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Evaluating the Circularity and Carbon Benefits of End-of-Life Timber Structures: An Integrated BIM-LCA Approach

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Abstract

As the construction industry seeks to reduce carbon emissions, timber has emerged as a key material due to its capacity for biogenic carbon storage and end-of-life (EoL) reuse. However, assessing the practical circularity potential of timber structures remains challenging. This is largely because recovered components suffer geometric and material losses at their connection points. This study evaluates the EoL reuse and recycling potential of a multi-storey timber building by combining Building Information Modelling (BIM) with Life Cycle Assessment (LCA). A digital model was used to quantify structural elements (beams, columns, and walls), explicitly accounting for material losses at connections to calculate the net recoverable timber. The recovered material (837.39 m^3) was assigned to various cascading use scenarios based on material strength: structural reuse, non-structural reuse, engineered wood production, and energy recovery. To align with ISO 14044 principles, a functional equivalence factor (Q-factor) was applied to measure the environmental benefits of substituting new materials. Results indicate an overall material loss of 16.62% due to connections. Among the evaluated EoL pathways, structural reuse yielded the greatest net carbon benefit (−128.7 tCO_2e), significantly outperforming lower-value alternatives such as energy recovery (−29.3 tCO_2e). Additionally, a Design for Disassembly (DfD) sensitivity analysis showed that reducing connection losses by 50% could increase net global warming potential (GWP) savings by up to 19.7%. In conclusion, connection design is a critical factor in enabling timber circularity. Furthermore, combining BIM material tracking with LCA methods offers a practical approach to quantifying the long-term carbon benefits of timber reuse strategies.

Keywords: Building Information Modelling (BIM); Life Cycle Assessment (LCA); circular economy; timber structures; end-of-life (EoL) recovery; Design for Disassembly (DfD); cascading use; industry 4.0; digital transformation

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1. Introduction

The construction industry consumes approximately 50% of global raw materials, generates one-third of global waste, and accounts for 37% of energy-related carbon emissions [1]. To meet stringent global decarbonisation targets, shifting from traditional carbon-intensive materials to bio-based alternatives is imperative. Structural timber offers a viable solution due to its renewability and substantial biogenic carbon storage capacities [2]. Extending the service life of timber components through post-use recovery and cascading reuse delays carbon dioxide release into the atmosphere. The net climate benefit of timber depends on both

its first-life application and its circular efficiency across multiple subsequent life cycles [3]. Optimising end-of-life (EoL) recovery pathways is therefore essential for establishing a circular economy in the built environment. Understanding the importance of recycling EoL wood is particularly critical given the rapid expansion of mass timber construction across the UK and Europe. While regions like the UK have historically relied heavily on masonry and concrete, the broader European market is experiencing a significant surge in timber building proportions to meet stringent decarbonisation targets. Maximizing the recovery of these structural materials for secondary construction—rather than defaulting to terminal energy recovery—is therefore essential to sustaining Europe's circular bioeconomy.

This circular transition is increasingly accelerated by stringent macro-level policy instruments and net-zero frameworks worldwide. Regulatory drivers such as the European Green Deal [4] and the UK Net Zero Strategy [5] mandate drastic reductions in whole-life embodied carbon, forcing the construction supply chain to pivot away from the traditional linear "take–make–dispose" model [6]. Under these frameworks, buildings are progressively conceptualized as temporary material banks rather than static structures, necessitating systemic changes in procurement and end-of-life planning [7]. However, operationalizing these mandates requires robust quantification methods to substantiate the environmental and economic value of diverted material streams before deconstruction occurs [8].

Within the context of Industry 4.0, the digital transformation of the construction sector—often termed Construction 4.0—relies heavily on digital twins and Building Information Modelling (BIM). These technologies not only optimize design but also serve as foundational tools for sustainable industry chains by tracking materials through their end-of-life (EoL) phase. By integrating these digital technologies with Life Cycle Assessment (LCA), 8D BIM bridges the gap between design-stage asset management and demolition-stage material tracking [9]. Reversible BIM, for instance, embeds critical structural and dismantling metadata—such as assembly hierarchies, connection typologies, and component degradation history—to systematically quantify element-level reuse potential [10]. Populating Material and Component (M&C) Banks with these digital inventories allows asset managers to correlate real-time material conditions directly with environmental performance indicators [10]. Concurrently, EN 15978-compliant carbon accounting provides a standardized modular framework for quantifying and comparing the environmental credits yielded by cascading resource scenarios [11].

Despite the clear theoretical benefits of timber cascading, its practical implementation is hindered by significant technical, regulatory, and market barriers. Reclaimed structural timber frequently lacks comprehensive documentation regarding its structural grading, moisture exposure, and mechanical loading history, making compliance with structural codes like Eurocode 5 exceptionally difficult [12]. The absence of standardized, cost-effective certification pathways for secondary timber often results in conservative downgrading or outright rejection by insurers and structural designers [13]. Furthermore, the economic viability of timber reuse is undermined by high cross-contamination risks, specialized deconstruction labour costs, and fragmented secondary material markets [14]. These systemic uncertainties prevent a seamless 1:1 material substitution at end-of-life, necessitating a pragmatic accounting method that scales environmental credits according to the actual functional utility retained by the reclaimed components [15].

This challenge is further compounded by a noticeable gap in the current literature. Most existing timber circularity and LCA studies evaluate cascading scenarios at a macro level, relying on static or generalized recovery rates derived from generic national databases [16]. This macro-level approach neglects the physical material losses inevitably incurred during selective dismantling due to complex structural fasteners (e.g., embedded

steel plates, dowels, bolts) and localized mechanical damage [17]. In structural practice, degraded or contaminated connection zones require trimming, which prevents the direct reuse of full-length elements. This connection-induced yield loss significantly reduces the net volume of timber available for high-value structural cascading. Accurate EoL performance evaluations therefore require building-specific models capable of integrating digital material quantification with realistic joint-level losses.

To address this gap, this study proposes an integrated workflow combining precise BIM-derived quantification with an LCA functional equivalence allocation model to evaluate the EoL recovery potential of multi-storey timber structures. Using a representative building composed of glulam framing and cross-laminated timber (CLT) walls as a baseline, a digital model was constructed in Autodesk Revit (Version 2025, Autodesk Inc., San Francisco, CA, USA). Cutback allowances, mathematically derived from structural connection details and cutting tolerances, were applied to accurately separate gross material volume from net recoverable volume. Based on residual flexural strength, the recovered timber is systematically allocated across four cascading scenarios: structural reuse, non-structural reuse, engineered wood production, and energy recovery. To align with ISO 14044 principles [18], the carbon substitution benefits for each scenario are scaled using a functional equivalence factor (Q-factor) to account for market and material degradation. Sensitivity analyses on timber emission factors and design-for-disassembly (DfD) connection improvements further quantify how joint design variables dynamically influence the building's net global warming potential (GWP).

Specifically, this research addresses three core questions: (1) How can connection-induced physical material losses be geometrically quantified at the whole-building scale? (2) To what extent do these localized cutbacks reduce the theoretical biogenic carbon storage and EoL substitution benefits? (3) How do varying cascading pathways and Design for Disassembly (DfD) optimizations dynamically influence the net global warming potential (GWP) of the structural system?

2. Materials and Methods

This study develops a closed-loop LCA framework to evaluate the end-of-life (EoL) performance of primary timber structural elements, using design information from a representative multi-storey building. For the purpose of the carbon assessment, the building's operational context was assumed to be in the UK, enabling the consistent application of UK-based emission factors (EFs) and grid carbon metrics.

The analytical workflow is structured into three key stages: (1) extracting geometric quantities and connection-induced material losses using a BIM model; (2) establishing a baseline cradle-to-gate carbon assessment and biogenic carbon storage; and (3) simulating EoL pathways through a strength-based functional equivalence allocation framework. The overarching system boundaries and this integrated analytical workflow are illustrated in Figure 1.

2.1. BIM-Based Structural Modelling and Material Quantification

The selected case study is a representative 7-storey mass timber commercial building, featuring a total gross floor area of approximately 3500 m^2 and an assumed design service life of 60 years. While the architectural layout is hypothetical, the structural system, grid spacing (typically 6 m × 6 m), and connection typologies (concealed steel T-plates, slotted plates, and steel dowels) were strictly designed in accordance with standard UK structural timber engineering practices. A multi-storey mass timber building was selected as the baseline case study because the complex, high-load connections required in such structures (e.g., deeply embedded steel plates and dense fastener arrays) represent a severe

bottleneck for EoL recovery. While timber is traditionally prevalent in 1–2 storey residential houses, multi-storey mass timber represents the future of sustainable urban development. Nevertheless, the proposed BIM-LCA workflow is highly scalable and can be equally applied to smaller residential framing typologies. Autodesk Revit (Version 2025) was employed as the primary BIM platform to construct the digital structural twin and extract element-level quantities. The main load-bearing system consists of glued laminated timber (glulam) beams and columns, alongside cross-laminated timber (CLT) wall panels (Table 1).

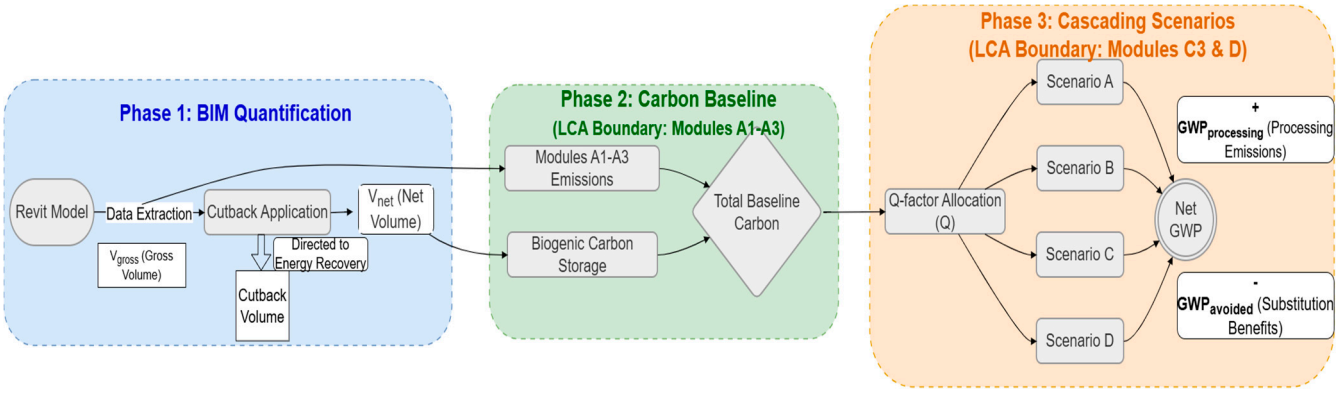

Figure 1. System boundary and analytical workflow integrating BIM quantification, baseline carbon assessment, and cascading EoL scenarios.

Table 1. Structural element types and cross-sectional dimensions.

Element ID	Element Type	Section (mm)
MZ1	Column	400 × 400
ML1	Primary beam	600 × 260
ML2	Secondary beam	520 × 240
ML3	Primary beam	680 × 260
ML4	Primary beam	400 × 240
WL1	Roof beams	400 × 240
FBL	Eaves beam	280 × 120
HJ	Truss member	240 × 240
FG	Truss member	240 × 140
CLT-1	Structural wall	160
CLT-2	Structural wall	200

Note: Element IDs (e.g., MZ, ML, WL, FBL) represent the specific component tags assigned within the BIM model. HJ and FG represent the top/bottom chords and internal web members of the roof truss system, respectively, which support the overarching roof envelope.

To accurately quantify the net recoverable timber volume, the initial idealised geometry was adjusted to account for practical material yield losses during EoL deconstruction. At connection interfaces, embedded steel plates, bolts, dowels, and localised damage typically contaminate or degrade the timber ends, rendering these regions unsuitable for full-length structural reuse. Consequently, connection-induced cutback allowances were applied within the BIM model (Figure 2).

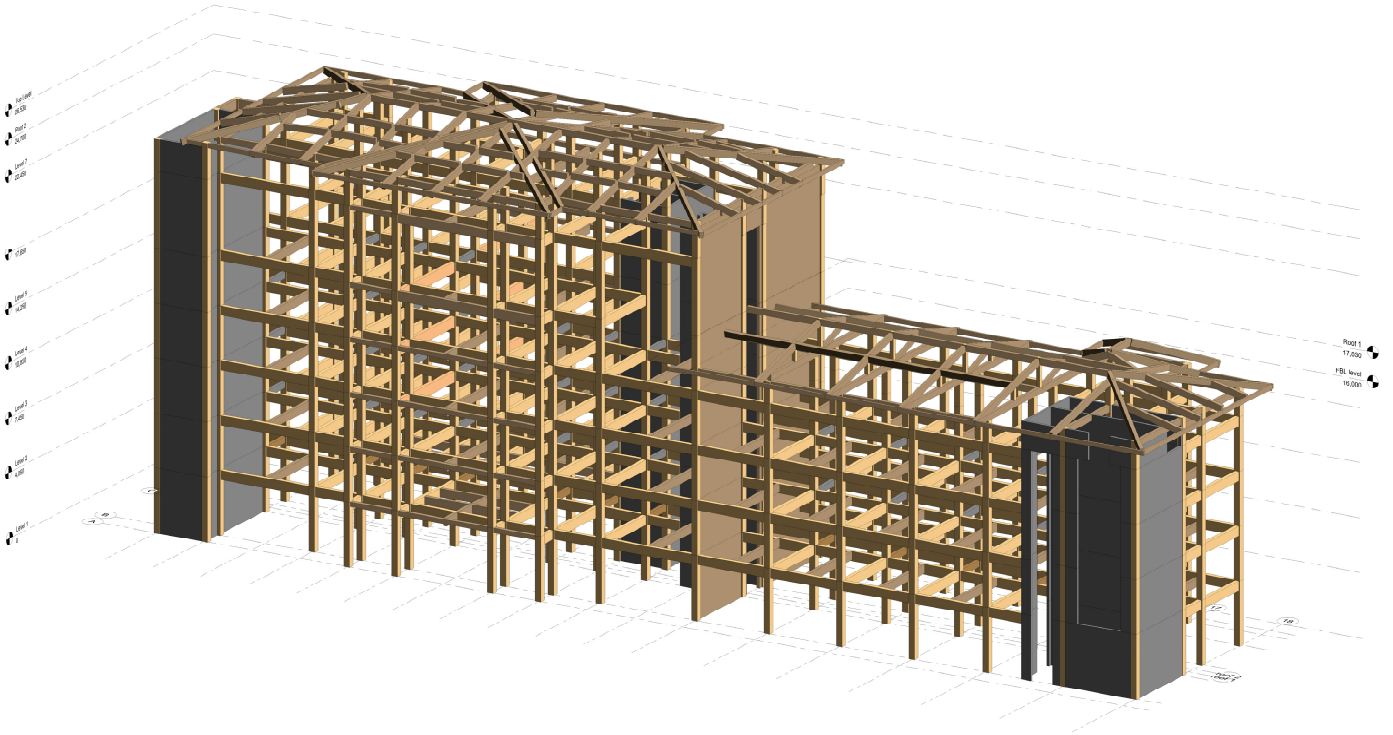

Figure 2. 3D model illustrating the idealised geometry of beams, columns and wall panels prior to the application of connection-induced cutbacks. The circled letters and numbers denote the standard structural grid lines (typically 6 m × 6 m spacing).

The specific cutback lengths were established by measuring the longitudinal extent of the steel plates and fasteners within the structural details. To this baseline, a mandatory 15 mm physical tolerance was added. This allowance accounts for operational constraints during selective dismantling, such as saw kerf widths, the extraction of embedded dowels, and the removal of localized wood fibre crushing surrounding the fastener holes [19]. Recent studies on reverse logistics in timber construction emphasize that conservative trimming allowances are critical to preventing blade damage during secondary processing and ensuring the structural integrity of the newly established member ends [15,20]. Conversely, CLT wall elements were assumed to be recovered as whole planar elements utilizing surface-based fixings; thus, no volumetric cutbacks were applied to these specific components. The extracted BIM quantities were subsequently processed using Python (Version 3.10, Python Software Foundation, Wilmington, DE, USA) via Google Colab to aggregate the gross structural volume (V_{gross}), the cutback waste volume, and the net recoverable volume (V_{net}) across all element categories. The nomenclature and key Life Cycle Assessment (LCA) parameters utilized in this study are summarized in Table 2.

Table 2. Nomenclature and key LCA parameters utilized in the assessment.

Parameter	Description	Value/Unit	Source
V_{gross}	Gross structural timber volume extracted from BIM	m^3	BIM model
V_{net}	Net recoverable timber volume after connection cutbacks	m^3	BIM model
$V_{\text{recovered}}$	Volume of timber allocated to a specific cascading scenario	m^3	BIM allocation
Q	Functional Equivalence Factor for environmental allocation	0.2–0.8	Assumed/ISO 14044 [18]
ρ_{glulam}	Density of glued laminated timber	472 kg/m^3	Material specifications
ρ_{CLT}	Density of cross-laminated timber	469 kg/m^3	Material specifications
EFA1−A3,glulam	Production emission factor for glulam	0.42 $kgCO_2e/kg$	ICE Database V3.0
EFA1−A3,CLT	Production emission factor for CLT	0.35 $kgCO_2e/kg$	ICE Database V3.0
$E_{\text{machining}}$	Specific energy requirement for secondary wood processing	40 kWh/m^3	Literature [21,22]
EF_{grid}	UK grid greenhouse gas intensity coefficient	0.177 $kgCO_2e/kWh$	DESNZ 2023 [23]
$EF_{biogenic}$	Biogenic carbon sequestration factor for timber	−1.833 $kgCO_2e/kg$	EN 16449:2014 [24]/Stoichiometry

2.2. Baseline Carbon Assessment

A baseline carbon assessment quantified the production-stage emissions and the biogenic carbon storage of the timber elements, providing a reference to evaluate the environmental implications of subsequent cascading EoL scenarios. While the primary focus of this study lies in quantifying the EoL substitution benefits (Module D), establishing the Module A1–A3 baseline is essential. It provides the necessary quantitative context to understand the relative magnitude of EoL savings against the initial environmental investment of the structural system, thereby adhering to the holistic reporting principles of EN 15978.

Production Stage Emissions (Modules A1–A3): The global warming potential (GWP) of the timber elements was calculated following the cradle-to-gate system boundary defined in EN 15804 [25]. This encompasses raw material extraction, transport, and manufacturing. The calculation utilizes the gross timber volume (V_{gross}) extracted from the BIM model—including the cutback waste—because all initial material undergoes industrial processing regardless of EoL trimming.

$$GWP_{\text{production}} = V_{\text{gross}} \cdot \rho \cdot EF_{A1-A3} \tag{1}$$

where ρ represents the material density (assigned as 472 kg/m^3 for glulam and 469 kg/m^3 for CLT), and $EF_{\text{A1–A3}}$ is the emission factor associated with production.

Biogenic Carbon Storage: Timber functions as a temporary carbon sink. Following EN 16449:2014, the biogenic carbon storage was quantified based on the net structural volume (V_{net}) remaining within the building over its service life, excluding the immediate connection waste.

$$C_{\text{biogenic}} = V_{\text{net}} \cdot \rho \cdot c_{\text{carbon}} \cdot \frac{44}{12} \tag{2}$$

Based on this stoichiometric relationship, the specific biogenic carbon sequestration factor ($EF_{biogenic}$) applied in this study is dynamically calculated as -1.833 kgCO_2e per kg of dry wood (derived from $0.5 \times 44/12$). Explicitly isolating this biogenic sequestration factor from the fossil-based production emissions (Modules A1–A3) ensures rigorous data transparency and accurately distinguishes the inherent carbon sink characteristics of the timber materials.

Where c_{carbon} is the default carbon content fraction of dry wood (0.5), and 44/12 is the molar mass conversion factor from elemental carbon to carbon dioxide.

2.3. Cascading Scenarios and Functional Equivalence Allocation

To evaluate EoL performance, a cascading framework was developed to represent the progressive reuse and downgrading of recovered timber. Recovered elements exhibit reduced structural utility due to localized damage, geometric trimming, and grading uncertainties. Therefore, a quality factor (Q) was introduced based on the ratio between the assumed residual characteristic bending strength and its original state (GL24, $f_{\text{m,k}} = 24$ MPa):

$$Q = \frac{f_{m,k,\text{cascade}}}{f_{m,k,\text{virgin}}} \tag{3}$$

It is important to note that these four scenarios represent mutually exclusive alternative EoL pathways, rather than fractional distributions of a single mass balance. Therefore, the Q-factors do not sum to 1.0. Instead, each factor defines the specific substitution efficiency for that given pathway (e.g., 1 m^3 of reclaimed timber displaces 0.8 m^3 of virgin timber in Scenario A). Crucially, in this study, the Q-factor is not intended as a deterministic mechanical property for structural design. Instead, it serves as a functional equivalence ratio within the LCA substitution framework, aligning with ISO 14044 allocation principles.

It scales the substitution benefits to realistically reflect the reduced utility of reclaimed timber when displacing virgin materials in secondary applications. Four scenarios were established (Table 3).

Table 3. Cascading scenarios based on functional equivalence allocation.

Scenario	End-of-Life Pathway	Functional Equivalence Factor (Q)	Assumed Functional Utility & Substitution Logic
A	Structural reuse	0.8	High-value structural relocation; elements are derated or re-machined for secondary load-bearing applications.
B	Non-structural reuse	0.6	Repurposed into non-load-bearing architectural elements (e.g., cladding, flooring) with reduced mechanical utility.
C	Engineered wood recovery	0.4	Mechanically reprocessed and downcycled into composite engineered wood products (e.g., particleboard, MDF).
D	Energy recovery/biomass	0.2	Thermal energy recovery via controlled incineration at the absolute terminal stage of the material life cycle.

Material removed during connection trimming was treated as a separate waste stream directed entirely to Scenario D (Energy recovery), as it is unsuitable for material reprocessing.

The net environmental impact of each cascading scenario balances the processing emissions required to prepare the recovered timber against the avoided emissions from substituting virgin material:

$$GWP_{\text{processing}} = V_{\text{recovered}} \cdot E_{\text{machining}} \cdot EF_{\text{grid}} \quad (4)$$

$$GWP_{\text{avoided}} = -(Q \cdot V_{\text{recovered}} \cdot \rho \cdot EF) \quad (5)$$

$$\text{Net GWP} = GWP_{\text{processing}} + GWP_{\text{avoided}} \quad (6)$$

where $E_{\text{machining}}$ is the fixed energy requirement for secondary processing (40 kWh/m^3), and EF_{grid} is the UK grid emission factor (0.177 kgCO_2e/kWh). This value is derived from life cycle inventory data for reclaimed wood processing, which aggregates the energy demands of scanning for metallic contaminants, mechanized de-nailing, trimming, and secondary planning required to reinstate standard geometric profiles [21,26]. Adopting this parameter ensures that the environmental penalty of preparing EoL timber for cascading applications is realistically captured, preventing an overestimation of the net substitution benefits [22].

2.4. Sensitivity Analysis Framework

To test the robustness of the carbon results, a sensitivity analysis targeted two highly influential variables: timber emission factors and connection cutback volumes.

Firstly, while the baseline assessment utilized traditional ICE database EFs (Version 3.0, 2019, 0.42 kgCO_2e/kg for glulam), an updated case was assessed using contemporary Environmental Product Declaration (EPD) values (0.28 kgCO_2e/kg for glulam and 0.25 kgCO_2e/kg for CLT). This comparison accommodates the high variability in mass timber embodied carbon driven by recent grid decarbonisation and manufacturing efficiency improvements [27]. Secondly, the impact of Design for Disassembly (DfD) was tested by applying a 50% cutback reduction—representing achievable improvements in demountable connection detailing—and a 100% idealised elimination case to benchmark the theoretical maximum carbon benefit of zero-waste recovery. It is important to note that while a 50% cutback reduction reflects achievable near-term improvements in demountable detailing, the 100% elimination scenario is included not as a current practical reality, but as an idealized theoretical benchmark. This extreme boundary condition serves to quantify the

absolute maximum carbon penalty imposed by traditional connection paradigms, thereby defining the ultimate theoretical limit of DfD optimization.

3. Results

3.1. Material Recovery Inventory and Connection-Induced Losses

The material extraction from the digital twin quantified the distribution of timber volume across the structural framework. Prior to accounting for EoL degradation, the structural system comprised a gross timber volume of 1004.29 m^3. Following the application of connection-induced cutback allowances, the net recoverable timber volume was calculated at 837.39 m^3, while 166.89 m^3 was classified as connection-affected waste. This corresponds to a structural material yield loss of 16.62% directly attributable to connection detailing.

Table 4 details the material inventory across the four primary element groups. The highest proportional material loss occurred in the column elements, where 75.28 m^3 was removed from a gross volume of 260.38 m^3, equating to a 28.91% loss. Beams accounted for the largest absolute gross volume (349.53 m^3) but exhibited a lower proportional loss of 20.93%. This discrepancy in proportional loss is primarily geometrically driven. Columns typically feature multiple heavy-duty connection interfaces—such as base moment connections and inter-storey splices—combined with a significantly shorter relative member length compared to continuous horizontal spanning beams. Consequently, the fixed connection cutback lengths consume a much higher mathematical proportion of the column's total gross volume. Wall elements recorded no modelled cutback loss (0%), based on the assumption that CLT panels utilize surface-based fixings and can be recovered as whole planar components without requiring end trimming.

Table 4. BIM-derived timber inventory and connection-induced material loss.

Element Group	Element ID	Number of Elements	Gross Volume (m^3)	Net Recoverable Volume (m^3)	Cutback Volume (m^3)	Material Loss (%)
Beams	ML1, ML2, ML3, ML4	829	349.53	276.37	73.16	20.93
Columns	MZ1	471	260.38	185.10	75.28	28.91
Roof elements	FBL, HJ, FG, WL1	355	91.99	73.54	18.44	20.05
Walls	CLT-1, CLT-2	220	302.39	302.39	0.00	0.00
Total	—	1875	1004.29	837.39	166.89	16.62

3.2. Baseline Carbon Assessment Results

The baseline carbon assessment quantified both the upfront production emissions and the biogenic carbon storage capacity of the timber structure (Table 5). Total production-stage emissions (Modules A1–A3) were calculated at 198.7 tCO_2e, based on the gross volume of timber extracted, thereby accounting for the manufacturing impacts of both the retained structure and the subsequent connection waste. Conversely, the total biogenic carbon sequestered within the net structural volume was calculated at 723.0 tCO_2e. The biogenic carbon storage exceeds the production-stage emissions across all element types, with total stored carbon being approximately 3.6 times greater than the initial manufacturing impacts.

Table 5. Production-stage emissions and biogenic carbon storage for structural timber elements.

Element Type	Production GWP, A1–A3 (tCO_2e)	Biogenic Carbon Storage (tCO_2e)
Columns	51.6	160.2
Beams and roof elements	87.5	302.8
Walls	59.6	260.0
Total	198.7	723.0

3.3. Net Carbon Performance of Cascading EoL Scenarios

Preparing the recovered elements involves secondary machining to remove degraded connection interfaces. The total processing emissions assigned to this machining phase amounted to 3.8 tCO_2e, generated entirely from columns, beams, and roof elements. No processing emissions were assigned to wall panels due to the zero-cutback assumption.

Table 6 presents the net GWP outcomes across the four strength-based cascading pathways. Negative values denote an avoided climate impact relative to the production of equivalent virgin materials. Structural reuse (Scenario A) generated the highest carbon benefit, achieving a net GWP of −128.7 tCO_2e. This benefit progressively diminishes as the functional equivalence factor (Q) decreases, with energy recovery (Scenario D) providing the lowest net benefit of −29.3 tCO_2e. Furthermore, the 166.89 m^3 of timber removed during connection detailing—containing approximately 144.1 tCO_2e of biogenic carbon—was allocated entirely to energy recovery, representing an immediate release of stored carbon and a substantial reduction in the overall circular value of the structural system.

Table 6. Total avoided and net GWP across cascading scenarios.

Scenario	End-of-Life Pathway	Functional Equivalence Factor Q	Avoided Emissions (tCO_2e)	Net GWP (tCO_2e)
A	Structural reuse	0.8	−132.5	−128.7
B	Non-structural reuse	0.6	−99.4	−95.6
C	Engineered wood recovery	0.4	−66.3	−62.5
D	Energy recovery	0.2	−33.1	−29.3

3.4. Sensitivity Analysis: Design for Disassembly and Emission Factors

A sensitivity analysis assessed the influence of DfD optimisation on net carbon performance. As detailed in Figure 3, reducing connection-induced cutbacks enhances the recoverable timber volume, leading to improved environmental outcomes. Implementing a 50% cutback reduction, representing a practical improvement in demountable connections, increased net GWP savings by 12.2% to 19.7% depending on the EoL pathway. The idealised scenario of 100% cutback elimination yielded maximum improvements ranging from 23.5% to 35.5%.

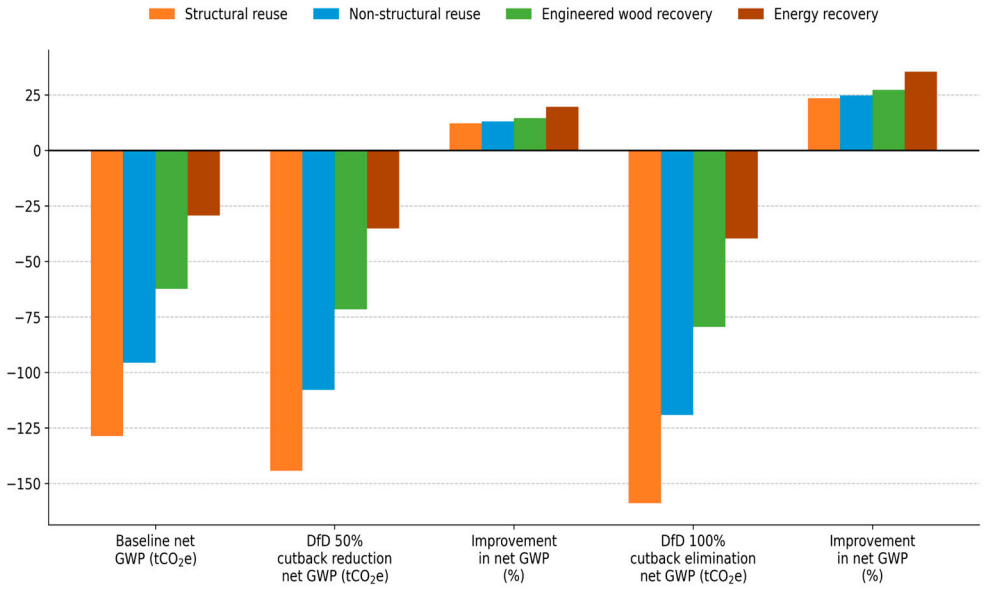

Figure 3. Total net GWP for baseline and DfD scenarios.

An additional sensitivity test examined the impact of adopting updated EPD-based emission factors (Table 7). Applying lower manufacturing EFs directly reduces the calculated avoided emissions obtained through material substitution. Consequently, the absolute magnitude of the net carbon benefits decreased substantially by 37.0% to 40.5% across all pathways. Despite this reduction, the fundamental ranking of the EoL scenarios remained unchanged, reaffirming structural reuse as the optimal environmental strategy.

Table 7. Sensitivity of net GWP to emission factor assumptions.

End-of-Life Pathway	Baseline EF Net GWP (tCO_2e)	Updated EF Net GWP (tCO_2e)	Reduction in Calculated Carbon Benefit (%)
Structural reuse	−128.7	−81.1	37.0
Non-structural reuse	−95.6	−59.9	37.3
Engineered wood recovery	−62.5	−38.7	38.1
Energy recovery	−29.3	−17.4	40.5

4. Discussion

4.1. Material Recoverability and the Impact of Connection Detailing

The digital quantification revealed a 16.62% volumetric loss directly attributable to connection trimming. This underscores that the theoretical reusability of timber is significantly constrained by joint detailing. While previous studies, such as Akanbi et al. [17], relied on generalised reusability ratios for entire structural systems, the present BIM-integrated workflow physically localises these losses at the component level. This component-specific approach provides a more realistic inventory for circularity assessments. However, achieving the modelled 50% or 100% reduction in cutbacks depends entirely on practical deconstruction conditions. As highlighted by Laasonen and Pajunen [28], actual disassembly is governed by factors such as joint accessibility, component independence, and standardization. Recent literature further corroborates that overcoming these technical and socio-economic barriers remains a primary challenge for implementing circular design in mass timber construction [29].

4.2. Evaluation of Cascading Carbon Benefits

The baseline assessment confirmed that the multi-storey timber structure functions as a significant biogenic carbon reservoir (723.0 tCO_2e), vastly exceeding upfront production emissions. This aligns with Churkina et al. [2], who demonstrated the carbon-sink potential of long-life structural timber. However, preserving this benefit post-service life necessitates high-value cascading. The scenario analysis indicates that direct structural reuse yields the maximum net carbon benefit (−128.7 tCO_2e). In contrast, diverting the material to energy recovery drastically diminishes the substitution credits (−29.3 tCO_2e) and results in the immediate release of stored carbon. A recent meta-analysis by Zheng et al. [30] corroborates this, demonstrating that the structural reuse of mass timber mitigates environmental impacts far more effectively than recycling or energy recovery.

4.3. Methodological Limitations of the Functional Equivalence Approach

A critical limitation of this study is the reliance on the Q-factor to model residual structural utility. While employing a functional equivalence ratio is standard practice in LCA substitution frameworks to handle grading uncertainties, it inherently compresses complex mechanical, durability, and market variables into a single scalar value. In reality, authorising reclaimed timber for load-bearing applications (Scenario A) demands rigorous non-destructive testing (NDT) and visual grading to verify compliance with structural codes [31]. Moreover, the current BIM quantification focuses exclusively on primary

structural connections, omitting non-structural material removals such as penetrations for mechanical, electrical, and plumbing (MEP) systems, which would further reduce the net yield of CLT walls. In practice, the actual cascading potential of reclaimed timber is also heavily compromised by unpredictable in-service degradation—including moisture ingress, fungal decay, and potential fire damage—as well as architectural spatial constraints caused by the shorter spans resulting from connection trimming. Furthermore, as demonstrated by the sensitivity analysis, dynamic assumptions regarding background emission factors significantly alter the magnitude of avoided emissions, a finding consistent with recent methodological reviews on LCA lifespan assumptions [32]. Future research must couple parametric BIM workflows with probabilistic reliability models, empirical grading data and architectural spatial constraints to bridge the gap between theoretical LCA functional equivalence and actual structural performance. Furthermore, future studies must seek to empirically validate this theoretical framework by tracking real-case deconstruction projects, comparing the BIM-predicted recoverable volumes against the actual material yields achieved on-site.

4.4. Comparative Analysis with Alternative Structural Systems

Evaluating timber circularity requires contextualization against conventional structural materials, such as steel and precast concrete. The findings of this study—specifically the 16.62% volumetric loss—highlight a fundamental limitation inherent to timber deconstruction. Unlike steel, which can be unbolted and remanufactured with minimal geometric penalty or melted without quality degradation [33], timber's fibrous matrix is highly susceptible to localized crushing and splintering around mechanical fasteners [34]. The irreversible embedding of screws, dowels, and slotted plates often necessitates destructive trimming to yield structurally viable components for subsequent life cycles [15]. Consequently, while mass timber systems provide unparalleled biogenic carbon storage during their primary service life, their post-use material yield is disproportionately constrained by joint reversibility. To bridge the recovery efficiency gap between timber and steel frameworks, structural design paradigms must increasingly adopt externalised or friction-based reversible connections that isolate stress concentrations and preserve the primary wood volume [19].

4.5. Policy, Regulatory, and Economic Implications for Timber Circularity

Although the cascading allocation model demonstrates that structural reuse (Scenario A) yields the maximum net carbon benefit, translating these theoretical savings into market reality faces steep regulatory and economic barriers. Current structural design codes, including Eurocode 5, are predominantly calibrated for virgin timber. The absence of standardized, cost-effective certification pathways for reclaimed elements forces practitioners to rely on conservative visual grading or prohibitive non-destructive testing regimes [31]. Furthermore, the economic viability of preserving component geometry is undermined by the labour-intensive nature of selective deconstruction compared to conventional demolition [20].

To realize the theoretical carbon savings associated with optimized Design for Disassembly (DfD), systemic policy interventions are required. The integration of digital Material Passports—a core objective of emerging circular economy frameworks—can permanently link physical timber elements with their BIM-derived load histories and connection metadata, thereby reducing downstream testing uncertainties [7,35]. Moreover, aligning international sustainability standards, such as ISO 20887:2020 for DfD [36], with carbon pricing mechanisms could financially penalize the premature incineration of structurally viable timber (Scenario D). Monetizing the retained biogenic carbon and avoided production emis-

sions would directly incentivize supply chains to prioritize high-value cascading (Scenarios A and B) over terminal energy recovery [14]. Importantly, this integrated quantification method directly supports the operationalization of the voluntary carbon market and the EU Carbon Removal Certification Framework (CRCF). To successfully issue carbon credits for temporary carbon storage in the built environment, rigorous Monitoring, Reporting, and Verification (MRV) protocols are essential. By utilizing Reversible BIM to track component volumes and Q-factors to scale degradation, the proposed workflow provides the granular, verifiable data necessary to substantiate dynamic carbon credit allocations across sequential building life cycles. Additionally, transitioning towards circular business models—such as Extended Producer Responsibility (EPR) or proprietary take-back schemes where the original construction firm also executes the EoL dismantling—could overcome the fragmented nature of the demolition sector. By keeping the reclaimed materials within a closed-loop corporate blueprint, manufacturers would be directly financially incentivized to maximize non-destructive recovery.

5. Conclusions

This study evaluated the EoL circularity and carbon performance of a multi-storey timber structure by integrating BIM material quantification with a functional equivalence LCA framework. The primary findings are:

- Connection-Induced Yield Losses: Incorporating realistic cutback allowances for embedded steel plates and fasteners results in a 16.62% yield loss from the gross structural volume. This localized damage fundamentally reduces the material pool available for high-value reuse, distinguishing timber's recovery challenges from those of highly reversible metallic structures.
- Cascading Carbon Performance: Maintaining timber at its highest functional level is imperative for maximizing climate change mitigation. Direct structural reuse provides a net carbon benefit of -128.7 tCO_2e, drastically outperforming non-structural recycling (-62.5 tCO_2e) and terminal energy recovery (-29.3 tCO_2e).
- Design for Disassembly (DfD): Optimizing joint detailing to halve connection-related material losses enhances net global warming potential (GWP) savings by up to 19.7%, confirming that connection design is the primary bottleneck for mass timber circularity.
- Methodological Integration: Utilizing functional equivalence factors (Q-factors) within ISO 14044 parameters effectively scales substitution benefits, providing a robust method to bridge the gap between BIM geometric inventories and LCA environmental credits.

To actualize these modelled environmental benefits, future engineering practice must prioritize standardized, accessible, and independent connection systems that adhere to DfD principles. Furthermore, achieving scalable timber circularity requires systemic policy shifts, including the mandate of digital material passports and the establishment of clear, code-compliant certification routes for reclaimed structural timber. Ultimately, this integrated BIM-LCA framework provides a robust methodological reference for the timber industry, demonstrating how digitalization can optimize reverse logistics and foster circular industry chains.

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