 pupils in a small classroom, combined with prolonged periods without ventilation, creates conditions of high relative humidity. If this moisture penetrates the building envelope without control, it may migrate into the CLT panel, condense in colder layers and deteriorate the timber from within. This phenomenon is especially dangerous because it remains hidden until damage is already advanced.

The solution lies in the careful design of the vapour permeability gradient. The envelope proposed in this project establishes a logical sequence of layers that regulates indoor humidity while preventing its penetration into the CLT. The vapour control layer placed on the inner face of the panel, combined with external insulation made of wood fibre or mineral wool, encourages outward drying and prevents internal moisture accumulation. The fundamental principle is that timber must be able to dry, and the sandwich system ensures this by controlling both vapour ingress and egress.

7.2. Interstitial condensation: an invisible but highly destructive enemy

Interstitial condensation is one of the most dangerous issues in timber construction. Unlike surface moisture from leaks, which can be visually detected, internal condensation is silent and progressive. It occurs when water vapour passing through the envelope encounters a layer whose temperature is below the dew point, causing condensation within the wall without visible signs until severe damage has occurred.

In traditional masonry or concrete envelopes, condensation can be harmful but rarely compromises structural integrity. In timber, however, the consequences are critical: retained moisture can cause differential swelling, degrade adhesive bonds between layers, promote fungal growth and even compromise the stability of the CLT panel. In extreme cases, this may lead to partial failure or building abandonment.

Classrooms are particularly prone to interstitial condensation due to high human activity and vapour production. For this reason, the inclusion of an internal service cavity and a vapour control layer is essential rather than optional. The use of intelligent vapour control membranes—whose permeability adapts to hygrothermal conditions—provides far greater safety than fully impermeable barriers, which may trap moisture within the envelope.

Combined with vapour-permeable external insulation, this configuration ensures that any residual moisture can dry outward. This outward diffusion behaviour is essential in temperate climates such as Spain's, where winter condensation risks coexist with favourable drying conditions for much of the year. The sandwich system therefore acts not only as thermal insulation but as a long-term hygrothermal protection mechanism for CLT.

7.3. Acoustics: CLT lightness and the need for multilayer design

Unlike reinforced concrete, which benefits from high mass and performs well against airborne noise, CLT is a relatively lightweight material. This structural lightness—advantageous for building on existing structures—becomes a challenge when meeting the strict acoustic requirements of educational buildings or rapid housing.

Classrooms require high levels of acoustic insulation both from external noise and between internal spaces. School environments are inherently noisy: simultaneous conversations, traffic, playground activity, corridors at peak times, moving furniture and HVAC systems. Emergency housing modules similarly require adequate acoustic comfort to ensure dignified living conditions.

On its own, a CLT panel does not meet these requirements. However, when integrated into a multilayer system, performance improves dramatically. The sandwich envelope adds mass through internal gypsum boards, incorporates acoustic absorption via mineral wool in the service cavity and enhances attenuation with external wood-fibre or rock-wool insulation. When these layers are decoupled from the structural panel through a lightweight substructure, they form a mass–spring–mass system that significantly improves airborne sound insulation and vibration control.

Airtightness is another critical factor. Even a theoretically well-designed acoustic envelope can fail if small gaps or poorly sealed joints exist, particularly at module interfaces. The proposed modular system integrates acoustic tapes, airtight joints and controlled assembly procedures that minimise leakage and maximise overall performance.

7.4. Fire safety: technical analysis and multilayer solutions

The fire behaviour of timber is one of the most extensively studied aspects of modern structural engineering. Contrary to the widespread belief that “timber burns”, CLT panels exhibit predictable, controllable behaviour that often surpasses that of metallic or hybrid systems.

When exposed to fire, timber chars at a relatively constant rate—typically between 0.6 and 0.7 mm/min for most structural species. The char layer acts as a thermal barrier, protecting the inner core of the panel, whose temperature rises slowly. This allows designers to calculate residual cross-sections that maintain load-bearing capacity for extended periods.

In educational buildings, where high fire-resistance ratings are required, CLT performs excellently when combined with protective linings, particularly gypsum plasterboards. Gypsum contains chemically bound water that is released as vapour when heated, significantly delaying temperature rise in the structural panel. Combined with the low weight of the system, this allows EI60 and even EI90 ratings to be achieved with relatively simple assemblies.

External insulation also plays a crucial role. Rock wool, being non-combustible and stable at high temperatures, is an optimal solution for strict fire requirements. Even wood-fibre insulation, while combustible, performs reliably when protected by ETICS or ventilated façade systems.

7.5. Integration of building services without compromising the structural panel

One of the most common mistakes in timber construction is excessive perforation of the structural panel to accommodate electrical, HVAC or plumbing services. CLT

should not be treated like gypsum partitions or masonry walls. Its strength depends on layer continuity, and each penetration reduces capacity, affects fire behaviour and creates moisture-vulnerable points.

In the proposed modular system, this issue is resolved through an internal service cavity independent of the CLT panel. Installed in front of the panel and formed by a lightweight substructure, this cavity accommodates all services without any contact with the structural timber. This solution offers additional benefits: improved acoustics, ease of maintenance and future adaptability, and long-term protection of the CLT.

7.6. Joints between modules and system airtightness

In modular construction, joint detailing is one of the most sensitive aspects. Poorly executed joints can compromise acoustics, airtightness, fire safety and durability. Joints must be treated as critical design elements rather than mere geometric connections.

The proposed system incorporates expanding sealing tapes, airtight internal and external membranes, module overlaps, concealed steel profiles and combined sealing strategies that ensure modules form a continuous, stable and airtight whole.

Uncontrolled air infiltration is a silent enemy: it reduces thermal efficiency, increases condensation risk, facilitates noise transmission and leads to uncomfortable, energy-inefficient spaces. In schools or emergency housing, this would result in cold, noisy and difficult-to-maintain environments. Consequently, joint design constitutes a cornerstone of the system.

7.7. Chapter conclusion

The technical challenges associated with CLT are real and must be addressed rigorously. However, when the hygrothermal, acoustic, structural and fire-protection requirements of mass timber are fully understood, it is possible to design systems that are extremely reliable, efficient and durable. The sandwich-type envelope developed in the following chapter is not merely a collection of construction layers; it is the technical response to decades of research, pathology studies and thousands of mass timber buildings worldwide.

Mastering these critical issues enables the construction of safe, comfortable and efficient educational modules, as well as dignified, high-quality housing modules for emergency situations such as those experienced in La Palma or following severe flooding events.

CHAPTER 8. DESIGN OF THE PROPOSED CONSTRUCTION SYSTEM: MULTILAYER ENVELOPE, CLT PANEL AND HYGROTHERMAL, ACOUSTIC AND FIRE-SAFETY SOLUTIONS

8.1. Introduction: towards an integrated construction system

The use of prefabricated CLT modules for educational extensions and rapid housing is only viable if the building envelope simultaneously addresses the four major technical challenges associated with timber construction: moisture control, thermal insulation, acoustic insulation and fire protection. The system proposed in this chapter is not an arbitrary accumulation of layers, but the result of a rigorous analysis of the most frequent pathologies observed in timber buildings and of the accumulated experience in countries where this type of construction is well established.

The envelope must ensure thermal efficiency, moisture safety, and service integration without compromising the CLT structure. Figure 8.1 presents the multilayer sandwich solution, clarifying the function of each layer in the proposed system.

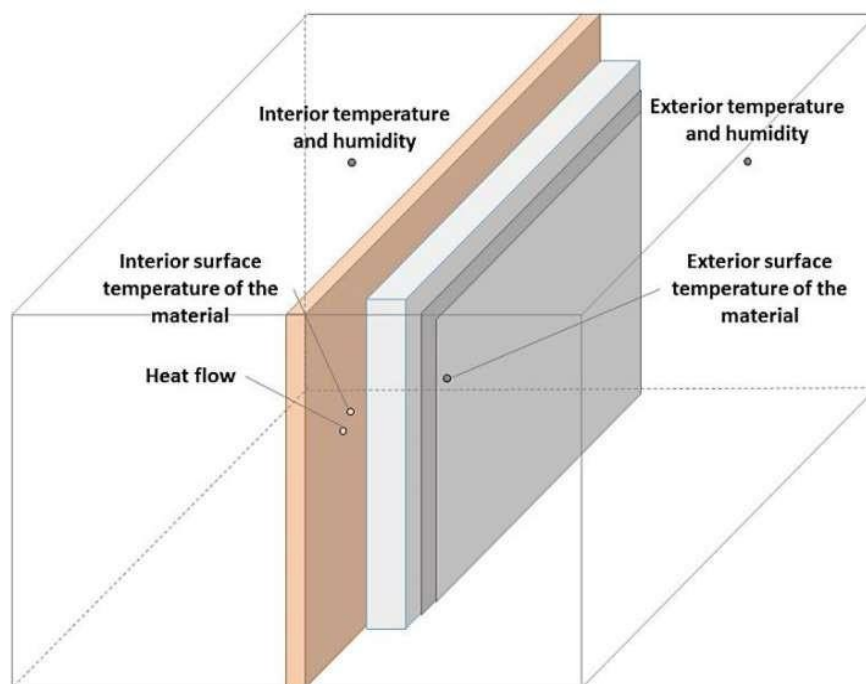


Figure 8.1— Multilayer sandwich envelope for CLT modules, showing the internal service cavity, structural CLT panel, intelligent vapour control layer, continuous external insulation and external finish.

The proposal consists of a sandwich-type multilayer envelope in which each layer fulfils a precise and complementary function. This system allows CLT panels to operate under optimal conditions, avoiding direct exposure to moisture, solar radiation, abrupt temperature variations or improper perforations. At the same time, it guarantees adequate acoustic performance for classrooms and dwellings, certifiable fire resistance and long-term durability comparable to—or exceeding—that of many conventional solutions.

This chapter develops each layer in detail, explaining its function, technical justification and interaction with the overall structural system. Alternative solutions are also analysed, and the reasons why the selected system offers the best balance between performance, sustainability, cost and speed of execution are clearly argued.

8.2. General concept of the multilayer envelope

The proposed envelope follows a fundamental principle of building physics: moisture must always be able to escape, but must not be allowed to enter excessively, and insulation should preferably be placed on the exterior to ensure optimal thermal and acoustic behaviour.

The CLT panel acts as the structural core of the envelope, but not as its only component. Surrounding it are layers that:

- regulate vapour diffusion,
- protect against driving rain,
- ensure airtightness,
- increase acoustic mass,
- provide sound absorption,
- enhance fire resistance,

The result is a robust, predictable and versatile envelope capable of adapting both to north-facing classrooms and to dwellings located in humid climates.

8.3. Detailed composition of the envelope

The multilayer system is described from the interior to the exterior, analysing not only what is placed, but why it is placed.

8.3.1. Internal layer: finish, service cavity and acoustic conditioning

The interior of the module must fulfil several functions simultaneously. It must provide a finish resistant to educational or domestic use, supply sufficient mass and damping to meet acoustic requirements, and allow services to pass without perforating the CLT.

The proposed solution consists of:

- an internal lining mounted on a light timber or metal substructure,
- a 4–6 cm service cavity filled with medium-density mineral wool, and
- one or two layers of gypsum plasterboard.

Gypsum plays a decisive role: it provides passive fire protection due to its chemically bound water content, adds acoustic mass and offers an ideal surface for interior finishes. Mineral wool contributes to acoustic insulation by absorbing mid- and high-frequency sound waves.

Separating this service cavity from the CLT panel allows electrical wiring, data networks and small ducts to be installed without weakening the structural panel, thereby preserving the integrity of the module.

The envelope design of CLT modular buildings must ensure structural capacity, thermal efficiency, moisture control, and service integration within a reduced thickness. Figure 8.3.1 illustrates the proposed multilayer wall configuration, showing the functional arrangement of structural, insulation, and protection layers in the CLT modular system.

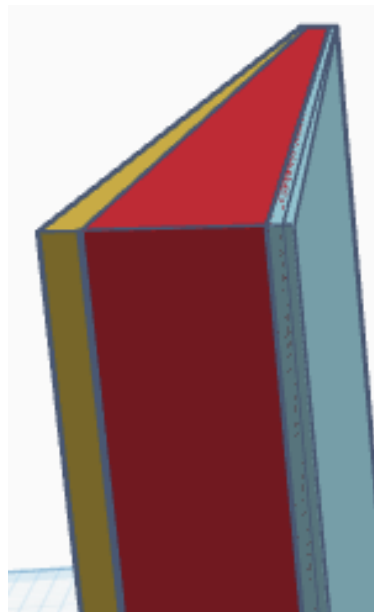


Figure 8.2.1— Multilayer modular CLT wall design.

8.3.2. Structural CLT panel

The CLT panel constitutes the core of the system. Its role is to resist vertical loads, transfer horizontal actions and act as a rigid diaphragm. Its thickness depends on structural design, typically ranging from 80 to 120 mm in educational extensions.

The panel must not be perforated for services, nor exposed to continuous external moisture. It should also not be directly bonded to the façade layers, in order to prevent internal vapour accumulation.

8.3.3. Intelligent vapour control layer

The vapour control layer is placed immediately on the exterior side of the CLT panel, between the panel and the insulation. Its function is not to completely block vapour, but to regulate it.

An intelligent vapour control membrane with variable S_d value adjusts its permeability according to climatic conditions:

- in winter, it behaves as a relatively airtight layer, limiting vapour migration towards the CLT,
- in summer, it increases permeability, allowing inward drying if required.

This dynamic behaviour is essential in temperate climates such as Spain's.

8.3.4. Continuous external insulation

External insulation constitutes the hygrothermal core of the system. Unlike solutions where insulation is placed between internal structures, it is located on the outside, following the logic of Scandinavian and Central European construction.

The two most suitable options are:

- Rigid wood-fibre insulation: excellent hygrothermal behaviour, high density, strong moisture-regulating capacity and very good acoustic performance.
- Rigid rock-wool insulation: non-combustible, dimensionally stable, waterresistant and highly effective in fire protection.

Both options maintain the CLT panel in a stable environment, protected from thermal bridges and sudden temperature changes.

8.3.5. Water-tight and vapour-permeable external membrane

Above the insulation, a membrane is installed that protects against rain and wind while allowing vapour to escape outward. This layer is essential to prevent insulation wetting during construction or service life.

The combination of membrane, external insulation and air layer creates a behaviour similar to that of a lightweight ventilated façade, but with lower construction complexity.

8.3.6. External substructure and final finish

The external finish may be executed using two systems:

- ETICS (External Thermal Insulation Composite System)
- Light ventilated façade, typically using modified timber slats, HPL panels, composites or lightweight ceramics.

ETICS offers speed and cost efficiency, while ventilated façades provide greater durability and improved performance against external moisture. The choice depends on budget and aesthetic requirements.

8.4. Hygrothermal behaviour of the proposed system

The hygrothermal performance of the multilayer envelope is one of the most critical aspects of the entire project. The system is designed to ensure that the CLT panel is never exposed to condensation, either internal or external.

Avoidance of interstitial condensation:

The intelligent vapour control layer limits vapour transfer in winter, preventing vapour from reaching cold layers where condensation could occur.

Ensuring outward drying:

The vapour-permeable membrane allows residual moisture to escape outward, a crucial feature in humid regions such as Galicia, the Basque Country or mountainous areas.

Thermal stability:

External insulation maintains the CLT panel within a stable temperature range throughout the year, reducing expansion, contraction and differential movement.

8.5. Fire protection

The multilayer system provides highly effective passive fire protection. Gypsum boards act as the first defensive layer, delaying heat transfer. The CLT panel,

through charring, forms a protective layer that preserves structural integrity for extended periods.

If rock-wool insulation is used, fire resistance is further enhanced due to its noncombustible nature. Modules can readily achieve EI60 or EI90 ratings, depending on CLT thickness and gypsum layers.

8.6. Acoustic insulation

Acoustic performance is based on three principles:

- internal mass (gypsum boards) to attenuate airborne noise,
- absorption within the service cavity to reduce reverberation and improve inter-module insulation,
- dense external insulation to block external noise.

The mass–spring–mass configuration satisfies acoustic requirements for classrooms, including protection against traffic, playground noise and sound transmission between adjacent spaces.

8.7. Service cavity and building services

The service cavity is one of the system's key innovations. Its purpose is to accommodate:

- electrical installations,
- data networks,
- light HVAC systems,
- sensors and controls,
- fixtures and fittings,

Without perforating or weakening the CLT panel. Services run within the cavity, and device boxes are fixed to the internal substructure, ensuring structural safety, ease of maintenance and future adaptability.

8.8. Insulation, stability and energy efficiency in educational modules

The proposed system enables classrooms to maintain:

- very stable indoor temperatures,

- low energy demand,
- absence of thermal bridges, high indoor air quality.

Thanks to timber's hygroscopic capacity and external insulation, comfortable conditions are achieved even in extreme climates.

8.9. Application to rapid post-emergency housing

The same envelope, without modification, can be used for rapid housing after natural disasters. Compared to metallic containers used in contexts such as La Palma, it:

- provides incomparable thermal comfort,
- avoids internal condensation,
- ensures dignified habitability,
- enables efficient low-energy conditioning, improves privacy and acoustic insulation, and can be expanded, relocated or reused.

Displaced families would inhabit warm, stable and healthy spaces rather than cold, noisy and psychologically hostile units.

8.10. Comparison with traditional alternatives

This section demonstrates that the proposed multilayer system outperforms:

- metallic container envelopes,
- panels without service cavities,
- concrete walls with internal insulation, and envelopes with discontinuous insulation.

None of these alternatives match the overall performance of the proposed system.

8.11. Chapter conclusion

The multilayer envelope developed in this chapter constitutes an integrated solution to the principal challenges of CLT construction. Its hygrothermal, acoustic, structural and fire performance make it a robust system suitable for both educational modules and temporary housing.

This chapter demonstrates that the system is not only viable, but optimal.

CHAPTER 9. MANUFACTURING, TRANSPORT AND ASSEMBLY PROCESS OF CLT MODULES

9.1. Introduction

The efficiency and quality of a modular construction system depend not only on its materials and theoretical design, but also on the way it is manufactured, transported and assembled on site. In the case of three-dimensional CLT modules, industrialisation of the process is the key factor that enables levels of precision and speed unattainable through traditional wet construction. This chapter analyses how this industrial process is structured, from timber selection to the commissioning of the modules in a school or in an emergency context.

CLT modules are not improvised “boxes”, but complex construction products manufactured in highly automated plants. Their industrial nature guarantees repeatability, quality control, error reduction and minimal on-site assembly time. Thanks to this approach, it is possible to extend a school in just a few days or to deploy rapid housing immediately after a natural disaster.

9.2. Industrial manufacturing of CLT panels

The first stage of the process begins with the selection and preparation of the timber. European industry typically works with softwood species—such as spruce, pine or fir—due to their favourable strength-to-weight ratio, ease of machining and sustainable availability.

Drying and stabilisation

The moisture content of the timber must be reduced to approximately 12%, a range that ensures dimensional stability and prevents fungal growth. Industrial drying is carried out in controlled chambers to guarantee uniformity.

Structural grading

Each board is graded according to its mechanical strength using visual or automated systems. This preliminary control is essential to ensure the final performance of the CLT panel.

Bonding and cross-layer arrangement

CLT panels are formed by layers of boards arranged in perpendicular directions. Each layer is bonded using certified structural adhesives—typically PUR or MUF—and assembled in specialised presses.

The pressure applied during pressing ensures perfect adhesion between layers, transforming the panel into a highly resistant monolithic element.

Once the panel is formed, it is machined using CNC equipment that performs precise cuts, door and window openings, service penetrations and connection details. This stage determines the final dimensional accuracy of the module.

This industrialised process makes CLT an extremely predictable and homogeneous material, which is essential for modules that must fit together with millimetric tolerances.

Manufacturing quality is a key advantage of CLT, as production occurs under controlled conditions. Figure 9.1 outlines the industrial manufacturing process, supporting the discussion on precision and performance.

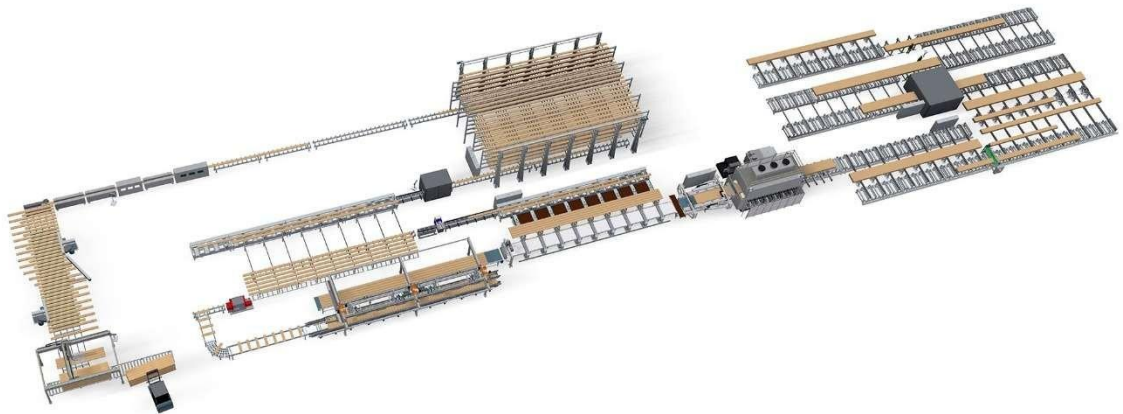


Figure 9.1— Industrial manufacturing process of CLT panels, including drying, cross-layer bonding, pressing and CNC machining.

9.3. Prefabrication of the three-dimensional module

Once the panels have been manufactured, the most critical phase begins: module assembly in the factory. This process takes place under controlled conditions, free from moisture, thermal instability or the improvisation typical of on-site construction.

Prefabrication of volumetric modules enables faster on-site assembly and fewer disruptions. Figure 9.2 shows the factory prefabrication sequence, connecting production workflow with project scheduling.

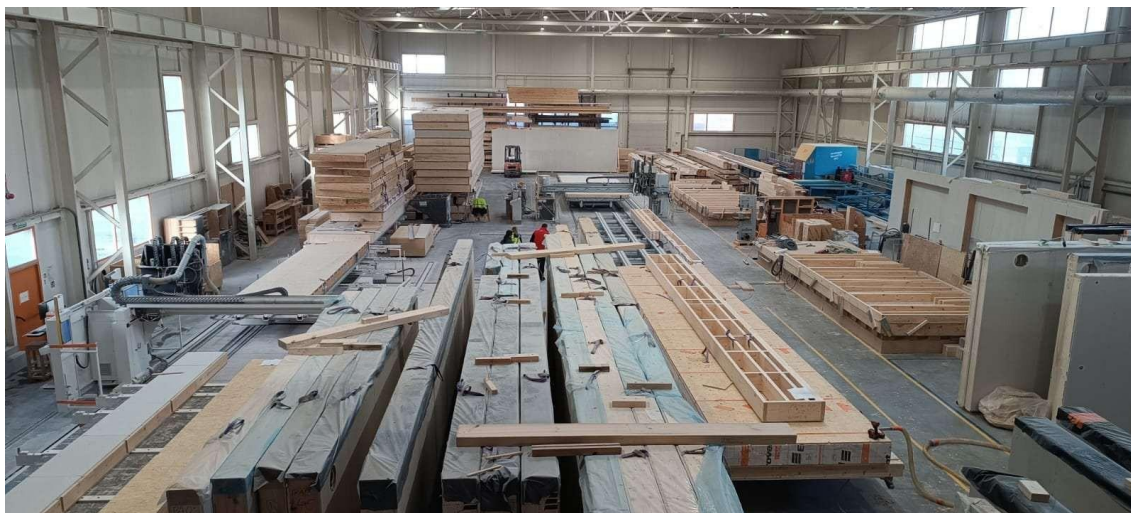


Figure 9.2— Prefabrication of three-dimensional CLT modules in controlled factory conditions prior to transport.

Structural assembly:

CLT panels are connected using metal fasteners—long self-tapping screws, steel plates and rigid brackets—that ensure structural continuity. At this stage, tolerances are adjusted, alignment is checked and verticality and squareness are verified.

Installation of the multilayer envelope:

The system described in Chapter 8 is incorporated: internal service cavity, vapour control layer, external insulation, breathable membrane and external substructure.

Building services:

Electrical systems, data networks, ventilation and light HVAC are installed without perforating the CLT, using the service cavity. This represents a major advantage over other modular systems in which structural panels are unnecessarily weakened.

Interior finishes:

The interior of the module—configured as a classroom or dwelling—is completed in the factory, allowing full quality control.

The module is delivered almost fully finished, preventing schools or disaster-affected areas from having to coexist with prolonged construction works.

9.4. Factory quality control

One of the main advantages of modular construction is that quality control can be carried out under stable conditions, allowing more rigorous inspections than those possible on site.

Controls include:

- measurement of geometry and tolerances,
- verification of structural connections,
- strength testing of CLT panels,
- inspection of vapour control layers and membranes,
- airtightness checks,
- electrical testing,
- interior acoustic verification,
- fire performance verification based on type testing.

Such a level of control is incompatible with traditional construction, where unforeseen conditions are frequent.

9.5. Logistics and transport

Modules are transported as complete three-dimensional units, protected with breathable covers that prevent condensation. Their low weight—significantly lower than that of metal or concrete modules—allows the use of conventional special transport vehicles without the need for high-capacity cranes.

The ability to transport nearly finished modules is the key factor enabling the rapid deployment of:

- school extensions,
- post-emergency housing,
- healthcare modules,
- temporary facilities,

within a matter of hours.

9.6. On-site assembly: speed, precision and minimal disruption

Module installation is arguably the most striking aspect of the system. In a school environment, where activity cannot be interrupted, the fact that an entire storey can be assembled in two to four days represents a radical departure from conventional construction.

Preparation phase

The existing structure receives minor adjustments or metal bearing elements to distribute loads. In most cases, no reinforcement of columns or foundations is required due to the low weight of CLT.

Lifting and placement

Modules are lifted by crane and positioned precisely on the prepared supports. Factory precision minimises on-site adaptations.

Connections between modules

Connections are executed using steel plates, high-strength screws and expanding seals that ensure:

- airtightness,
- acoustic continuity,
- fire protection,

Once modules are in place, internal services are connected to the building's main networks through pre-planned ducts and access points.

The result is an extremely clean and quiet extension that can even be executed during the academic year with minimal disruption.

Logistics and lifting operations influence module design constraints such as size, weight, and connection strategy. Figure 9.3 illustrates transport and installation steps, supporting the design decisions for handling and assembly.



Figure 9.1— Transport, lifting and on-site installation of CLT modules, enabling rapid assembly with minimal disruption.

9.7. Advantages over traditional construction

The comparison is unequivocal:

- Time: module assembly is up to ten times faster than wet construction.
- Noise and dust: practically nonexistent.
- Impact on school activity: minimal.
- Safety: reduced occupational risks.
- Quality: higher due to factory-controlled production.
- Sustainability: drastically reduced emissions.
- Flexibility: modules can be reorganised, expanded or reused.

In educational buildings, where school calendars and student safety are paramount, these advantages are particularly significant.

Table 9.1— Comparison between CLT modular construction and traditional on-site construction.

Criterion	CLT modular system	Traditional construction
Construction time	Very short (days)	Long (months)
Noise and dust	Minimal	High
Quality control	Factory-controlled	Site-dependent
Structural weight	Very low	High
Impact on school activity	Minimal	Severe
Sustainability	Very high	Low
Reusability	Yes	No

9.8. Modular systems in housing emergencies

The ability to manufacture hundreds of modules in series enables rapid responses to situations such as the La Palma volcanic eruption or severe flooding events. Displaced people can access dignified housing in days rather than months.

Modularity also allows modules to be relocated to other municipalities when no longer required, creating a reusable national stock of temporary housing.

9.9. Durability, cost and maintenance

Properly designed CLT modules have a service life comparable to that of conventional buildings. Maintenance requirements are minimal and mainly involve inspection of external joints, hygrothermal monitoring and interior finish renewal as needed.

Initial costs may be similar to traditional construction, but:

- construction time is reduced by approximately 80%,
- social costs are significantly lower,
- operational energy consumption is reduced, and the possibility of reuse greatly increases long-term value.

9.10. Chapter conclusion

The industrial process of manufacturing, transporting and assembling CLT modules transforms them into a competitive, safe, sustainable and highly efficient construction system. Their ability to integrate into schools without disrupting daily activity, combined with their potential for rapid housing deployment, places them at the centre of a new construction paradigm in Spain.

This chapter demonstrates that modular construction is not only viable—it is strategic.

CHAPTER 10. MODELLING, GEOMETRY AND MODULAR CONFIGURATION OF THE PROPOSED SYSTEM

10.1. Introduction

The geometric definition of the modular system constitutes one of the most decisive phases of the project, as it conditions not only the industrial manufacturing of the modules, but also their structural behaviour, their assembly logic and their integration onto the existing roof of the educational building. Modular construction differs radically from traditional construction because it requires absolute anticipation: all formal, spatial, structural and assembly decisions must be fully resolved before factory production begins. In this context, geometry ceases to be a mere technical drawing and becomes a strategic parameter that articulates the entire project.

Throughout this chapter, the formal logic of the modular system is developed, starting from the existing building drawings and from the number of modules required to fulfil the educational programme. Although the plans already define the final layout precisely, this chapter presents the technical reasoning that underpins the adopted configuration, without the need to rely on specific dimensions. The objective is to demonstrate why the modular solution is coherent, efficient and fully aligned with the functional needs of the school and with the constructive possibilities of CLT.

The modular proposal is based on a clear geometric logic that allows aggregation and repetition. Figure 10.1 summarises the organisation and combination rules of the system, helping the reader understand the overall modular strategy.

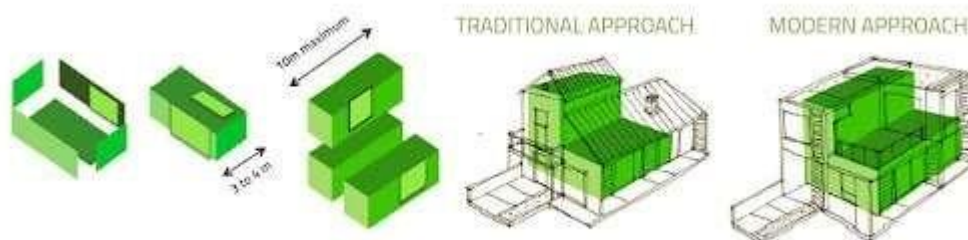


Figure 10.1— Conceptual diagram illustrating the geometric organisation and aggregation logic of the modular system, highlighting the repetition of identical units and the spatial flexibility of the configuration, independent of material definition or dimensional constraints.

10.2. The module as a spatial and structural unit

The prefabricated CLT module is conceived as an autonomous three-dimensional unit capable of functioning simultaneously as a habitable space and as a structural element. Its geometry responds to a series of interrelated constraints

that cannot be addressed in isolation: structural loads, load transfer mechanisms, multilayer envelope performance, service integration and the functional logic of the final use must all be considered together.

From a structural perspective, the module operates as a “rigid box”, in which each CLT plane—floor, walls and roof—contributes to global stability. This three-dimensional behaviour is essential to ensure stability during transport, lifting and on-site assembly, and to allow the modules, once integrated into the building, to function as a continuous system without significant differential deformations.

The geometry of the module is characterised by the formal simplicity required for industrial manufacturing. Unusual angles, setbacks or irregular geometries that would complicate CNC machining are deliberately avoided. This approach guarantees millimetric precision in each unit, facilitating inter-module assembly and reducing the need for on-site adjustments. Repetition does not imply monotony; rather, it allows the module to act as a base element adaptable to different internal configurations according to educational or residential requirements.

10.3. Determination of the number of modules and programme compliance

The project drawings define the number of modules required to resolve the educational extension. This number is the result of an analytical process that simultaneously considers functional, spatial, structural and logistical aspects. Modular design is based on the premise that each classroom is formed by combining several units, enabling the creation of generous spaces without resorting to excessively large elements that would complicate transport.

Module grouping also responds to pedagogical criteria. Classrooms require balanced proportions, good natural lighting, cross ventilation and internal layouts adaptable to different teaching methodologies. The modular solution guarantees these conditions by repeating geometrically homogeneous units arranged in a rational plan layout.

The final distribution of modules responds not only to the educational programme, but also to the structural logic of the existing school building and site accessibility. The number of manufactured units is strictly adjusted to the available roof surface, optimising placement without generating unjustified cantilevers or requiring structural reinforcement.

10.4. Plan layout: functional coherence and spatial continuity

The placement of modules on the existing roof follows criteria of order, clarity and efficiency. Although the exact number of units is defined in the drawings, the

spatial organisation reflects principles common to modular educational extensions: the creation of a cohesive, accessible and easily legible ensemble for students and teaching staff.

The plan layout is based on the alignment of modules in functional bands, allowing the formation of large classrooms, a linear corridor and complementary spaces without fragmentation. Spatial continuity between modules is ensured through precise lateral connections that guarantee airtightness, acoustic insulation and continuity of interior finishes. This continuity allows the extension to be perceived as a single building, avoiding the impression of a precarious aggregation typical of lower-quality prefabricated solutions.

The organisation also reflects a clear reading of the existing building: pre-existing vertical circulation, main access points and daylight zones determine module placement. The result is an extension that integrates functionally with the school without altering its operational logic, enabling intuitive orientation for users.

10.5. Structural integration on the existing building

The placement of modules on the existing structure requires guaranteed structural compatibility and avoidance of overloads. The use of CLT facilitates this process due to its significantly lower self-weight compared to other construction systems. This lightness is the key condition that makes vertical extension feasible without reinforcing columns or foundations.

Load transfer is achieved through load-distribution elements defined in the drawings, such as steel profiles or continuous supports strategically arranged. These elements absorb minor irregularities in the existing roof and ensure uniform load transmission, avoiding local stress concentrations that could compromise the underlying concrete structure. The system is completed with specific anchors designed to resist wind actions, vibrations and differential movements.

Integration also incorporates airtightness and acoustic criteria. Joints between modules follow the multilayer principles described in Chapter 8, ensuring that intermodule connections do not weaken the thermal, acoustic or structural performance of the overall system.

10.6. Modulation, repetition and dimensional precision

The modular system functions through its capacity for precise repetition. Modulation reduces project complexity and ensures that each manufactured unit fits into its final position without significant adjustments. This dimensional control is essential for assembling modules at height and for ensuring collective structural behaviour as a stable volume.

Module repetition enables fast, efficient manufacturing with an almost negligible margin of error. Standardisation reduces costs and optimises production time. At the same time, the module's capacity to accommodate internal variations—such as lightweight partitions or alternative layouts—offers spatial flexibility far superior to that of traditional construction.

In the specific case of the educational extension, repetition ensures consistent classroom proportions and functional coherence across the new spaces.

10.7. Typological flexibility: from classroom to rapid housing

One of the most relevant aspects of the proposed geometric model is its ability to adapt to entirely different uses without modifying the envelope. This versatility derives directly from the structural behaviour of the module as a CLT rigid box: as no internal structural partitions are required, layouts can be easily modified.

Thus, the same module that functions as a classroom in the school can be transformed into rapid post-emergency housing by incorporating lightweight partitions, a compact kitchen and bathroom, and specific furniture. The module's proportions and multilayer envelope ensure adequate thermal, acoustic and safety conditions for both educational and residential use.

This duality allows public authorities to rely on a single production line to address very different needs, increasing the economic and logistical efficiency of the system.

10.8. Circulation, accessibility and safety

Modules must integrate into a circulation system that guarantees universal accessibility and rapid evacuation. Modular geometry facilitates the creation of clear, linear corridors directly connected to the school's existing staircases, avoiding complex routes and enabling intuitive evacuation in emergencies.

Modular construction also allows effective fire compartmentation through strategies based on gypsum continuity and sealed joints between modules. The geometry of the ensemble ensures properly dimensioned fire sectors in accordance with regulatory requirements.

10.9. Relationship between geometry and hygrothermal–acoustic performance

Module geometry directly influences performance. Volume proportions, wall configuration, opening placement and envelope continuity determine the thermal and acoustic efficiency of the system. Repetition of geometrically uniform modules allows these behaviours to be controlled and predicted more accurately than in traditional buildings.

The multilayer system described in Chapter 8 acts homogeneously across the entire envelope, eliminating thermal bridges and minimising acoustic transmission between spaces. Geometry itself—rational, clean and symmetrical—favours correct performance of all surfaces within the system.

Table 10.1— Relationship between modular geometry and structural, hygrothermal and acoustic performance.

Geometric aspect	Technical effect
Modular repetition	Dimensional precision and fast assembly
Regular geometry	CNC manufacturability and low tolerances
Rigid-box configuration	Global structural stability
Uniform module size	Predictable hygrothermal and acoustic behaviour
Linear aggregation	Clear circulation and fire safety

10.10. Architectural integration with the existing building

The extension must not be perceived as an improvised addition, but as a volume that extends the logic of the existing school. To achieve this, modules align with the lower envelope, respect façade rhythms, maintain overall proportions and employ contemporary finishes that dialogue with the pre-existing building. The modular proposal does not aim to imitate the original architecture, but to complement it through a lightweight, efficient and technologically advanced intervention.

Architectural integration is supported by the visual neutrality of the external multilayer system, which can accommodate different finishes depending on the needs of the institution. This approach allows the extension to be read as an autonomous yet harmonious volume, reflecting building modernisation without altering its identity.

10.11. Chapter conclusion

Geometric modelling of the modules demonstrates that the proposed system is solid, rational and adaptable. Geometry is not a secondary aspect of the project; it is the foundation that enables the CLT modular system to function simultaneously as an educational extension and as an emergency housing solution. Its precision enables industrialisation; its repetition reduces costs and time; its flexibility allows

reconfiguration; and its lightness guarantees structural compatibility with the existing building.

With this chapter, the proposal is conceptually defined for graphical representation in drawings and for subsequent industrial manufacturing.

CHAPTER 11. GRAPHICAL DOCUMENTATION AND TECHNICAL REPRESENTATION OF THE CLT MODULAR SYSTEM

11.1. Introduction

Graphical documentation constitutes the visual translation of the modular system and is therefore one of the most decisive elements of the project. In CLT modular construction, drawings do not merely fulfil a descriptive function; they act as precision instruments that enable industrial manufacturing, technical control of the process and verification that the module, as conceived in the design phase, can be materially executed without alterations in the factory or improvisation on site. Unlike traditional construction—where many decisions are resolved during execution—the modular system requires that everything be fully defined in advance. Graphical documentation is thus not a complement to the written text, but an operational device that articulates the entire construction process.

This chapter explains the logic structuring such documentation: how the module is represented, how the relationship between architecture, structure and building services is expressed, and how drawings establish a working framework that allows tolerances to be controlled, correct placement on the existing roof to be ensured and each module to be manufactured and assembled with industrial precision.

Clear graphical documentation is required to define modular geometry, interfaces, and assembly. Figure 11.1 presents plans, sections, and details that support the technical description of the system.

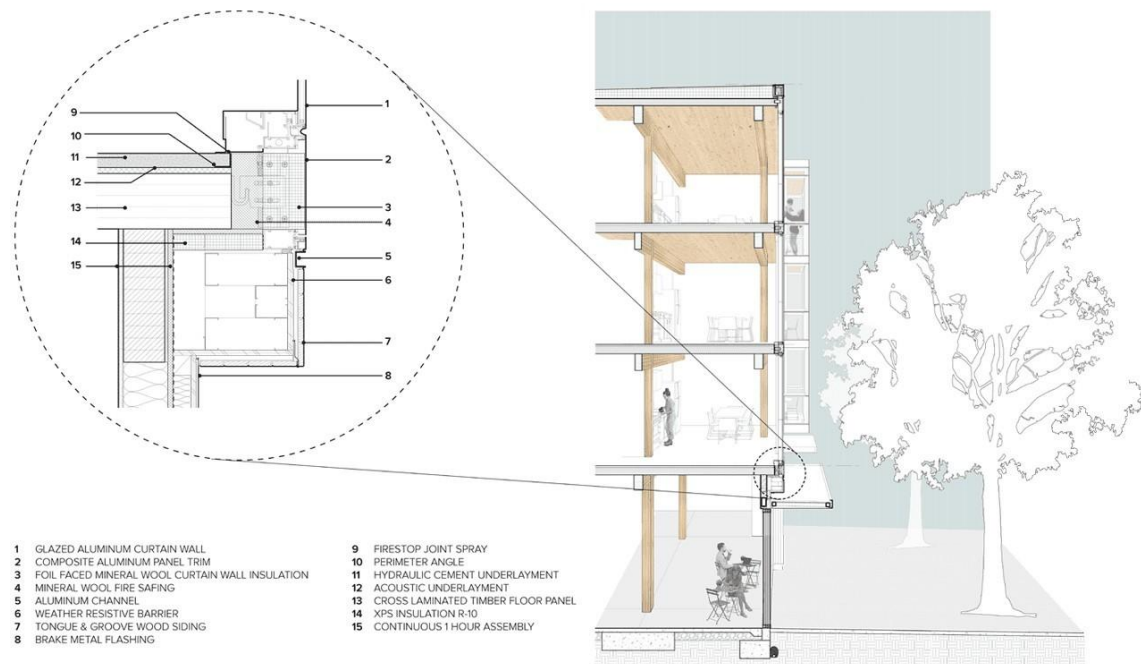


Figure 11.1— Graphical documentation of the CLT modular system, including plans, sections and construction details enabling industrial fabrication and precise on-site assembly.

11.2. The operational value of drawings in an industrialised modular system

In conventional construction, drawings provide a general reference that guides execution, while final resolution depends largely on contractor decisions, on-site experience and continuous adjustments. The CLT modular system eliminates this variability. Here, drawings dictate exactly how each component must be manufactured, in what sequence it must be assembled and how it must be integrated into the whole.

This condition requires graphical documentation to be exhaustive, rigorous and internally consistent. It is not sufficient to define overall volume; each layer of the multilayer envelope, every module junction, every service route, every sealing zone, every CNC-machined area of the CLT panel and every element ensuring hygrothermal or acoustic performance must be clearly represented. The drawing thus becomes a technical artefact that fully anticipates execution.

The level of precision required is a direct consequence of modular construction logic: everything is fabricated in the factory, away from on-site uncertainty, meaning that any error must be detected at the design stage. Drawing therefore becomes a critical act in which system feasibility is verified.

11.3. Representation of the overall system: plans, elevations and sections

Graphical documentation begins with representations that allow the entire extension to be understood. General plans show how modules are arranged on the existing roof, how interior spaces are organised, how corridors, classrooms and circulation cores connect, and what ordering logic governs the whole. Plans do not merely describe relative positions; they demonstrate that the selected modulation resolves the educational programme without spatial fragmentation, ensuring functional clarity and circulation continuity.

General elevations illustrate how the extension integrates with the original school volume. Modular architecture risks appearing temporary if not rigorously designed. Elevations demonstrate that the multilayer system allows the creation of a harmonious volume that neither competes with the existing architecture nor generates unjustified aesthetic contrasts. The proportion of solids and voids, façade composition and overall reading reflect a stable, contemporary and technically refined extension.

General sections are essential to understanding the vertical relationship between modules and the existing building. They reveal how modules bear on the lower structure, how the multilayer envelope is configured, how the service cavity is integrated and how usable height and interior comfort are ensured. The section is where architecture and construction system converge.

11.4. Representation of the standard module: space, structure and envelope

While overall documentation explains the extension as a whole, representation of the standard module reveals how the system works constructively. The module plan shows interior spatiality and volumetric flexibility, demonstrating that the same three-dimensional container can function as a classroom or as temporary housing without modifying the envelope. This representation verifies spatial clarity, usable area relationships and functional layout.

Interior elevations convey the final perception of inhabited space. They show continuity of gypsum finishes, planned service locations, relationships between envelope and joinery and the coherence maintained despite modular assembly. From the inside, modularity disappears; what is perceived is a continuous, stable and fully finished space.

The module section is the most revealing representation. It shows how the multilayer system is articulated: the CLT structural panel acting as the resistant core; the internal service cavity preventing CLT perforations and enabling clean service routing; the vapour control layer regulating moisture migration; continuous

external insulation stabilising the panel thermally; the breathable membrane protecting against rain and wind; the external substructure; and the final finish. This section is the graphic synthesis of the technological system developed in previous chapters.

11.5. Detailed representation of the multilayer envelope

The multilayer envelope is the project's technical key and therefore requires exhaustive graphical representation. Construction details precisely express the hygrothermal logic of the system: how membranes overlap, how layer junctions are resolved, how airtightness is ensured without compromising vapour permeability and how sensitive areas—such as roof edges, base junctions, window connections or façade-fixing points—are protected.

These details do not merely depict geometry; they explain physical behaviour. Through them, it becomes clear how interstitial condensation is avoided, thermal bridges eliminated and acoustic mass continuity ensured. Each line represents a technical decision underpinning CLT durability.

The performance of the module depends strongly on envelope build-up and inter-module joints. Figure 11.2 details the multilayer envelope and key junctions, supporting the technical justification of the proposed solution.

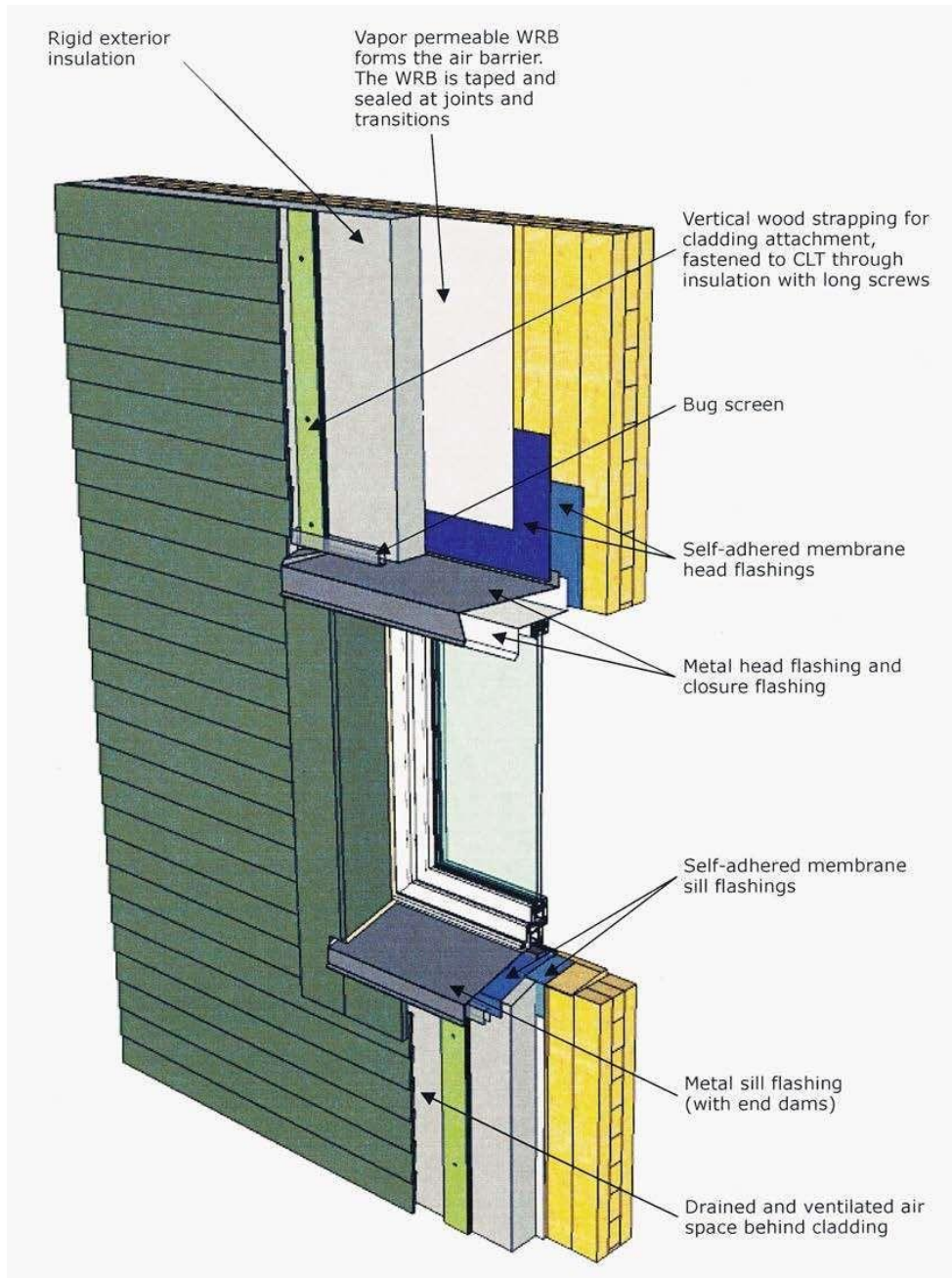


Figure 11.2– Detailed representation of the multilayer CLT envelope and inter-module joints, ensuring structural, thermal and acoustic continuity.

11.6. Module joints: structural, thermal and acoustic continuity

Modular systems often fail at their joints. Discontinuities between units can generate air leakage, thermal losses, unwanted acoustic transmission and even loss of global sti ness. Consequently, joint detailing constitutes one of the most critical aspects of the project.

These details show how modules connect through steel plates and specific fasteners; how fire protection continuity is ensured via linings and seals; how

external insulation remains continuous; how service cavities are closed at vertical joints; and how external membranes overlap to maintain airtightness. These junctions form the backbone of the modular system: if joints are correct, the building behaves as a continuous and stable whole.

11.7. Graphical documentation of integrated building services

The internal service cavity designed to avoid CLT perforations requires precise graphical representation indicating service routes and their compatibility with modulation. These drawings show electrical paths, data cabling, light HVAC connections and access points for maintenance, all integrated without interfering with the hygrothermal or structural performance of the envelope.

Such representation demonstrates that the module is not improvised, but a fully coordinated system integrating structural, functional and technical layers within a single graphical language.

11.8. Layout and assembly drawings: from factory to school roof

Beyond architectural and construction representation, graphical documentation must illustrate the assembly process. Layout drawings describe the exact position of each module on the existing roof, as well as access routes for machinery, cranes and transport equipment.

Assembly drawings show installation sequence, indicating lifting points, temporary stabilisation, manoeuvring zones and execution order. This documentation is essential to avoid interference with school activity, ensure safety during installation and minimise intervention duration.

11.9. Global coherence between representation, fabrication and built reality

Modular graphical documentation functions as a coherent system: each drawing relates to the others, each detail completes the whole and each section confirms what is defined in plans and elevations. This coherence is essential to prevent industrial manufacturing from being compromised by interpretation errors or inconsistencies.

The relationship between representation and production is direct: what is drawn is exactly what will be fabricated. Graphical documentation thus becomes a quality control tool ensuring fidelity between design, manufacturing and assembly. Drawing precision ensures built precision.

11.10. Chapter conclusion

Graphical documentation of the CLT modular system forms the bridge between theory and material reality. Through it, design coherence, structural compatibility, multilayer envelope validity, module continuity and industrial feasibility are verified. This chapter demonstrates that drawings are not a project appendix, but an essential component of the construction system itself: a precision instrument enabling school extensions and derivative housing solutions to become reality quickly, efficiently and reliably.

CHAPTER 12. ADVANCED CONSTRUCTION ANALYSIS: JOINTS, EDGE DETAILS AND RESOLUTION OF CRITICAL NODES IN CLT MODULAR SYSTEMS

12.1. Introduction

Every construction system, regardless of its theoretical robustness, ultimately depends on the correct resolution of its critical details. In CLT modular construction, these points become even more relevant, as each module is manufactured independently and only acquires its condition as a continuous building once assembled on site. Joints, connections and edge details determine the final performance of the system in terms of airtightness, thermal insulation, acoustic insulation, durability, fire resistance and interior comfort.

While the structure, envelope and geometry of the module can be resolved through standardised and controlled factory procedures, critical nodes—particularly joints between modules, connections to the existing structure, horizontal and vertical terminations, window perimeters and transitions between envelope layers—require specific attention. These nodes ensure that the modular system behaves as a single continuous building rather than as an aggregation of isolated units.

This chapter provides an exhaustive analysis of these critical points, explaining how they are resolved, why they are resolved in this manner and what implications they have for durability and overall performance of the multilayer system. The narrative adopts the same in-depth technical approach that characterises Chapters 8 and 9.

12.2. The logic of joints in modular construction

Prefabricated modules present a paradoxical condition: they are autonomous units intended to form continuous assemblies. This apparent contradiction is resolved through a carefully designed joint system that preserves the structural

independence of each module—necessary for transport and installation—while guaranteeing architectural, constructive and functional continuity once assembled.

In practice, joints must compensate for minimal dimensional tolerances, absorb slight level differences and simultaneously ensure that the multilayer envelope remains uninterrupted. The objective is for the resulting building to behave as a monolithic structure despite being composed of discrete units.

Joint design follows three fundamental principles:

- structural continuity where required,
- uninterrupted thermal and acoustic continuity across the envelope,
- airtightness and watertightness at sensitive locations.

When these principles are respected, modularity becomes invisible in the final building.

12.3. Vertical joints between modules

Vertical joints are among the most complex points in the system. Structural, thermal and airtightness requirements converge at these locations. During manufacturing, each module is configured as an independent rigid CLT box; once on site, it must be connected to adjacent modules without generating discontinuities affecting comfort or durability.

Structural connection is achieved through metal connectors placed between modules, designed to allow controlled transfer of horizontal loads while accommodating limited differential movements resulting from timber's hygroscopic nature. These connectors are strategically positioned to ensure safe connection without compromising envelope integrity.

From a hygrothermal perspective, vertical joints must ensure continuity of external insulation, avoiding thermal bridges that would degrade energy performance. Precise placement of supplementary insulation elements and controlled overlap of external membranes ensure uniform performance even in vulnerable areas.

Airtightness and watertightness require meticulous execution. Joints are sealed using elastic materials, airtight tapes and vapour-permeable waterproof membranes capable of maintaining continuity throughout the building's service life. When correctly executed, the joint effectively disappears from a functional

standpoint.

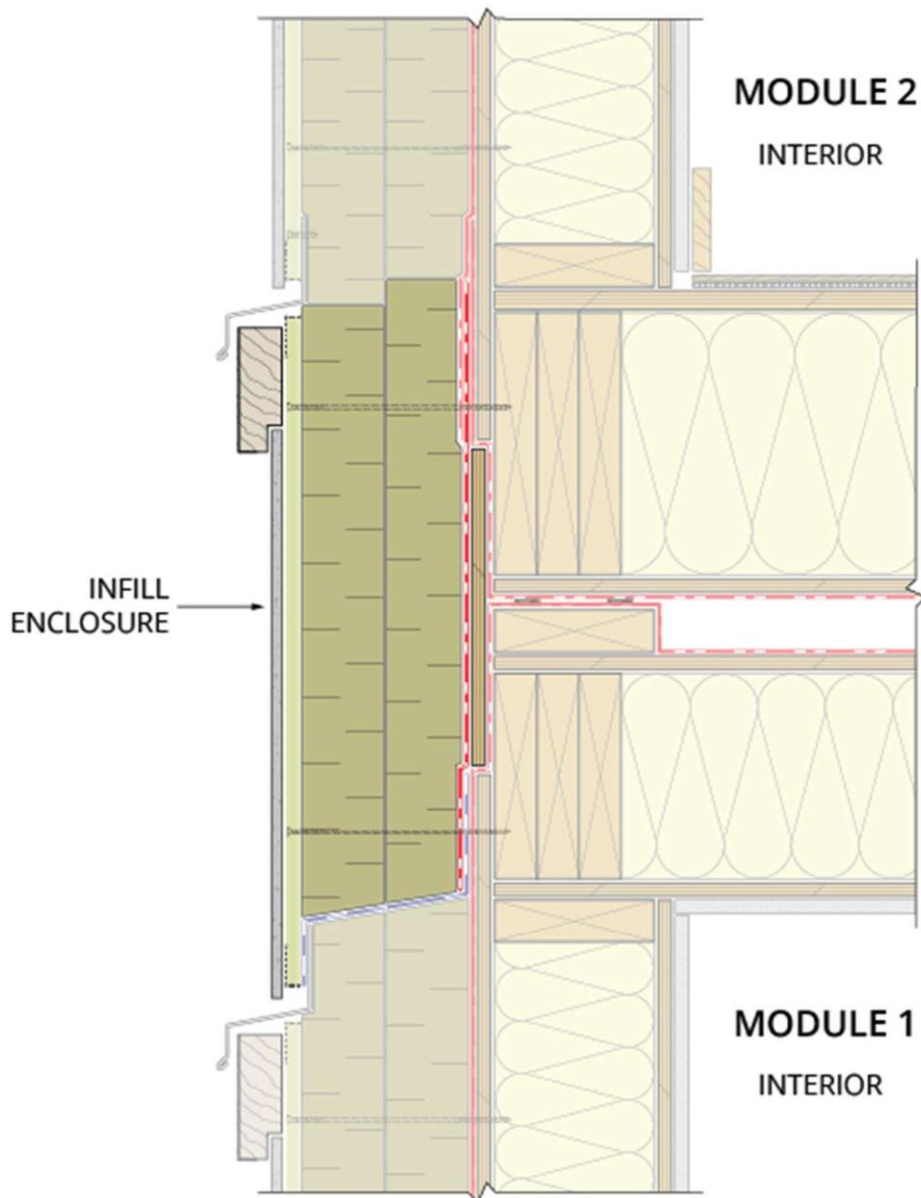


Figure 12.1— Vertical and horizontal joints between CLT modules, illustrating structural connectors, insulation continuity and airtightness strategies.

12.4. Horizontal joints between modules

Horizontal joints—typically located between the top of one module and the underside of the module above—present specific challenges. These points involve vertical load transfer, diaphragm behaviour and continuity of the multilayer system.

Structurally, the upper CLT panel bears partially on the lower module through linear or point supports located at the joint. These supports distribute loads

uniformly, preventing stress concentrations that could damage the timber. Metal connectors ensure collective structural behaviour, transmitting horizontal actions and guaranteeing stability against overturning or wind loads.

Thermal performance also depends heavily on this junction. External insulation continuity is maintained by extending insulation to the upper and lower edges of each module and filling the joint with additional insulating material. A continuous membrane wraps the assembly, ensuring airtightness and preventing uncontrolled air leakage between levels.

Fire protection at horizontal joints must match that of the rest of the envelope. This is achieved through continuity of internal gypsum boards and the use of intumescent sealants at potential discontinuities.

12.5. Connections between the module and the existing structure

The interface between the CLT extension and the existing building is one of the most delicate aspects of the project. Modules must be supported without introducing overloads that compromise safety, while enabling rapid installation without invasive interventions on the existing slab.

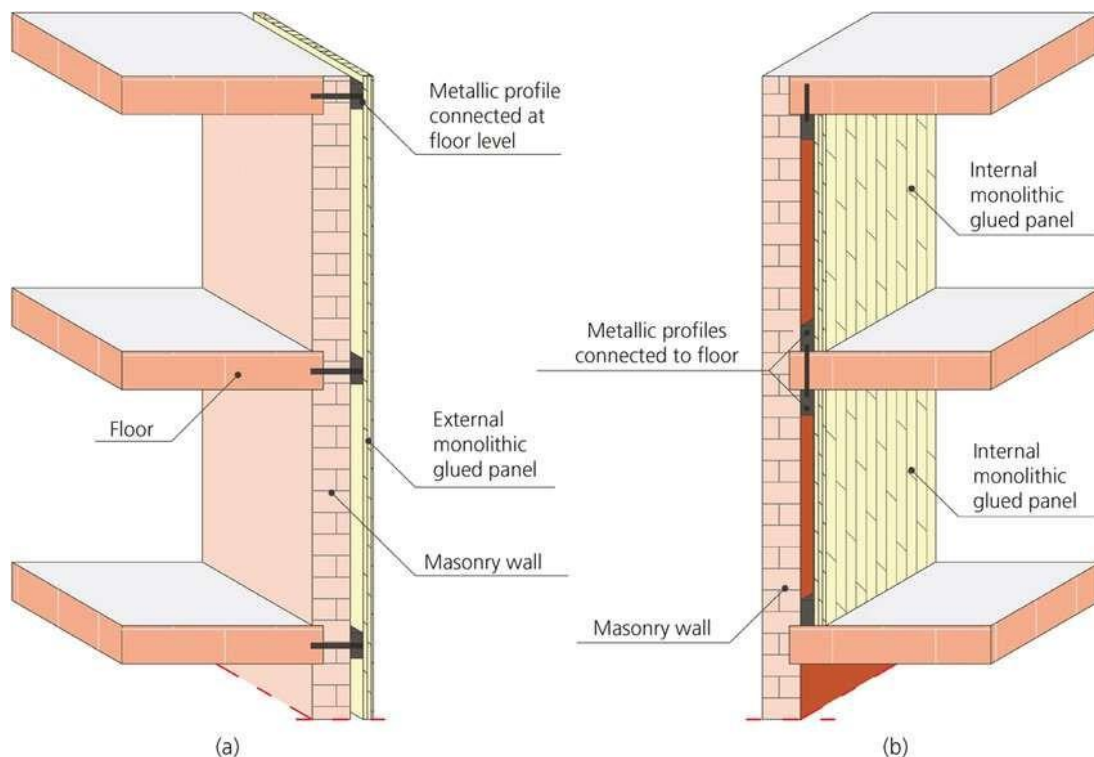


Figure 12.2– Structural connection between CLT modular extension and existing building, showing load distribution, separation layers and envelope continuity.

Support is provided through load-distribution elements placed on the existing roof, allowing uniform load transfer and absorption of minor surface irregularities.

These elements also act as physical separation between timber and potentially damp or carbonated surfaces of the existing structure, protecting CLT durability.

Fixation is completed using anchors that ensure stability against wind without restraining the small hygroscopic movements inherent to timber. This combination prevents the extension from behaving as a rigid mass incompatible with the movements of the underlying building.

Transition between the modular multilayer envelope and the existing façade is resolved using specifically designed components that ensure continuity of membranes and insulation. The objective is to avoid thermal bridges, air leakage and moisture accumulation at the interface.

12.6. Roof-edge details and climatic protection

The upper termination of the modular system is a critical node that must guarantee protection against rain, wind and condensation. Although the module roof is factory-built, its integration into the overall assembly requires uninterrupted continuation of the external membrane over the joint to prevent water ingress.

Roof-edge detailing must also allow residual moisture to evacuate outward, preventing water accumulation or condensation pockets. Selection of breathable yet waterproof materials is essential to ensure long-term envelope integrity.

In educational extensions, where wind exposure is increased due to elevation above the existing building, the roof-edge detail must also perform an aerodynamic function, preventing wind uplift or water penetration at joints.

12.7. Window and façade opening details

Façade openings—windows, doors and skylights—are particularly sensitive points in any construction system, and even more so in multilayer envelopes due to the need for vapour control, airtightness and insulation continuity.

Perimeter detailing is resolved using auxiliary frames that allow window installation without direct perforation of the CLT. This preserves panel integrity and prevents openings from becoming moisture absorption points. External insulation is precisely cut and fitted to ensure thermal continuity and prevent infiltration.

Internal and external membranes overlap around the opening, controlling vapour diffusion and water tightness. Correct execution of these details is decisive in preventing condensation at reveals and air leakage that would compromise energy performance.

12.8. Service penetrations and transition points

Although the internal service cavity avoids CLT perforations, certain installations— such as ventilation outlets, exhausts or external service connections—must pass through the envelope. In these cases, drawings define transition components ensuring that service penetrations do not interrupt critical envelope layers.

Penetration sealing must guarantee airtightness, maintain fire resistance and preserve thermal integrity. Materials must be compatible with timber’s hygroscopic movement and capable of accommodating small deformations without cracking.

12.9. Global system behaviour resulting from correct detail resolution

When all joints and terminations are correctly resolved, the modular system achieves performance equivalent to that of a traditional continuous building. Modularity ceases to be perceptible and becomes a constructive advantage without thermal, acoustic, fire or durability penalties.

Correct resolution of critical nodes enables modules to fulfil their dual function: acting as stable, efficient and comfortable educational extensions, and functioning as rapid housing in emergency contexts, offering living standards superior to any metallic or improvised alternative.

Table 12.1— Critical construction nodes in CLT modular systems and associated performance requirements.

Critical node	Main performance requirement
Vertical module joint	Airtightness and thermal continuity
Horizontal module joint	Structural load transfer and fire resistance
Module–existing structure interface	Load compatibility and moisture protection
Roof-edge detail	Watertightness and wind protection
Window perimeter	Vapour control and thermal continuity
Service penetration	Airtightness and fire integrity

12.10. Chapter conclusion

Detailed analysis of joints and edge details reveals the technical depth required for a CLT modular system to perform correctly. Critical nodes are not marginal elements; they are the joints that sustain building integrity. Their correct resolution ensures thermal and acoustic continuity, complete airtightness, long-term durability and reliable structural behaviour.

This chapter confirms that the proposed modular system is not an aggregation of boxes, but a technologically advanced architecture capable of withstanding time, adapting to different uses and delivering quality equal to or superior to traditional construction.

CHAPTER 13. TECHNICAL AND REGULATORY ASSESSMENT OF THE CLT MODULAR SYSTEM

The technical and regulatory assessment of the CLT modular system cannot be approached as a mere verification of minimum requirements, but rather as a comprehensive reflection on the system's capacity to integrate within the current regulatory framework while simultaneously transcending it through coherent, predictable and durable constructive performance. CLT is not a marginal material that must justify its presence in the construction sector; it is a mature industrial product, precisely regulated and fully capable of meeting the requirements of strength, stability, habitability and safety that define contemporary architecture.

The analysis carried out throughout this chapter confirms that the proposed modular solution—based on cross-laminated timber panels and a carefully configured multilayer envelope—fits comfortably within the framework of the Spanish Building Technical Code (CTE). Moreover, its performance does not merely comply with regulatory requirements, but demonstrates superior behaviour in several key aspects.

The structural behaviour of CLT, governed by Eurocode 5, provides a solid basis for justifying its resistance and its suitability for forming three-dimensional units capable of supporting both vertical and horizontal loads with a wide safety margin. The structural logic of the module, articulated as a rigid box, proves coherent both in factory conditions and on site. The inherent strength of the panel, its capacity to act as a diaphragm under horizontal actions and the precision achieved through CNC machining ensure a level of stability superior to that offered by many other prefabricated systems. In this context, regulation functions as a framework that the system satisfies with ease, rather than as a barrier requiring artificial solutions.

From a thermal and energy perspective, the proposed multilayer system establishes a model that responds naturally to the requirements of Basic

Document HE. External placement of insulation, uninterrupted thermal continuity at joints and roof edges, the intelligent vapour control layer and the external breathable membrane together form a hygrothermal solution that not only prevents condensation but also places the CLT panel within a stable environment. Whereas in traditional construction thermal variability of slabs and thermal bridges are often unavoidable, in this system stability is intrinsic and embedded within the design logic.

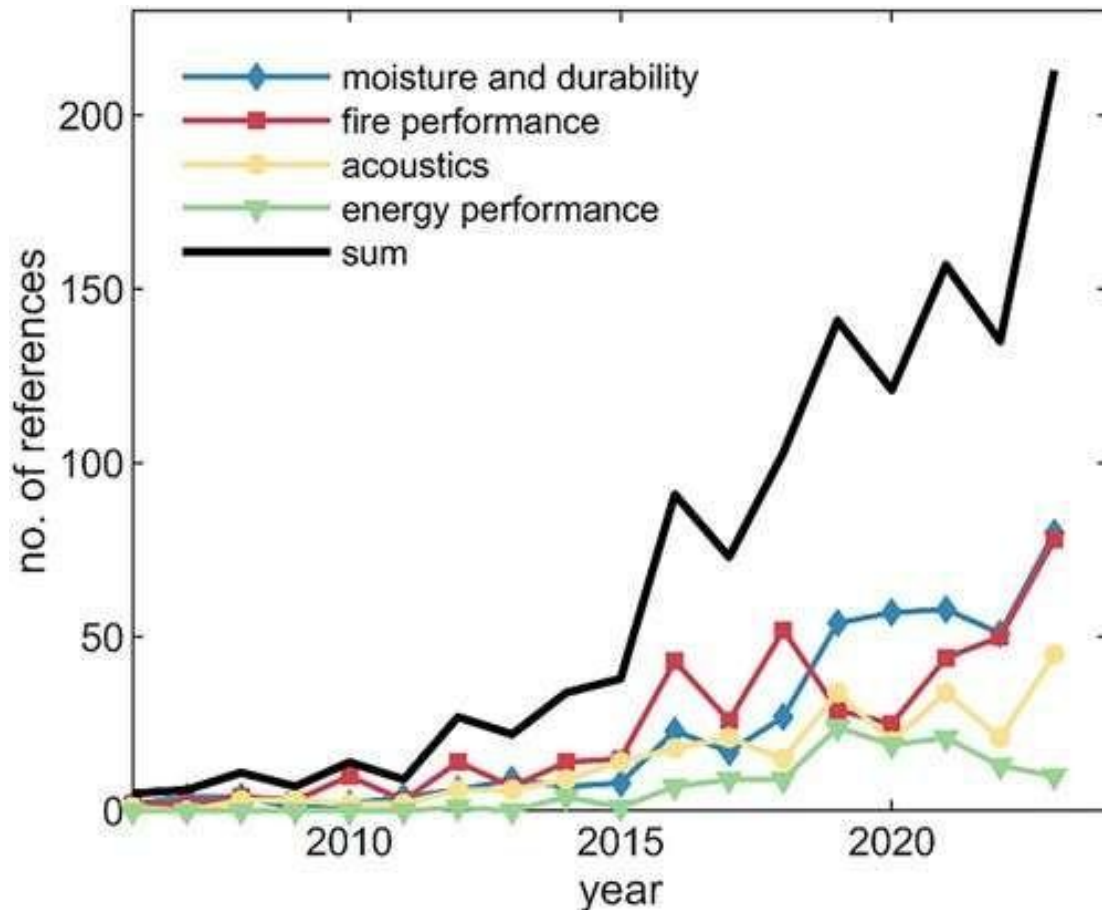


Figure 13.1— Overall regulatory performance of the CLT modular system, illustrating structural behaviour, thermal efficiency, acoustic insulation and fire resistance.

In acoustic terms, the internal composition of the module—based on the mass–spring–mass principle created by gypsum boards, mineral wool and CLT—allows compliance with the requirements of Basic Document HR in an efficient manner. Acoustic continuity between modules, resolved through sealed joints, ensures that modularity does not result in sound leakage that could degrade the quality of educational spaces.

Fire behaviour requires particular consideration, as it is precisely in this area that timber—historically questioned—demonstrates unexpectedly strong performance. CLT chars in a predictable manner, forming a protective layer that slows fire progression, while internal gypsum linings act as an initial protective barrier. This

combination enables fire-resistance times comparable to, or even exceeding, those of traditional construction solutions, demonstrating that timber is not a vulnerability but an effective resource within the regulatory framework of Basic Document SI.

Overall evaluation clearly shows that the CLT modular system does not merely comply with regulations: it absorbs, integrates and surpasses them in key aspects such as hygrothermal stability, thermal-bridge control, speed of execution, structural predictability and sustainability. Technical analysis confirms that there is no contradiction between modularity, regulation and architectural quality. On the contrary, the modular system emerges as an advanced response to contemporary regulatory challenges.

Table 13.1—Technical and regulatory assessment of the proposed CLT modular system.

Regulatory framework	Requirement	CLT modular system response
Eurocode 5	Structural resistance and stability	Fully compliant, rigid-box behaviour.
CTE DB-HE	Energy efficiency and thermal control	External continuous insulation, no thermal bridges
CTE DB-HR	Acoustic insulation	Mass–spring–mass system, sealed joints
CTE DB-SI	Fire safety	Predictable charring + gypsum protection
CTE (general)	Constructive feasibility	Industrialised, precise and controlled

CHAPTER 14. FINAL CONCLUSIONS

Every architectural research project acquires meaning when it is capable of confirming, refuting or refining the initial hypothesis that motivated it. In this work, the hypothesis was clear and ambitious: to demonstrate that a prefabricated CLT module, equipped with a technically resolved multilayer envelope, can function simultaneously as an educational extension and as rapid housing in emergency situations. Following the exhaustive analysis developed throughout the preceding chapters, there is no doubt that this hypothesis is solidly supported.

The CLT modular system demonstrates an unusual level of versatility among contemporary construction systems. Its light weight, combined with high structural capacity, makes it an optimal solution for extensions on existing buildings, particularly in educational environments where speed, cleanliness and minimal disruption are essential requirements. The module is not only installed rapidly; it integrates naturally into the host building, without requiring significant structural reinforcement and while guaranteeing impeccable technical performance.

The proposed solution also stands out for its hygrothermal behaviour. Where metal containers commonly used in emergency situations provide poor habitability, the CLT module offers thermal stability, acoustic comfort, humidity regulation and a psychologically healthier environment, thanks to the presence of timber and the absence of cold surfaces. The multilayer envelope behaves as a perfectly coordinated technical system that protects the structural panel, prevents condensation and maintains overall envelope equilibrium.



Figure 14.1– CLT modular system as a consolidated architectural solution, capable of functioning both as an educational extension and as rapid housing with high technical and spatial quality.

Analysis of fire behaviour, inter-module joints, service integration and moisture control confirms that the solution is not merely viable, but robust. The passive fire protection systems integrated into the module, the controlled charring behaviour of

CLT and the internal continuity of gypsum linings demonstrate that the system is as safe as any traditional alternative.

This project has shown that modular architecture in CLT should not be interpreted as emergency architecture, but as a model of contemporary architecture capable of responding to both permanent and temporary needs. The module is not a provisional substitute; it is a mature architectural component that can be integrated into public infrastructure with the same legitimacy as concrete or steel buildings.

Overall, the conclusions reinforce the idea that CLT modularity represents a transformative construction strategy: it reduces construction time, improves sustainability, minimises environmental impact, delivers high-quality spaces and adapts to multiple contexts without losing coherence or technical reliability.

CHAPTER 15. FUTURE RESEARCH LINES

Modular construction using CLT is still in a phase of expansion, opening the door to multiple research lines capable of enriching and extending the proposed system. A first and particularly relevant line of development lies in energy optimisation through dynamic simulations incorporating seasonal climate variations, relative humidity indices, thermal gradients and the real behaviour of external insulation. Such simulations would allow further refinement of the multilayer envelope composition, exploring adjustments in densities, thicknesses or materials in order to maximise the module's energy efficiency.



Figure 15.1— Potential future research pathways for CLT modular systems, including energy optimisation through dynamic simulations, integration of renewable energy systems, industrial automation, reconfigurability and applications in emergency and public infrastructure.

Another significant research field concerns the active integration of renewable energy systems into the modular concept. Although the module is conceived as a passive and efficient unit, there is considerable potential for it to evolve into a small self-sufficient system through the incorporation of photovoltaic panels, compact

battery storage and energy management devices. This approach would be especially valuable in emergency contexts, where energy autonomy can make the difference between dignified habitability and precarious living conditions.

Industrialisation itself also represents fertile ground for future development. Enhancing automation of production lines, standardising inter-module connections and advancing towards reconfigurable models capable of rapidly transforming a classroom into a dwelling—or vice versa—are realistic objectives fully aligned with the spirit of the proposed system.

In parallel, it is highly relevant to investigate the psychological impact of timber use in educational and residential environments. Scientific evidence suggests that the presence of wood reduces stress, improves concentration and humanises interior spaces. A systematic study of these effects would further reinforce the suitability of CLT in public architecture.

Finally, the role of the modular system within healthcare, humanitarian and logistical infrastructure opens applied research lines extending beyond housing and education. CLT modularity has the potential to become a strategic tool in national emergency response, providing versatile, healthy spaces within very short timeframes.

CHAPTER 16. EXTERNAL SOURCES

16.1 Books and technical manuals

Gagnon, S., & Pirvu, C. (2011). CLT Handbook. FPInnovations.

Green, M., & Karsh, J. (2012). Tall Wood Buildings: Design, Construction and Performance.

Harte, A. (2017). Mass Timber Structures. Springer.

Herzog, T. et al. (2012). Timber Construction Manual. Birkhäuser.

16.1.2 Scientific articles

Brandner, R. et al. (2016). "Cross-laminated timber (CLT): overview and development." Engineering Structures.

Mohammad, M. et al. (2019). "Fire resistance of mass timber structural systems." Fire Safety Journal.

Schober, K. et al. (2017). "Acoustic behaviour of multi-layer timber envelopes." Building Acoustics.

16.1.3 Relevant standards and regulations

Spanish Building Technical Code (CTE): DB-SE, DB-SI, DB-HR, DB-HE.

Eurocode 5: Design of timber structures.

UNE-EN 16351: Cross-laminated timber.

16.1.4 International reports and guidelines

TRADA. Timber Frame Construction Guide.

WoodWorks. Mass Timber Design Guide.

Emergency housing studies

UN-Habitat. Shelter after Disaster.

IFRC. Emergency Housing Guidelines.

16.2 Image resources

Figure 3.1 English cruck-built barn (traditional timber framing)

• <https://www.istockphoto.com/es/foto/ingl%C3%A9s-cruck-construido-granero-gm152311768-15422079>

Figure 3.2 Before I start, what am I doing wrong? (Timber shed structure discussion)

• https://www.reddit.com/r/shedditors/comments/1kpz8wx/before_i_start_what_am_i_doing_wrong/

Figure 3.3 Platform framing vs. balloon framing

• <https://www.boomandbucket.com/es/blog/platform-framing-vs-balloon-framing>

Figure 3.4 Material or grain directions in wood (L, T, R)

• https://www.researchgate.net/figure/Material-or-grain-directions-in-wood-L-T-R-stands-for-longitudinal-tangential-and_fig6_348694385

Figure 4.1 Conventional assembly layup of cross-laminated timber (CLT)

- https://www.researchgate.net/figure/Conventional-assembly-layup-of-cross-laminated-timber-CLT-90_fig1_313192887

Figure 4.2 Breathable membranes, VCLs, VSDs and water vapour control

- <https://www.celticsustainables.co.uk/blog/breathable-membranes-vcls-vsds-water-vapour-whats-it-all-about/>

Figure 4.3.1 Exposing cross-laminated timber slabs

- <https://ateliercrescendo.ac/exposing-cross-laminated-timber-slabs/>

Figure 5.1 Engineered timber products (CLT, GLT and LVL)

- <https://lightwood.org/engineered-timber-products/>

Figure 5.2 3D structural and architectural views of a hybrid CLT building

- https://www.researchgate.net/figure/3D-structural-and-architectural-views-a-4-story-hybrid-building-archetype-and-b_fig1_374115993

Figure 5.3 Environmental and structural performance of CLT buildings

- <https://www.sciencedirect.com/science/article/pii/S1350630721006270>

Figure 6.1 Modular construction with timber – Part I

- <https://maderayconstruccion.com/construccion-modular-con-madera-parte-i/>

Figure 7.1 Energy performance of timber-based building systems

- <https://www.mdpi.com/1996-1073/13/12/3127>

Figure 8.2 Passive House strategies for timber and modular buildings

- <https://www.phi.archi/news/blog-post-title-two-csfsz-w6wdz-ese45>

Figure 8.2.1 Transport of prefabricated houses and modular buildings

- <https://gruascano.com/transporte-casas-prefabricadas/>

Figure 9.1 Cubik Home modular housing system – technical interview

- <https://www.lab-recherche-environnement.org/wp-content/uploads/entretien-croise-cubik-home-1.pdf>

Figure 9.2 Cubik Home modular housing system – technical interview

- <https://www.lab-recherche-environnement.org/wp-content/uploads/entretien-croise-cubik-home-1.pdf>

Figure 9.3 CLT exterior wall assembly with exterior insulation and ventilated cladding

- https://www.researchgate.net/figure/CLT-exterior-wall-assembly-with-exterior-insulation-and-ventilated-cladding-showing_fig2_273458912

Figure 10.1 Control layer continuity for mass timber building enclosure design

- <https://www.woodworks.org/resources/control-layer-continuity-for-mass-timber-building-enclosure-design/>

Figure 13.1 Conceptual model of strengthening interventions with CLT panels

- https://www.researchgate.net/figure/Conceptual-model-of-strengthening-interventions-with-CLT-panels-a-from-the-outer-side_fig1_342610328

Figure 14.1 Recent advances in modular timber construction systems

- <https://www.tandfonline.com/doi/pdf/10.1080/17480272.2025.2507145>

Figure 15.1 Prefabricated housing design and new urban models

- <https://www.idealista.com/news/inmobiliario/vivienda/2021/03/22/789607-este-diseno-de-casas-prefabricadas-quiere-revolucionar-el-concepto-de-urbanismo>