

Review

Adapting Medieval Heavy Timber Joinery for Modern Circular

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The global construction sector occupies a critical threshold in the climate crisis, generating approximately 37% to 40% of annual greenhouse gas emissions. While factory-manufactured engineered wood products sequester biogenic carbon during growth, contemporary mass timber buildings rely heavily on permanent polyurethane adhesives and high-torque metallic fasteners at their structural intersections. These standard joining methods precipitate mechanical fracturing during decommissioning, forcing a linear lifecycle model upon building components. This paper presents a conceptual narrative review of European heavy timber framing principles spanning 1000 to 1500 AD to evaluate how historic woodworking geometries can be digitally re-engineered via multi-axis Computer Numerical Control (CNC) milling to provide a potential theoretical pathway for Design for Disassembly (DfD). Based on a synthesis of existing literature, this review examines significant structural challenges, including an indicated 12-to-15-fold reduction in joint bending stiffness and high vulnerability to moisture-induced micro-slip. To address these limitations, evaluating contemporary material enhancements, such as pre-compressed wood connectors. Ultimately, this conceptual synthesis suggests that coordinating physical, reversible timber-to-timber connections with digital tracking documentation demonstrates the potential for mass timber frameworks to function as circular, multilifecycle material banks.

Keywords: *Design for Disassembly, Digital fabrication, Cross Laminated Timber, Compressed Wood, Circular economy, Wood-on-wood joinery, Adhesive bonds, Medieval Joinery*

Introduction**1.1 The Material Threshold and the End-of-Life Paradox**

The contemporary mass timber movement stands as a profound attempt to decarbonise the urban environment through the utilisation of Cross-Laminated Timber (CLT) and Glued Laminated Timber (Glulam) (Lin et al., 2025; Sotayo et al., 2020). These engineered wood products operate as a vital carbon sink, although their environmental benefits are currently truncated by a linear service life (Flindall et al., 2023; Lin et al., 2025). On decommissioning, majority of contemporary timber components face a material death, with recovery rates for high-value wood waste estimated at only 6% in some industrial regions (Flindall et al., 2023). This outcome results directly from a reliance on non-reversible joining techniques that render the non-destructive separation of members nearly impossible (Aloisio et al., 2025; Lin et al., 2025). Consequently, the industry requires a foundational shift toward Design for Disassembly (DfD) to ensure that building components are preserved as structural assets rather than discarded as biomass (Li et al., 2024; Cabrero et al., 2025).

Contemporary construction methods present a significant paradox where renewable materials are joined using permanent and destructive fastening technologies (Flindall et al., 2023; Li et al., 2024). High-torque self-tapping screws and chemical adhesives facilitate structural efficiency but precipitate mechanical

fracturing during deconstruction (Lin et al., 2025; Husgafvel et al., 2022). This process mirrors a form of material abjection, where a once-legitimate structural component is abandoned or degraded due to its contamination by secondary materials (Lin et al., 2025). To escape this linear model, buildings must be reconceptualised as material banks where every component is held in a state of suspended animation, ready to be released and repurposed without degradation (Cabrero et al., 2025). Achieving this regenerative built environment necessitates a return to the structural threshold of the medieval period (1000–1500 AD), where joinery was inherently reversible (Proposal, 2026; Sandin et al., 2022).

The implementation of wood-on-wood joinery offers a mechanical solution to this end-of-life paradox (Brown, 2023; Kramberger et al., 2022). Medieval master carpenters utilised interlocking geometries and mechanical friction to maintain structural integrity across centuries (Brown, 2023; Panoutsopoulou and Mouzakis, 2022). These traditional systems were designed for repair by disassembly, a philosophy that allowed individual members to be replaced if they showed signs of degradation (Cabrero et al., 2025; Fukuda, 2017). By reviving these principles through the precision of 5-axis CNC fabrication, manufacturers can create complex, interlocking nodes that are both structural and fully demountable (Brown, 2023; Al-Qaryouti et al., 2016). The present paper investigates how these historical principles can be technically enhanced to meet modern performance standards for stiffness, safety, and digital traceability (Aloisio et al., 2025; Markou et al., 2025).

2.0 Methodology

The structural convergence of historic heavy timber craftsmanship and automated manufacturing is evaluated through a conceptual, comparative framework that maps qualitative

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architectural archaeology directly against quantitative mass timber engineering metrics. To achieve the dual demands of structural permanence and circular material flows, this methodology operates as a cross-disciplinary, narrative synthesis. The analytical scope is strictly bounded by the European heavy timber framing tradition of the medieval period, specifically from 1000 to 1500 AD, to evaluate how these historic, interlocking wood-on-wood configurations can be re-engineered for modern Design for Disassembly (DfD). To ensure transparency and reproducibility within this narrative framework, literature identification was guided by a purposive data-gathering process conducted across primary indexed electronic repositories, specifically Scopus and the Web of Science Core Collection, supplemented by targeted grey literature and institutional report mining via wide ranging academic repositories such as Google Scholar. Source selection focused on tracking three broad, interlocking thematic concepts, which comprised the qualitative mechanical logic of traditional interlocking joinery, the quantitative performance metrics of engineered wood assemblies under environmental or mechanical stress, and the supply-chain integration of digital tracking protocols. A contemporary publication window constraint of 2005–2026 was applied to ensure the synthesis captures parallel advancements in multi-axis Computer Numerical Control (CNC) fabrication, high-fidelity Finite Element Method (FEM) micro-modelling, and modern circular product governance directives.

Sources gathered from this query architecture were additionally evaluated based on qualitative inclusion criteria that prioritised peer-reviewed journal articles documenting empirical investigations of unglued connection interfaces, formally published theses addressing automated digital joinery fabrication, and validated technical reports documenting multi-storey mass timber disassembly metrics. Under these parameters, three qualitative industrial case studies were purposively selected to represent a diverse matrix of architectural scales and structural configurations, consisting of the HasleTre commercial office complex in Norway, the Cygnum Reflect 140 low-energy residential framework in Ireland, and the Cuenca Village modular infrastructure installation in Spain. These specific cases provide a comprehensive analytical gradient spanning from large scale commercial post-and-beam configurations to multi-axis panellised prefabrication. By removing contemporary non-reversible polyurethane adhesives and high-torque metallic connectors at joining intersections, the paper indicates a technical framework to transition the construction sector away from its traditional linear model. Crucially, while factory mass timber panels (Cross-Laminated Timber and Glued Laminated Timber) remain conventionally adhesive-bonded engineered products, this study isolates its investigation strictly to unglued connection interfaces and reversible timber-to-timber joints. The paper executes this narrative synthesis by structuring its analytical logic into three sequential, interconnected evaluative tracks that examine mechanical prestress, hygrothermal rheology, and multi-scalar systemic validation.

2.1 Geometric Transfer and Prestress Capacity

The mechanical viability of substituting chemical adhesives

at joining intersections with unglued connection interfaces depends on transferring historic interlocking geometries into automated manufacturing workflows. Historical carpentry treatises demonstrate that the medieval draw-bored mortise and tenon joint relies on an intentional geometric offset between peg apertures to pull the connection into a permanent state of tension (Shanks and Walker, 2009; Sobon and DeStefano, 2020). Empirical structural engineering evaluations indicate that conventional glued Cross-Laminated Timber panels are consistently 12 to 15 times stiffer than standard wooden-doweled alternatives, presenting a substantial engineering performance gap for flooring systems where deflection and serviceability are critical (Aloisio et al., 2025). By processing these historic offset profiles using automated 5-axis Computer Numerical Control milling, modern manufacturers demonstrate the potential to achieve precise tolerances that optimise face-to-face friction without intensive manual labour (Al-Qaryouti et al., 2016; Brown, 2023). The precision of computational execution replaces the rigid surface-bonding of polyurethane adhesives at joint interfaces with a dynamic, friction-locked connection that safely distributes localised stress concentration vectors parallel to the grain (Shanks and Walker, 2009; Uysal and Haviarova, 2021). Consequently, evaluating this geometric transfer suggests a physical foundation to close this performance gap, shifting the engineering focus from permanent chemical bonding to automated, geometry-based joint reliability (Aloisio et al., 2025; Brown, 2023; Kramberger et al., 2022).

2.2 Hygrothermal Rheology and Mitigation Strategies

Building directly onto these geometric parameters, the long-term safety of reversible timber-to-timber connections requires a technical solution to mitigate the high sensitivity of wood-on-wood nodes to environmental moisture fluctuations. Empirical hygrothermal data indicates that a decrease in wood moisture content from 12% to 8% triggers a 34% reduction in overall panel bending stiffness because the wood cells contract, causing the internal wooden dowels to shrink away from the joint walls (Aloisio et al., 2025). Conversely, material science evaluations of modified timber indicate that pre-compressed wood elements exhibit a powerful shape-recovery effect, expanding when exposed to atmospheric humidity to exert continuous internal swelling pressure within a connection node (Mehra et al., 2024).

The compiled data cross-examines this moisture-induced behaviour to demonstrate that integrating compressed wood connectors counteracts standard volumetric shrinkage (Mehra et al., 2024). As environmental humidity varies, the moisture-activated expansion of the compressed wood acts as an internal mechanical spring, filling any geometric voids and maintaining constant joint tightness without splitting the surrounding timber structure (Mehra et al., 2024). This hygrothermal assessment suggests that pairing historical carpentry logic with modified material science directly mitigates seasonal stiffness losses, rendering unglued connection interfaces structurally reliable under changing atmospheric conditions (Aloisio et al., 2025; Mehra et al., 2024).

2.3 Multi-Scalar Systemic Recovery Validation

While material adjustments solve local connection vulnerabilities, evaluating the industrial scalability of reversible all-wood configurations requires cross-examining empirical evidence from built projects across diverse architectural scales and information tracking frameworks. At a commercial scale, data from the HasleTre office building in Norway indicates that substituting steel connection brackets with hardwood dowels in a glulam framework reduces total structural steel usage by 70% while safeguarding the structural integrity of the components for a second service life (Flindall et al., 2023). Moving to a residential scale, structural auditing of the Cygnum Reflect 140 House in Ireland reveals that combining solid timber framing with a formal Disassembly Information Record increases the recovery rate of high-value, undamaged wood by nearly 300% compared to traditional demolition methods (Walsh and Shotton, 2024).

The paper compiles these multi-scalar industrial outcomes alongside automated construction data from Spain's Cuenca Village project to evaluate the practical intersection of automated physical joinery and top-down governance protocols (Cabrero et al., 2025; Markou et al., 2025). This analysis indicates a direct operational correlation between physical disassembly mechanics and the EU Eco-design for Sustainable Products Regulation frameworks, demonstrating that Digital Product Passports must log an element's precise load history to remove insurance re-certification bottlenecks (Markou et al., 2025). This multi-scalar synthesis suggests that physical wood-on-wood connections must be systematically paired with clear digital and physical tracking documentation to achieve the overarching objective of adapting medieval heavy timber joinery for modern circular mass timber construction, thereby transforming commercial frameworks into fully certifiable material banks (Cabrero et al., 2025; Walsh and Shotton, 2024).

3.0 Historical Precedents

3.1 The Structural Logic of Medieval Carpentry (1000–1500 AD)

The structural execution of European heavy timber framing between 1000 and 1500 AD relied upon an empirical comprehension of the orthotropic, macro-structural characteristics and hygroscopic mechanics of green timber (Sandaker et al., 2019). Master carpenters engineered intentional geometric tolerances that capitalised upon transverse volumetric wood shrinkage, ensuring that connection nodes would consolidate under dead loads rather than undergo mechanical fracturing (Sandaker et al., 2019). A primary manifestation of this geometric design logic is the draw-bored mortise and tenon joint, which introduces an intentional axial alignment offset between the peg apertures of the mortise walls and the tenon tongue (Shanks and Walker, 2009; Sobon and DeStefano, 2020). When a tapered, dry hardwood peg is driven through these eccentric bores, the sub-millimetre discrepancy forces the tenon deeper into the mortise pocket, shifting the entire assembly into a permanent state of elastic prestress (Sobon and DeStefano, 2020). This internal residual clamping force effectively preserves joint tightness, counteracting the natural tangential and radial shrinkage that

occurs as the primary structural members season over decades (Shanks and Walker, 2009; Sobon and DeStefano, 2020).

The long-term shear capacity of these historical connections was significantly enhanced by utilising riven timber components that preserved continuous longitudinal fibre orientation (Sobon and DeStefano, 2020). Traditional pinning pegs between 1000 and 1500 AD were cleft along natural grain boundaries with an axe rather than sawn, an execution method that eliminated cross-grain runout and permitted the peg to accommodate substantial bending strains without brittle failure (Shanks and Walker, 2009; Sobon and DeStefano, 2020). These octagonal pegs engage the interior cylindrical surfaces of the round drill holes with localised compression zones, operating as a continuous mechanical spring that maintains joint tightness across fluctuating seasonal relative humidity cycles (Sobon and DeStefano, 2020). Applying this historical logic to contemporary contexts facilitates the development of connection nodes that distribute internal shear stresses across wide timber bearing faces, eliminating the highly destructive stress concentrations typically induced by rigid, modern metallic fasteners (Aloisio et al., 2025; Shank and Walker, 2009). Consequently, the interlocking geometry of the connection itself acts as the primary driver of structural performance and rotational stiffness (Uysal and Haviarova, 2021).

Contemporary digital fabrication tools enable the optimisation and scaling of these historical interlocking profiles through multi-variable computational modelling pipelines (Brown, 2023; Kramberger et al., 2022). Automated multi-axis Computer Numerical Control (CNC) milling machinery can reliably execute complex timber-to-timber scarf joints that were previously constrained by the intensive manual labour and highly localised skills of historical craftsmen (Al-Qaryouti et al., 2016; Brown, 2023). High-fidelity Finite Element Analysis (FEA) provides the structural framework to simulate complex three-dimensional stress fields, frictional slip surfaces, and relative displacement vectors within these interlocking nodes before physical manufacturing (Brown, 2023; Li et al., 2024). These computational models explicitly account for the orthotropic elasticity matrix of wood, pinpointing stress concentrations relative to the annual ring and grain directions (Shanks and Walker, 2009; Brown, 2023). This synthesis of historical carpentry mechanics from the 1000–1500 AD period and digital industrial automation indicates a rigorous framework for rapid connection prototyping, advancing the core research objective of adapting medieval heavy timber joinery for modern circular mass timber construction by delivering code-compliant design guidelines (Brown, 2023; Kramberger et al., 2022).

4.0 Technical Synthesis

4.1 Addressing the Stiffness Gap and Moisture Risks

The primary structural hurdle for unglued mass timber systems is the substantial reduction in bending stiffness compared to conventionally glued alternatives (Aloisio et al., 2025). Experimental investigations indicate that glued Cross-Laminated Timber (CLT) panels are consistently 12 to 15 times stiffer than wooden-doweled CLT (WDCLT) panels of an equivalent layup (Aloisio et al., 2025). This discrepancy translates to a relative difference exceeding 1000%, a performance gap that

restricts the application of WDCLT in flooring systems where serviceability and deflection criteria are paramount (Aloisio et al., 2025). Additionally, the mechanical integrity of these wood-on-wood systems depends fundamentally on friction generated by the swelling and moisture-expansion of internal hardwood dowels (Aloisio et al., 2025; Flindall et al., 2023). This friction remains highly sensitive to fluctuations in ambient moisture content (Aloisio et al., 2025). Empirical data indicates that a reduction in wood moisture content from 12% to 8% results in a 34% reduction in overall panel bending stiffness due to localised dowel shrinkage and subsequent micro-slip within the connection boundaries (Aloisio et al., 2025).

To overcome these structural and environmental vulnerabilities, the engineering framework must pivot from raw timber elements toward modified engineered wood products. Specifically, the integration of compressed wood (CW) connectors offers a technical solution to mitigate these stiffness losses and moisture risks by exploiting thermo-mechanical densification at unglued connection interfaces (Mehra et al., 2024). Compressed wood delivers enhanced material properties, yielding significant increases in density, ultimate tensile strength, and surface hardness compared to natural, unmodified timber (Mehra et al., 2024). Additionally, compressed wood exhibits a powerful shape-recovery effect, scientifically classified as moisture-activated hygro-elastic memory, where the cell walls attempt to return to their pre-compressed dimensions over time, ensuring a permanent, tight interference fit despite severe atmospheric fluctuations (Mehra et al., 2024). Empirical structural testing indicates that timber portal frames utilising these advanced compressed wood connectors achieve a lateral load-carrying capacity nearly identical to that of conventionally glued, rigid frameworks (Mehra et al., 2024). Therefore, the deployment of physically modified wood products demonstrates the potential to bridge the performance gap between fully reversible all-wood joints and traditional permanent connections (Mehra et al., 2024).

In addition to these material-level modifications, achieving total structural reliability across a building's lifecycle necessitates a parallel shift toward prescriptive, geometry-based design safeguards (Sandaker et al., 2019; Sobon and DeStefano, 2020). Independent of moisture-driven stiffness losses, a primary structural risk inherent to pegged wood-on-wood joinery is tenon relish failure, a brittle failure mode where a dowel shears completely through the end block of the tenon parallel to the grain under high pulling forces (Sobon and DeStefano, 2020). Relish failures are particularly dangerous because the shearing action is entirely concealed within the mortise housing, providing no visible warning signs of impending structural collapse (Mills, 2005; Sobon and DeStefano, 2020). To eliminate this risk, the

Timber Frame Engineering Council (TFEC) standard guidelines dictate that for connection joints subjected to structural tension, the minimum end distance measured parallel to the grain from the centre of a peg hole to the terminal tip of the tenon must be at least four times the peg diameter (4d) (Sobon and DeStefano, 2020). These combined design strategies systematically transition the engineering focus from reactive, post-construction inspections to proactive, geometry-based structural reliability, supporting the foundational objective of adapting medieval heavy timber

joinery for modern circular mass timber construction by delivering verifiable structural safety without the need for destructive metallic hardware (Li et al., 2024; Sobon and DeStefano, 2020).

5.0 Case Study Analysis

5.1 Industrial Applications of Design for Disassembly

The commercial office development of HasleTre in Oslo, Norway, presents a primary empirical baseline for the real-world execution of Design for Disassembly (DfD) using entirely unglued connection interfaces (Flindall et al., 2023). Completed in 2022, the 3,000-square-metre structure utilises a Glued Laminated Timber (Glulam) post-and-beam primary structural frame supporting multi-span Cross-Laminated Timber (CLT) floor slabs (Flindall et al., 2023). To mitigate the standard linear decommissioning cycle driven by destructive, high-torque metallic brackets, the building's engineering team substituted traditional steel connection plates within the post-and-beam nodes with large-diameter beech hardwood dowels (Flindall et al., 2023). This deliberate replacement achieved a 70% reduction in total structural steel usage across the project footprint (Flindall et al., 2023). Additionally, structural monitoring reveals that isolating the load paths exclusively through wood-on-wood bearing interfaces preserves the structural margins of the primary CLT slabs, retaining their mechanical properties for direct architectural reallocation in a secondary building lifecycle (Flindall et al., 2023). Lifecycle assessment (LCA) data as-built validates that this mechanical framework delivered an overall 59% reduction in greenhouse gas emissions compared to baseline commercial construction standards, supporting the immediate carbon abatement potential of reversible structural connection nodes (Flindall et al., 2023).

Expanding the analytical scope from commercial frame elements to panellised residential infrastructure, the architectural execution of the Cygnum Reflect 140 House in Ireland highlights how modest design reconfigurations maximise the material recapture of high-value structural lumber (Walsh and Shotton, 2021; Walsh and Shotton, 2024). The engineered intervention focused on substituting conventional, chemically combined composite I-joists with solid, single-species sawn timber elements while deploying high-density wood nails in the framing panels instead of conventional steel screws (Walsh and Shotton, 2024). This configuration limits mechanical fracture and splitting at the component end-blocks during deconstruction sequences (Walsh and Shotton, 2024). Quantitative auditing of the deconstruction phase supporting that these timber-only configurations achieved a recovery rate for high-value structural timber that was 300% higher than identical baseline frames utilising non-reversible connectors (Walsh and Shotton, 2024).

Extending this operational paradigm to complex geometries, the Cuenca Village modular infrastructure installation in Spain demonstrates the mechanical viability of pairing historical interlocking carpentry nodes with contemporary 5-axis Computer Numerical Control (CNC) prefabrication pipelines (Cabrero et al., 2025; Markou et al., 2025). The project relies on computer-aided automated manufacturing to mill highly complex, interlocking scarf and lap joints that facilitate rapid mechanical assembly

and non-destructive dismantling without a single application of permanent chemical polyurethane adhesives at the connection nodes (Cabrero et al., 2025). These projects collectively indicate that migrating from metallic plates and chemical bonding toward digitised, unglued connection interfaces forms a structurally viable pathway for industrial-scale circular construction (Cabrero et al., 2025; Li et al., 2024).

5.2 The Operational Role of Disassembly Documentation

The empirical observations gathered from the Cygnum project emphasise that the long-term circular viability of wood-on-wood installations relies inherently on standardised deconstruction planning (Walsh and Shotton, 2024). The introduction of a formal Disassembly Information Record (DIR) indicates an active engineering framework that details the exact sequences, spatial clearances, and tooling required for future contractors to safely reverse the connection interfaces (Walsh and Shotton, 2024). Field observations from decommissioning trials reveal that in the absence of explicit structural instructions, demolition teams routinely prefer rapid, destructive sawing between structural framing members over the meticulous extraction of individual mechanical fasteners (Sandin et al., 2022; Walsh and Shotton, 2024). This aggressive field practice immediately degrades the material, downgrading premium timber panels into low-value biomass or downcycled aggregate (Flindall et al., 2023; Lin et al., 2025). Consequently, illustrating critical geometric junctions and joint release mechanisms within a legally binding DIR is mandatory to protect the initial structural capital (Walsh and Shotton, 2024). These industrial outcomes suggest that advanced technical solutions remain heavily dependent on explicit documentation to preserve structural utility across extended building lifespans (Markou et al., 2025; Walsh and Shotton, 2024).

5.3 Synthesis of Practical Implementations

A critical cross-examination of these industrial applications reveals that the physical scalability of unglued mass timber structures depends on the uniform integration of automated fabrication and standardised deconstruction documentation. The empirical outcomes from Norway, Ireland, and Spain demonstrate that while replacing steel plates with beech dowels at the HasleTre office building successfully lowers structural steel dependency by 70%, such physical adjustments only retain value if the architectural components remain undamaged during deconstruction (Flindall et al., 2023). This physical limitation is directly addressed by the deployment of Disassembly Information Records (DIR) at the Cygnum Reflect 140 House, which explicitly mitigates the destructive onsite tendency of deconstruction teams to saw through interlocking junctions, securing a 300% increase in high-value timber recapture (Sandin et al., 2022; Walsh and Shotton, 2024). Additionally, the automated production pipelines analysed in the Cuenca Village project indicate that 5-axis CNC machining can reliably deliver the strict geometric tolerances required to make unglued carpentry connections commercially scalable (Cabrero et al., 2025).

A synthesis of these commercial deployment metrics indicates that structural engineering solutions should ideally be integrated alongside comprehensive building lifecycle management

(Cabrero et al., 2025; Walsh and Shotton, 2024). The precision of computer-aided manufacturing provides the tight interlocking fits necessary to maintain required load-bearing capacities and joint tightness without chemical bonding agents (Al-Qaryouti et al., 2016; Brown, 2023). Although, empirical field studies reveal that the subsequent structural preservation of that timber material during building disassembly is heavily dependent on clear informational maps to guide future deconstruction contractors (Flindall et al., 2023; Sandin et al., 2022). In the absence of an explicit, legally archived Disassembly Information Record or equivalent digital passport framework to govern the active deconstruction phase, the complex carpentry nodes optimised by automated milling face a heightened risk of being structurally compromised or fractured during extraction sequences (Markou et al., 2025; Walsh and Shotton, 2024).

The vulnerability is particularly acute because standard demolition crews routinely default to high-torque sawing through connection members if clear, non-destructive reversing guidelines are omitted from the design phase (Sandin et al., 2022; Walsh and Shotton, 2024). These industrial precedents indicate that the long-term success of adapting medieval carpentry for modern mass timber systems relies on linking physical joinery with comprehensive information management. Combining these strategies provides the structural and logistical pathways necessary to turn commercial building components into accessible material banks across multiple lifecycles (Cabrero et al., 2025; Flindall et al., 2023; Walsh and Shotton, 2024).

6.0 Conceptual Frameworks

The empirical data and documentation frameworks extracted from the preceding industrial applications necessitate formal structural abstraction to yield a scalable architectural methodology. Consequently, this section indicates the theoretical and evaluative boundaries required to align the physical disassembly of mass timber components with measurable structural performance and lifecycle tracking metrics. While empirical precedents validate the onsite assembly tolerances of unglued connection nodes, transitioning Design for Disassembly (DfD) from an abstract architectural ambition into a quantifiable, code-compliant engineering discipline relies heavily on predictive modelling (Cabrero et al., 2025; Ottenhaus et al., 2025). By cross-examining systemic structural models alongside resource-recovery hierarchies, these theoretical frameworks supply the precise criteria necessary to ensure that unglued, wood-on-wood assemblies satisfy modern safety codes while systematically preserving long-term material asset value.

6.1 Material Banks and the SP-WC Philosophy

The Material Banks concept operates as a primary theoretical model for re-conceptualising buildings as material repositories rather than future demolition waste vectors (Cabrero et al., 2025; Durmisevic, 2019). By archiving the geometric baseline, manufacturing origin, and continuous structural history of every component, the construction sector can shift from a linear lifecycle towards a regenerative, multi-lifecycle framework (Cabrero et al., 2025; Lin et al., 2025). Central to this logistical transition

is the Strong Panel–Weak Connection (SP-WC) engineering philosophy, which restricts structural damage away from high-value mass timber panels by localising non-linear stresses within sacrificial, replaceable connection fuses (Li et al., 2024). Under extreme lateral loading events, such as seismic activity, these mechanical wood-on-wood connectors undergo predictable ductile deformation while the primary

Cross-Laminated Timber (CLT) panels remain strictly within their elastic performance phase, ensuring the panels can be extracted and reallocated without structural degradation (Li et al., 2024). Limiting the loss of structural capacity during an element's initial building cycle provides the physical mechanism needed to keep premium structural timber suspended in a continuous circular state of value (Li et al., 2024).

6.2 Cascading Use and Adaptability Hierarchies

In parallel with these structural metrics, the Cascading Use hierarchy outlines a resource management framework that prioritises high-value structural recovery pathways for timber over direct bioenergy conversion (Lin et al., 2025). According to this structural taxonomy, the direct adaptive reuse of the entire multi-storey frame represents the most carbon-efficient strategy, followed by the non-destructive extraction of individual component elements, and finally mechanical recycling into secondary composite board products (Cabrero et al., 2025; Lin et al., 2025). Delaying carbon release through direct structural component reuse maximises the environmental value of mass timber as a long-term biogenic carbon sink (Lin et al., 2025). The structural integration of Design for Adaptability (DfA) alongside DfD further ensures that internal building layouts can seamlessly accommodate future programmatic changes, extending the initial service life of the sub-assemblies before deconstruction is required (Lin et al., 2025; Walsh and Shotton, 2024). This integrated conceptual model provides the multi-layered logic necessary for manufacturers and engineers to execute regenerative mass timber developments (Li et al., 2024; Lin et al., 2025).

6.3 Evaluation of Circular Metrics

The synthesis of these analytical tools and structural models indicates that achieving high-tier material circularity relies on linking mathematical ease-of-disassembly indexing with proactive component safety design. The integration of the ReBuilding Index suggests that connection configurations can be numerically optimised to minimise deconstruction actions, potentially reducing on-site labour and mitigating accidental component fracturing (Ottenhaus et al., 2025; Walsh and Shotton, 2024). Concurrently, the application of the Strong Panel–Weak Connection (SP-WC) engineering philosophy supports the structural rationale for reversible, unglued connection interfaces, indicating that energy dissipation can be safely restricted to easily replaceable timber pegs or compressed wood wedges while keeping primary load-bearing Cross-Laminated Timber (CLT) panels within an undamaged elastic zone (Li et al., 2024).

Integrating these theoretical structures suggests that structural circularity is heavily dependent on matching initial calculative scoring tools with active material protection boundaries. The

implementation of mathematical indexing permits a predictive pre-construction assessment of how logistically viable disassembly workflows will be for future contractors, while the deployment of localised ductile fuses indicates whether the physical assets extracted are likely to satisfy the structural constraints required for immediate re-certification.

In the absence of this dual verification process, digitised multi-axis carpentry connections face a heightened vulnerability to potential commercial rejection due to unquantified deformation or micro-structural deterioration accumulated during service. Therefore, aligning these mathematical scoring methodologies with protective ductile engineering offers a systemic pathway to address the core challenges of adapting medieval heavy timber joinery for modern circular mass timber construction, supplying the theoretical and calculative frameworks necessary to transition commercial building frames into legally certified material banks (Cabrero et al., 2025; Li et al., 2024; Ottenhaus et al., 2025).

7.0 Policy, Traceability, and Digital Material Passports

The transition to a circular timber economy remains hindered by regulatory bottlenecks, notably the absence of standardised grading for salvaged structural members (Cabrero et al., 2025; Flindall et al., 2023). Re-certifying reclaimed timber components can lead to significant downgrading due to unknown load histories and potential hidden defects (Cabrero et al., 2025; Flindall et al., 2023). Evolving building codes focus primarily on the utilisation of new materials and do not yet provide specific design guidelines for adhesive-free wooden-doweled Cross-Laminated Timber (CLT) panels (Aloisio et al., 2025; Li et al., 2024). Addressing these policy gaps is an important step toward making structural timber reuse financially viable for manufacturers (Cabrero et al., 2025; Flindall et al., 2023).

Evolving policies, such as the EU Eco-design for Sustainable Products Regulation (ESPR), drive the adoption of Digital Product Passports (DPP) to bridge data gaps across supply chains (Markou et al., 2025). Material Passports (MP) operate as a digital twin of the physical building, documenting material properties, species, and maintenance history to facilitate high-value structural reuse (Markou et al., 2025; Senarathne et al., 2025). Employing GS1 Global Traceability Standards ensures data interoperability across the supply chain, allowing stakeholders to make informed decisions about secondary materials (Markou et al., 2025). Policy precedents in Nordic countries, which require carbon footprint documentation for new buildings, serve as an active model for other regions to incentivise circularity (Lin et al., 2025). These measures encourage the use of low-carbon materials and construction techniques from a top-down governance perspective (Cabrero et al., 2025; Lin et al., 2025).

The role of insurance and warranty providers represents another factor influencing the adoption of reclaimed timber (Cabrero et al., 2025; Walsh and Shotton, 2024). Industry agreement is necessary to ensure that timber protected by geometry and moisture control alone remains acceptable for structural reuse without the mandatory application of biocidal chemicals (Cabrero et al., 2025). Documentation frameworks,

including Material Inventories and Disassembly Information Records (DIR), require secure deposition with local authorities to guarantee data access decades into the future (Markou et al., 2025; Walsh and Shotton, 2024). Standardising these records permits future deconstruction contractors to evaluate material characteristics without expensive on-site testing (Markou et al., 2025; Walsh and Shotton, 2024). Harmonising high-tech digital passports with durable physical documentation safeguards data longevity over a building's functional lifespan (Markou et al., 2025; Walsh and Shotton, 2024).

7.1 Policy Governance and Lifespan Alignment

The synthesis of these regulatory frameworks indicates that mitigating structural policy bottlenecks requires aligning top-down data tracking protocols with the physical properties of reversible joinery. Evolving statutory frameworks supporting that while physical wood-on-wood joints allow for non-destructive removal, the components cannot legally be re-certified unless their historical moisture profiles and structural load logs are verified via compliant data passports (Cabrero et al., 2025; Markou et al., 2025). This administrative validation is supported by the implementation of the EU Eco-design for Sustainable Products Regulation (ESPR), which indicates a clear legal timeline for tracking component origins and material history (Markou et al., 2025). Additionally, the long-term storage of Disassembly Information Records (DIR) ensures that future demolition contractors can verify component capacities without executing destructive on-site material testing (Markou et al., 2025; Walsh and Shotton, 2024).

When these data streams are cross-examined, they demonstrate that physical circularity relies heavily on institutional verification. The precision of Multi-Axis Computer Numerical Control (CNC) fabrication provides the geometric clearances needed to reverse joints, but digital tracing tools provide the chain of custody required by insurers and engineers. By logging an element's structural loading history, these tracking systems eliminate financial risks for insurers regarding potential internal timber defects. Coordinating strict data governance models with reversible engineering solutions addresses the core challenge of adapting medieval heavy timber joinery for modern circular mass timber construction, supplying the institutional verification necessary to safely manage commercial frameworks as certifiable material banks (Cabrero et al., 2025; Li et al., 2024; Markou et al., 2025).

8.0 Conclusion

8.1 Bridging Medieval Craft and Industrial Automation

The adaptation of historical heavy timber joinery for modern mass timber construction presents a potential theoretical pathway for achieving Design for Disassembly (DfD) (Brown, 2023; Li et al., 2024). Historical engineering principles from the 1000–1500 AD period, such as draw-boring and interlocking scarf joints, offer conceptual alternatives to permanent chemical adhesives and destructive metallic connectors (Brown, 2023; Sobon and DeStefano, 2020). Although existing experimental data indicates

that adhesive-free systems exhibit a significant reduction in bending stiffness, the synthesised evidence indicates that utilising compressed wood connectors and pre-stressed wedges could partially mitigate this performance gap (Aloisio et al., 2025; Mehra et al., 2024). Additionally, this synthesis suggests that adherence to prescriptive structural safeguards, such as the (4d) end-distance rule, offers a geometric method to reduce the risk of brittle tenon relish failure modes (Sobon and DeStefano, 2020). Evolving multi-axis Computer Numerical Control (CNC) digital fabrication and robotic assembly workflows suggest an operational framework where these complex, unglued interlocking joints could be executed at a commercially scalable level (Brown, 2023; Kramberger et al., 2022).

Furthermore, the conceptual implementation of Digital Material Passports and GS1-compliant tracking systems offers a programmatic method to preserve the structural and financial value of deconstructed components across multiple lifecycles (Cabrero et al., 2025; Markou et al., 2025). The transition from linear to circular mass timber systems remains an ongoing investigation focused on theoretically aligning historical craft logic with contemporary industrial automation protocols (Brown, 2023; Cabrero et al., 2025). While substantial regulatory bottlenecks, certification constraints, and labour costs continue to pose significant systemic challenges, secondary lifecycle modelling within the reviewed literature indicates a potential carbon savings incentive of approximately 21%, calculated specifically across a second structural building lifespan where mass timber components are directly repurposed rather than downcycled or incinerated (Flindall et al., 2023; Li et al., 2024). Evaluating these historical configurations within twenty-first-century digital pipelines suggests that mass timber frameworks could theoretically function as circular material banks, supporting long-term forest preservation and urban decarbonisation goals across extended lifespans (Cabrero et al., 2025; Li et al., 2024).

8.2 Research Limitations

The findings and framework articulated in this paper carry explicit boundary conditions inherent to a qualitative and conceptual methodology. As this study operates as a non-systematic narrative review, the synthesis excludes wider algorithmic or statistical literature searches, which means peripheral data streams regarding unglued mechanical fastening behaviours may remain uncaptured. Additionally, the illustrative selection of the three specific industrial case studies, while providing necessary qualitative depth across varying architectural scales, bounds the immediate, scalable transferability of these outcomes across alternative engineered wood products or regional construction taxonomies. The synthesised performance metrics, particularly regarding stiffness retention and moisture swelling pressures, remain highly conditional upon specific micro-climatic contexts and initial timber seasoning baselines. These findings should therefore be treated as a conceptual structural outline rather than verified empirical design criteria.

8.3 Future Research Agenda

To advance the integration of digitised historical joinery within

mainstream industrial mass timber applications, a targeted empirical research agenda is required to address unresolved physical and economic vectors. Initial efforts require physical testing to transition to full-scale destructive and non-destructive laboratory loading trials to validate the actual moment-rotation capacities of multi-axis CNC joints under realistic dead and live loads. Subsequent validation demands longitudinal hygroscopic and rheological monitoring to track long-term creep deformation and moisture performance under severe environmental cycling. Evolving fields of investigation must execute iterative physical disassembly and reassembly trials to evaluate how repeated mechanical wear and friction degrade internal dowel tolerances over multi-lifecycle phases.

Additionally, the systemic interaction of unglued connection interfaces must be evaluated against international fire safety regulations, indicates how charring rates and thermal degradation impact hidden wooden locking pegs. Comprehensive durability audits are required to assess potential biological decay within concealed mortise housings. Evolving policy must also support drafting rigorous design standardisation frameworks to align wood-on-wood configurations with evolving Eurocode structural guidelines. Simultaneously, detailed micro-economic feasibility assessments remain mandatory to weigh the higher initial manufacturing tolerances and computational planning expenses of automated multi-axis carpentry against the long-term material asset recapture value at end-of-life.

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