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Modern Methods of Construction as a Way to Reduce Construction Waste in The Context of a Circular Economy

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Abstract. The abstract should include the purpose of research, principal results and major conclusions. References should be avoided, if it is essential, only cite the author(s) and year(s) without giving reference list. Currently, the AEC industry (Architecture, Engineering, and Construction) offers many material and design options for the design, production and implementation of buildings. Great emphasis is placed on buildings with environmental aspects that save the environment, while meeting all norms, standards and requirements of even the most demanding customers. Modern methods construction-based wood meet all these attributes. In addition, they have significant environmental benefits, as they leave a low ecological footprint throughout the entire life of the building. Modern methods construction-based wood can be classified as fast and ecological construction, because wood as a renewable raw material offers many advantages for the construction industry. One of them is the reduction of construction waste. Moreover, the construction waste generated in this way can be reused and recycled. These three approaches represent the three principles (3R) of the circular economy. The paper devotes to the analysis of the modern methods construction-based wood on site and off site options. The aim of the paper is to identify the type and source of construction waste for selected structural systems of wooden constructions (stud frame, panel, modular and log), which differ in the degree of industrialization and prefabrication. They can be manufactured under controlled conditions in production halls (off-site) and only assembled on the construction site, or manufactured and assembled on the construction site (on-site). Based on analytical knowledge, hypotheses are defined regarding the amount of construction waste, the place of its origin and the influence of the structural system of wooden buildings on the generation of construction waste. The conclusions of the paper were determined based on the frequency of waste generation in the studied areas, which provided the basis for the processing of the hypotheses.

Keywords: Construction; modern methods construction-based wood; construction waste; production; realization

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INTRODUCTION

The architecture, engineering, and construction (AEC) sector is currently undergoing a fundamental paradigm shift driven by the urgent need to mitigate climate change and reduce the environmental degradation associated with human activities. Globally, the construction industry is responsible for nearly 40% of energy-related greenhouse gas emissions and generates approximately one-third of all waste (1,2). In response to strict European Union environmental policies and shifting market demands, contemporary construction must satisfy not only rigorous technical standards and client requirements but also integrate comprehensive sustainability metrics throughout a building's life cycle (3).

EU circular policies drive a shift from traditional construction waste management to Modern Methods of Construction (MMC), utilizing digital material passports, prefabrication, and design-for-deconstruction to eliminate

waste (4). To meet these multifaceted attributes, modern methods of construction (MMC) based on timber have emerged as a highly viable, eco-friendly, and rapid alternative to traditional carbon-intensive building practices (5, 6). As a renewable and bio-based raw material, wood sequesters carbon during its growth period, resulting in a significantly lower ecological and carbon footprint over the entire lifespan of the structure compared to concrete or steel alternatives (7).

A critical imperative of timber-based MMC is its potential to achieve enhanced material efficiency and minimize construction and demolition waste (CDW) (8). This capacity aligns directly with the 3R principles (Reduce, Reuse, Recycle) of the circular economy (CE) framework. The systematic application of the 3R framework in timber construction allows for the reduction of raw material consumption at the source, while ensuring that the generated timber scrap is highly compliant with subsequent reuse strategies or downcycling and recycling loops (9, 10). Consequently, circular wood management minimizes primary resource extraction and avoids the landfilling of valuable organic matter.

However, the volume, composition, and spatial distribution of timber construction waste are heavily dictated by the choice of the structural system and the degree of industrialization (11). Modern timber architecture utilizes a variety of structural typologies - ranging from traditional log systems to engineered beam (post-and-beam), panelized (two-dimensional elements), and volumetric modular (three-dimensional units) systems. Concurrently, these systems alter the geographic location of fabrication processes, distinguishing between conventional on-site assembly and advanced off-site prefabrication under controlled factory conditions (12).

RESEARCH MATERIAL AND METHODS

While off-site prefabrication is widely recognized for optimizing material cutting, improving quality control, and mitigating site-level waste, there remains a distinct research gap regarding the empirical comparison of waste streams across different industrialized timber systems. Specifically, precise data mapping the frequency, type, and exact source of waste generation between on-site and off-site boundaries across distinct structural systems remains fragmented.

To address this knowledge gap, the objective of this paper is to systematically identify the types and precise sources of construction waste generated by four selected structural systems of wooden construction (stud frame, panel, modular, and log). This study provides a comparative analysis of their performance within both on-site and off-site settings. Based on analytical and empirical evidence, specific scientific hypotheses are formulated and evaluated concerning the total volume of generated waste, its localized place of origin, and the direct influence exerted by the structural configuration. Ultimately, the conclusions of this research are derived from a rigorous frequency analysis of waste generation within the investigated parameters, establishing a robust baseline for waste-minimization protocols in sustainable timber manufacturing.

Research Material

Given that this study aims to identify the specific types and sources of construction and demolition waste (CDW) across selected structural timber systems - namely stud-frame, panelized, modular, and log constructions—which inherently exhibit varying levels of industrialization and prefabrication across both off-site and on-site phases, the primary research material comprises representative case studies from each analyzed category. Consequently, four distinct system archetypes are selected as the empirical foundation to isolate and quantify the waste streams unique to each manufacturing and assembly paradigm.

Prior to investigating the issue of construction waste generation within wood-based MMC, it is essential to categorize the relevant structural timber systems and provide a concise characterization of their production and assembly methods. The analysis is conducted across four core categories of timber-based structural systems (Figure 1):

- stud frame system (stick-built or two-by-four construction),
- panelised system (2D prefabrication),
- volumetric modular system (3D prefabrication),
- log system (mass timber construction).

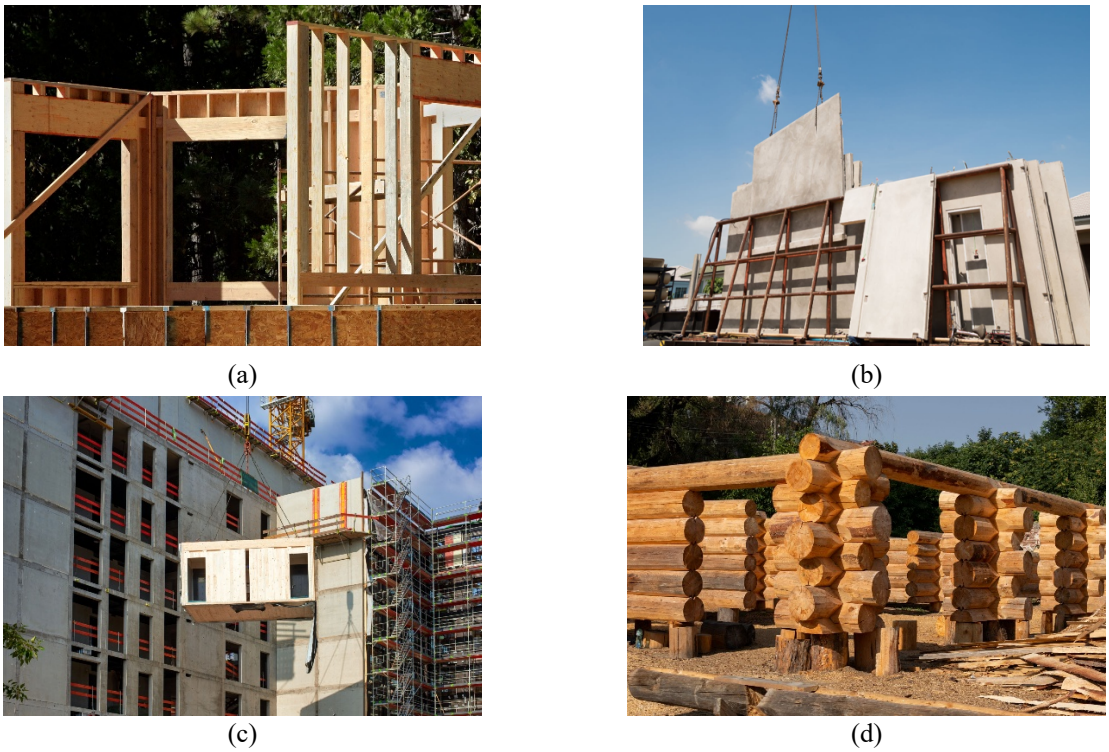
The stud frame system is characterized by ow degree of prefabrication and by predominantly on-site realization. The stud frame system relies on assembling the load-bearing framework directly on the construction site. Off-site processing is minimal, limited to timber drying, planning, and pre-cutting into generic structural dimensions. The

critical tasks of precise cutting, shaping, and sheathing are performed entirely on-site. This system carries the highest risk of generating heterogeneous construction waste on-site due to manual processing errors and off-cut adjustments.

The panelised system is characterized by medium to high degree of prefabrication and by balanced off-site and on-site distribution. Entire wall, floor, and roof elements are manufactured as flat 2D panels inside climate-controlled factories using specialized automated machinery or CNC formatting tables. Panels are transported to the site often pre-fitted with insulation, internal sheathing, and sometimes windows. On-site assembly is rapid, requiring a crane to lift and secure the panels onto the foundation. This method shifts the vast majority of processing waste from the construction site to the factory floor, where systematic recycling is highly feasible.

The volumetric modular system is the highest degree of prefabrication; 85–90% of all operations occur off-site. This system represents the pinnacle of industrialized construction, where complete 3D volumetric units (modules) are finished entirely within a factory setting. Production lines mimic automotive manufacturing, integrating structural frames with interior finishes, plumbing, electrical installations, fixtures, and cabinetry. The completed modules are transported to the site, crane-lifted onto ready-made foundations, and connected to the utility networks. On-site structural material waste is virtually eliminated.

The log system is presents a specific system of wood-based constructions. The system is mechanized off-site profiling with artisanal on-site stacking. The structural integrity relies on horizontally stacked solid or laminated timber logs joined at corners via interlocking notches. In modern log construction, elements are pre-engineered using automated CNC log-cutting lines. The structure is often pre-assembled at the factory to check tolerances, then disassembled, numbered, and sent to the site. On-site labour is reduced to systematic stacking, minimizing raw material cutting on the plot.



(a) (b) (c) (d)

FIGURE 1. Types of wood-based constructions: (a) stud frame system, (b) panelised system, (c) volumetric modular system, (d) log system.

A detailed analysis (13) (table 1) of the material and product composition applied across individual construction phases subsequently establishes the determinative framework for identifying the associated technological and operational activities and their possible waste trajectory.

TABLE 1. The material and product composition and waste trajectory for wood-based constructions. (13)

Construction stage	Materials and Products Used	Associated Activities (Waste Trajectory)
Stud Frame System (Stick-Built)		
Structural framework	Solid structural timber (KVH), glued laminated timber (Glulam/BSH) for larger spans, metallic connectors, nails, and screws.	On-site sawing of timber to exact dimensions, drilling, and joinery. Generates significant solid wood off-cuts and sawdust.
Sheathing and bracing	Oriented strand boards (OSB), gypsum fiberboards, and plasterboards.	On-site formatting of sheet materials. Cutting out openings for windows and doors generates substantial panel scrap.
Insulation and membranes	Mineral wool (rock or glass wool), vapor barriers, and breathable membranes.	Manual fitting of insulation between studs. Yields residual insulation scraps and membrane off-cuts.
Panelized System (2D Prefabrication)		
Off-site panel fabrication	Engineered wood products (KVH, LVL, CLT), insulation cores, and multi-layer sheathing.	Industrial large-scale cutting. Material use is optimized via software; resulting scraps are captured for factory-level briquetting or energy recovery.
Logistics and on-site erection	Prefabricated panels, heavy crane machinery, anchoring steel brackets, and expanding sealing tapes.	Crane-assisted positioning of panels onto the foundation. Negligible material waste; waste streams consist mostly of packaging waste (pallets, plastic film).
Jointing and detailing	Structural fasteners, joint sealants, and system tapes.	Sealing and bridging the structural boundaries between adjacent panels.
Volumetric Modular System (3D Prefabrication)		
Complete off-site production	Combined timber framing, CLT elements, drywalling, tiling, sanitary ware, electrical wiring, and piping.	Serial manufacturing with strict sorting. All technological waste stays in the factory, allowing precise sorting into clean mono-fractions (gypsum, plastics, wood).
Transport and on-site interlocking	Fully fitted modules, specialized crane rigging, and heavy-duty mechanical connection systems.	Positioning modules on foundations/piers. No raw material manipulation takes place on-site; waste is confined to protective transit packaging.
Utility integration	Flexible plumbing couplers, electrical busbars, and aesthetic trim pieces.	Interconnecting the pre-engineered utility and infrastructure shafts between adjacent modules.
Log System (Mass Timber Construction)		

Off-site profiling	Solid timber logs or glued laminated log profiles.	Milling of longitudinal grooves and corner joints. Produces a high volume of uniform wood chips and sawdust (100% recyclable in wood-processing industries).
On-site stacking	Numbered log profiles, internal hardwood dowels for alignment, and specialized sealing strips (sheep's wool or memory foam).	Stacking logs like a model kit. Very few adjustments or cuts are made on-site, minimizing structural waste.
Settlement management	Heavy-duty adjustable screw jacks and vertical tensioning rods.	Installation of settling fixtures. Critical to accommodate the natural hygroscopic shrinking and settling of mass timber in its early years.

Detailed analysis confirms that the construction stage and structural system directly determine the waste trajectory of timber buildings. The stick-built stud frame system suffers from high material scrap due to intensive on-site manipulation. Conversely, prefabricated panelized and volumetric 3D systems optimize material utilization via software and confine technical waste to off-site factories, transforming construction site waste into clean, sorted industrial fractions or protective packaging. Finally, mass timber log systems shift the waste stream into uniform, complete recyclable wood chips during the off-site profiling stage.

Research Methods

To identify and quantify the material composition and origin of construction waste during the prefabrication and assembly phases of timber structures, a dedicated monitoring methodology was developed. The baseline framework for categorizing waste streams was derived from the European Waste Catalogue (ECW). In compliance with ECW, the primary waste categories evaluated included:

- concrete, bricks, tiles, and ceramics,
- wood, glass, and plastics,
- bituminous mixtures, coal tar, and tarred products,
- metals (including their alloys),
- soil (including excavated soil from contaminated sites), stones, and dredging spoil,
- insulation materials and asbestos-containing construction materials,
- gypsum-based construction materials,
- other construction and demolition wastes.

To ensure a higher resolution comparative analysis that accounts for the material specificity of timber structures, this classification was modified and extended to include subcategories of materials and semi-finished products applied during individual construction stages. The analytical matrix was augmented with the following items:

- lumber and solid wood,
- engineered wood products (EWP),
- asphalt waterproofing membranes,
- expanded/extruded polystyrene (ESP, EXP),
- mineral and glass wool,
- bio-based and natural insulation materials.

A dedicated waste analysis matrix was established for each analyzed structural system. The matrix header systematically records the code and designation of the waste according to its respective group, subgroup, and species.

In terms of spatial allocation, the matrix is binarily divided by the location of waste generation:

- off-site subsystem (waste generated within the manufacturing facility/factory phase);
- on-site subsystem (waste generated during final assembly and erection on the construction site).

The timeline of both subsystems reflects the technological stages of construction, tracking three core phases: substructure (foundations), superstructure (including internal partition walls), and roofing (Table 1).

Primary data regarding material optimization and the management of manufacturing leftovers were gathered through structured interviews and electronic questionnaires conducted with selected contractors representing four pivotal timber construction systems: log, stud-frame, panelised, and modular (volumetric).

To facilitate an objective comparative evaluation of waste generation, a unified single-story residential building (bungalow typology) was selected as the reference model. The building features a rectangular floor plan and a gabled roof, with a total built-up area of 100 m^2. The scope of the analysis is strictly confined to the structural framework (load-bearing system)), defined by the exclusion of windows and doors, building service installations (MEP), and final surface finishes (flooring, plastering, facades). Regarding foundation technology, the log, stud-frame, and panelised systems exhibit identical material demands for the substructure. Conversely, the modular system incorporates an alternative foundation method using ground screws, significantly modifying the baseline waste balance during the initial construction phase.

To guide the empirical investigation into waste generation during the prefabrication and assembly of timber structures, the following research hypotheses were formulated:

H1: The volume of construction waste generated within the off-site manufacturing facility is significantly lower than that generated during on-site assembly. (6, 14)

H2: On-site construction methods generate a higher volume of timber waste during the superstructure phase compared to off-site manufacturing methods. (6)

H3: The variety and frequency of waste streams are greater in stud-frame structural systems than in log, panelized, and modular construction systems. (14, 15)

H4: Within on-site execution, stud-frame structural systems generate a higher amount of timber waste compared to log construction systems. (15)

H5: Within off-site manufacturing, panelized construction systems yield a higher volume of timber waste compared to modular (volumetric) systems. (16)

H6: Timber waste constitutes the largest quantitative share of the total waste stream generated during both the manufacturing and execution phases of wooden buildings. (17)

RESULTS AND DISCUSSION

The findings of this study are systematically evaluated from two complementary perspectives to ensure a comprehensive analysis of the material flows. The first section delineates the Spatial and Technological Distribution of Waste Streams, mapping the precise origin and typology of residues across the off-site (manufacturing facility) and on-site (construction site) subsystems, structured chronologically by construction phases. Building upon this empirical baseline, the second section focuses on Hypothesis Testing and Verification, where the previously formulated assumptions H1-H6 are rigorously evaluated against the gathered field and factory data to determine their statistical and practical validity within modern timber construction paradigms.

Spatial and Technological Distribution of Waste Streams

The mapping of construction waste reveals distinct generation patterns based on spatial allocation (differentiating between the off-site manufacturing environment and the on-site assembly domain) across three core technological phases: substructure, superstructure, and roofing. The data reflects how the choice of construction system fundamentally alters where and when specific material residues are produced.

The off-site manufacturing environment is characterized by a highly localized and selective waste footprint. During the initial substructure (foundation) phase, factory-level waste is completely non-existent across all analyzed construction typologies. Material processing and subsequent waste generation in the factory environment only begin during the superstructure and roofing stages, and are strictly confined to industrialized modern methods of construction (MMC), specifically panelized and volumetric modular systems.

Within the off-site facility, the panelized system generates a continuous stream of both raw lumber and engineered wood product (EWP) waste during both the superstructure and roofing fabrication phases. In contrast, the volumetric modular system limits its factory timber waste exclusively to raw lumber during the superstructure phase, exhibiting zero EWP residues in the roofing stage. Crucially, the traditional stud-frame and log systems exhibit zero off-site waste across all technological stages, indicating that their raw material processing occurs entirely outside a controlled factory environment. The distribution of factory waste for mineral wool, plastics, and gypsum-based materials closely mirrors the timber patterns. These waste streams emerge during the off-site superstructure phase solely for the

panelized and modular configurations. In the subsequent roofing phase, this industrial footprint contracts, with only the panelized system continuing to generate plastic and mineral wool residues within the factory.

In contrast to the controlled factory environment, the on-site construction domain displays a pervasive, multi-material waste footprint that spans all evaluated structural configurations and operational phases. Material waste associated with the foundation stage exhibits high homogeneity among the stud-frame, log, and panelized systems. These three typologies simultaneously trigger identical waste streams consisting of concrete, iron, steel, asphalt waterproofing membranes, and excavated soil. Conversely, the volumetric modular system completely bypasses this mineral and heavy-metal waste matrix during the foundation phase. Instead, it generates localized site residues of lumber, EWPs, plastics, and mineral wool, reflecting its distinct sub-structural installation requirements, such as ground screw configurations. The field assembly of the superstructure and roofing introduces extensive waste overlap. The stud-frame system demonstrates a continuous material waste presence across all primary categories (including wood fractions, plastics, mineral wool, and gypsum) during both assembly phases. The log system exhibits a more streamlined profile on-site, generating exclusively lumber and plastic waste during the superstructure stage, with the addition of aluminum and gypsum residues during the roofing phase. Despite substantial factory prefabrication, both the panelized and modular systems continue to generate on-site waste during final assembly. The panelized system triggers lumber, EWP, plastic, and mineral wool waste across both the superstructure and roofing phases. The modular system mirrors this pattern but introduces unique material variances, such as generating structural steel waste exclusively during the on-site roofing assembly, while completely avoiding EWP waste during the final roofing stage.

Validation of the Formulated Hypotheses

To evaluate the spatial distribution of material waste streams, Hypothesis 1 (H1) was formulated as follows: Less construction waste is generated within the off-site manufacturing facility than on the construction site. Industrializing the production of wood-based buildings by shifting processes from the open field to a controlled indoor environment offers significant advantages, including reduced assembly times, optimized workforce utilization, and independence from adverse seasonal weather conditions. Most importantly, higher automation and advanced cutting nesting algorithms applied in factory settings maximize material efficiency and streamline subsequent waste recovery loops.

The empirical data collected from the selected structural systems strongly support and confirm H1. A comparative frequency analysis reveals a stark contrast between the two operational boundaries. Within the off-site manufacturing facility, only 15 instances (24%) of waste generation were documented for the tracked materials. Conversely, on-site construction production recorded 47 (76%) instances of waste generation which representing a three-fold increase compared to the factory environment. This significant imbalance statistically verifies that advanced prefabrication effectively suppresses localized material waste by centralizing raw material processing into a standardized, industrial environment.

Hypothesis H2 postulated that on-site construction methods generate a higher volume of timber waste during the superstructure phase compared to off-site manufacturing methods. To analyze this assumption within the paradigm of MMC, the evaluated structural timber systems were categorized based on their production environment. The on-site group comprises log and stud-frame systems, whereas the off-site group encompasses panelized and modular (volumetric) systems. From a technological standpoint, off-site prefabrication shifts material processing into a highly controlled factory environment. Although this methodology requires higher initial capital expenditure for manufacturing facilities, advanced machinery, and logistics, it significantly optimizes material efficiency and accelerates on-site assembly. Conversely, executing traditional systems directly on-site eliminates factory overheads but exposes the material processing to adverse climatic conditions and a higher probability of human error, which directly correlates with increased material degradation and cutting losses.

The empirical analysis of the waste distribution confirms a distinct variance in waste occurrence frequencies between the two paradigms. The collected data indicates that on-site assembly methods account for 60% of the observed timber waste occurrences during the superstructure phase, while off-site manufacturing methods account for the remaining 40%. Consequently, based on the documented distribution frequency, Hypothesis H2 is confirmed. The results substantiate that increased levels of prefabrication and industrialization effectively minimize timber waste streams during the critical superstructure execution phase.

Hypothesis H3 presumed that the frequency and diversity of construction waste generated by the stud-frame structural system would exceed those of log, panelized, and modular construction systems. This assumption was primarily rooted in market prevalence, as stud-frame structures represent the most frequently executed timber construction typology within the regional market. The data compiled across all technological phases refutes this

assumption. The frequency analysis of waste generation occurrences reveals that the panelized system exhibits the highest cumulative waste density, accounting for 31% of the recorded waste entries. The stud-frame and log structural systems demonstrate highly comparable distributions, accounting for 25% and 24% of the total waste occurrences, respectively. Conversely, the modular (volumetric) system generated the lowest environmental footprint in terms of waste diversity, representing only 20% of the observed occurrences.

Consequently, based on the documented empirical frequency distribution, Hypothesis H3 is rejected. The divergence between the initial assumption and the empirical results reveals an important technological paradox in panelized prefabrication. Although panelized systems utilize advanced off-site prefabrication, the multi-layered design of the 2D elements introduces heightened material complexity (incorporating combinations of structural timber, structural sheathing, multiple insulation layers, and membranes). Furthermore, as confirmed by the surveyed contractors, dimensional discrepancies or manufacturing tolerances during the factory phase frequently necessitate geometric adjustments and corrective trimming during the final on-site assembly. These cumulative factors trigger secondary waste streams that ultimately elevate the overall waste frequency of panelised construction above that of traditional site-built stud-frame systems.

Hypothesis H4 postulated that within the scope of on-site construction methods, stud-frame structural systems generate a higher frequency of timber waste compared to log construction systems. Investigating wood-based residues specifically within site-built environments is critical, given that natural timber and engineered wood products constitute the primary material inputs for both evaluated typologies. The data gathered from field monitoring supports this assumption. The frequency analysis of timber waste occurrences during the construction phase demonstrates a clear disparity between the two systems. As illustrated by the empirical distribution, the stud-frame structural system accounts for 67% of the recorded timber waste entries, whereas the log construction system represents only 33%.

Consequently, based on the documented frequency distribution, Hypothesis H4 is confirmed. The technological driver behind the lower waste frequency in log construction lies in the high degree of geometric pre-determination inherent to mass timber logs. Log home components are typically manufactured to exact specifications off-site; the timber packages arrive at the construction site as fully finished, numbered log profiles requiring only mechanical stacking onto the foundation. This processes eliminates cutting losses on site. Conversely, traditional on-site stud-frame execution heavily relies on the manual dimensioning, cutting, and trimming of individual structural elements (studs, plates, and rafters) directly on the field. This continuous, site-based modification of raw timber elements increases both human error and cutting residues, ultimately generating twice the frequency of timber waste compared to the log system.

Hypothesis H5 assumed that within off-site manufacturing environments, panelized construction systems yield a higher frequency of timber waste compared to modular systems. Both systems represent industrialized MMC, where the fabrication process occurs on a controlled production line. This factory setting inherently allows for enhanced monitoring and optimization of material flows prior to transporting the prefabricated components or complete volumetric units to the final assembly site.

The empirical data gathered from the manufacturing matrices confirms this assumption. The frequency analysis of wood-based waste occurrences (encompassing both lumber and engineered wood products) indicates that the panelized system accounts for 59% of the recorded factory waste entries (corresponding to 10 identified waste cases). In contrast, the modular system accounts for 41% of the occurrences (corresponding to 7 identified waste cases).

Consequently, based on the documented distribution frequency, Hypothesis H5 is confirmed. The variance in waste frequency is primarily driven by the material composition and the structural design logic inherent to each system. In the evaluated panelized system, material processing simultaneously involves substantial amounts of both raw lumber and engineered wood products (EWPs) across the superstructure and roofing components, resulting in a broader diversity of cutting residues. Conversely, the modular system features a more streamlined timber profile in the factory phase, focusing predominantly on raw lumber for structural framing, while utilizing engineered wood products restrictively (e.g., as structural sheathing for floor modules over ground screw foundations). This differing intensity of multi-material processing on the assembly line directly explains the superior waste minimization achieved by the higher-order volumetric modular paradigm over the 2D panelized system.

Hypothesis H6 postulated that timber-based residues constitute the largest quantitative share of the total waste stream generated during both the manufacturing and execution phases of wooden buildings. This assumption stems from the lifecycle logic of timber structures, where raw wood and engineered wood products (EWPs) represent the fundamental structural and material inputs. The data gathered from the cumulative waste matrices validates this assumption. The frequency distribution across all technological phases and spatial domains indicates that wood-based waste represents a cumulative share of 37% (composed of 24% raw lumber residues and 13% engineered wood products, such as oriented strand boards - OSB). The secondary significant waste fraction is mineral wool at 18%,

followed by gypsum-based materials at 13%. The remaining material fractions, including heavy mineral waste (concrete at 5%, tiles/ceramics at 4%), metals (iron/steel at 7%, aluminum at 4%), and plastics or bituminous products, occupy minor shares in the overall matrix.

Consequently, based on the documented empirical distribution, Hypothesis H6 is confirmed. The absolute dominance of the timber fraction highlights a critical focus area for material efficiency strategies within the construction sector. The high concentration of lumber and EWP waste is heavily tied to the superstructure phase, where the volume of active material processing peaks. While non-timber fractions (such as concrete, steel, and soil) are strictly localized to the foundation stage, timber waste remains an active factor across almost all construction phases and structural systems. This omnipresence underscores that optimizing nesting patterns, improving precision cutting, and developing high-value cascading recycling methods for factory and field wood fractions are the most impactful levers for enhancing circularity in modern timber construction.

CONCLUSION

Construction and demolition waste accounts for 35% of all waste generated in the EU, driving a critical regulatory shift toward a circular economy. While traditional waste management focuses on low-value recycling, European directives increasingly mandate high-value material recovery and lifecycle decarbonization. This pressure transforms waste management into a catalyst for MMC. Advanced practices (such as pre-demolition audits and digital material passports) reframe buildings as material banks. Ultimately, this shifts the industry toward off-site prefabrication and Design for Deconstruction (DfD), preventing waste at the source and enabling closed-loop components.

The transition toward a sustainable, low-carbon bioeconomy has significantly elevated the strategic importance of timber construction as a mechanism for carbon sequestration and environmental mitigation. However, optimizing the ecological balance of these structures requires a holistic lifecycle approach that addresses waste generation during both the manufacturing and execution phases. This study provided a comprehensive analysis of construction waste flows across four distinct structural timber paradigms (stud-frame, log, panelized, and modular volumetric systems), mapping their spatial and technological distribution.

The findings demonstrate that modern methods of construction (MMC), particularly volumetric modular systems, achieve superior material efficiency by limiting or entirely shifting waste generation from the field into a controlled factory environment. In contrast, traditional site-built methods (stud-frame systems) exhibit a higher diversity and frequency of waste streams on-site due to manual dimensioning and exposure to adverse climatic factors. Furthermore, the qualitative and frequency analysis confirmed that timber-based residues (lumber and engineered wood products) constitute the absolute majority (37%) of the cumulative waste footprint. This omnipresence underscores wood fractions as the primary target for high-value cascading recycling and circular economy strategies.

To achieve higher levels of environmental protection and circular resource efficiency, this study highlights the urgent need for systemic interventions:

- enhanced reporting agendas,
- on-site sorting incentives,
- producer responsibility and closed-loop circularity.

This can be achieved through introducing a standardized, detailed reporting framework at building offices that specifies waste volumes by material categories rather than aggregate mixed volumes; implementing economic and operational drivers to encourage rigorous source-separation directly at the construction field, which serves as a baseline for material reuse; and expanding material tracking to allow manufacturers and builders to legally reclaim and upcycle sorted clean wood residues into primary or secondary production lines, thereby improving national recycling metrics.

Ultimately, minimizing the environmental footprint of wooden buildings depends not only on advanced prefabrication techniques but also on reforming the administrative and economic paradigms to transform construction waste from a disposal liability into a valuable secondary raw material.

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