INM WHITE PAPERS

WOOD CONSTRUCTION AS A MANUFACTURING CHALLENGE: ADVANCED TIMBER MANUFACTURING TO ENHANCE FOREST HEALTH AND MEET HOUSING DEMANDS

Rachel Blowes
Jabari Canada
Sam Sundstrom
Samantha Ratanarat
Oliver Moldow
Austin Tsailin
Sheila Kennedy
Caitlin Mueller

Massachusetts Institute of Technology
77 Massachusetts Avenue
Cambridge, MA 02139
June 2026

© 2026 by Rachel Blowes, Jabari Canada, Sam Sundstrom, Samantha Ratanarat, Oliver Moldow, Austin Tsailin, Sheila Kennedy, and Caitlin Mueller. All rights reserved. Short sections of text, not to exceed two paragraphs, may be quoted without explicit permission provided that full credit, including © notice, is given to the source.

Wood construction as a manufacturing challenge: Advanced timber manufacturing to enhance forest health and meet housing demands

Rachel Blowes, Jabari Canada, Sam Sundstrom, Samantha Ratanarat, Oliver Moldow, Austin Tsailin, Sheila Kennedy, and Caitlin Mueller

June 2026

ABSTRACT

As the U.S. faces a housing shortage, timber manufacturing processes may need to shift to support the production of affordable housing. Timber value chains encompass activities required for housing production, such as forestry and harvesting, wood product manufacturing, and construction. These value chains impact interdependent challenges, from manufacturing employment to forest resilience. This paper discusses findings from interviews with timber value chain stakeholders and from a literature review. Housing production methods are surveyed, and the existing timber value chain structure and challenges are outlined. While a high level of technology adoption is evident across these value chains for characterizing resources and optimizing manufacturing outputs, data is not typically shared across fragmented industries. Several design case studies are discussed to explore how digital tools and fabrication methods can enhance the utilization of wood resources in housing. Digitally linked timber-producing systems show potential to promote collaboration between forest experts, manufacturers, builders, and designers. For this reason, a digital thread is proposed to link data collected across fragmented industries. Additionally, several models are outlined to improve the utilization of timber in housing.

Rachel Blowes
School of Architecture and Planning
Massachusetts Institute of Technology
77 Massachusetts Avenue
Cambridge, MA 02139
rachelmb@mit.edu

Caitlin Mueller
School of Architecture and Planning
Massachusetts Institute of Technology
77 Massachusetts Avenue
Cambridge, MA 02139
caitlinm@mit.edu

Executive Summary

To address challenges in affordable housing, advances in wood manufacturing and residential construction are needed.

Housing affordability is a major challenge in the U.S., due in part to a shortage in the available supply of lower-cost homes (Joint Center for Housing Studies of Harvard University, 2025). This shortage has prompted housing advocates and policymakers to call for a substantial increase in the production of housing (Executive Office of Housing and Livable Communities, 2025; National Low Income Housing Coalition, 2025). To meet current and future housing needs, both new residential construction and renovation and repair work are required to expand and maintain the domestic housing stock. These building activities require material resources sourced largely through timber value chains, a system of interlinked manufacturing operations that transform harvested roundwood into building components and systems.

In the U.S., housing is built primarily using on-site light wood framing (U.S. Census Bureau, 2024a). This construction type is the most widely used method for housing production in the U.S., where 94% of single-family housing units built in 2024 were wood-framed (U.S. Census Bureau, 2024a). While timber value chains are globally linked, housing is mainly produced locally. Alternative approaches to housing production, such as manufactured housing, have been proposed and implemented, though few have gained significant traction in the housing market. Compared with other industries, construction productivity growth has stagnated (McKinsey Global Institute, 2017). The recent increase in housing demand has not been met with updated approaches to conventional construction methods. Manufacturing is central to many stages of housing production, from material sourcing and processing to the fabrication of building components and systems. Throughout this paper, the current state of housing production in the U.S. is outlined, and opportunities for innovation in manufacturing and construction are identified across timber value chains.

Meeting the need for residential construction gives rise to environmental impacts.

As wood is a natural resource, its consumption is interlinked with geobiological systems. Forest management and harvesting practices associated with the production of building materials must be carried out with an understanding of their impacts. Moreover, buildings and construction are major sources of carbon emissions, which contribute to climate change (G. A. for B. and C. United Nations Environment Programme, 2025). With the rise of mass timber, wood is being proposed as a lower-carbon alternative to concrete and steel for high-density housing typologies. This shift may increase demand for wood products in the coming decades (Nepal et al., 2021). Developing approaches to use timber products efficiently will be an important strategy to limit the carbon impact of new residential construction while expanding the housing stock.

Domestic timber value chains include processes that are deeply linked but fragmented across industries.

Domestic timber value chains support residential construction, and solid wood product markets are interconnected with housing demand (Brandeis et al., 2021). Timber value chains comprise several distinct industries, each focused on producing commodified standard units such as roundwood logs, dimensional lumber, prefabricated roof trusses, or entire buildings. Each of these industries engages technology in unique ways and collects and manages extensive data. 'Digital' forestry technologies enable the monitoring of forest resources and can inform forest management and harvesting practices (Müller et al., 2019). Technologies ranging from advanced scanning to saw cutting optimization are used to improve the efficiency of milling operations. Automated fabrication technologies and robotics facilitate the manufacturing of engineered mass timber products and premanufactured wood components. To develop building plans and facilitate construction, designers engage tools such as CAD and BIM. These tools can be integrated with computational analysis methods to understand the structural and environmental performance of designs or to monitor building component inventories. While these technologies inform decision-making and facilitate operations within each timber industry, their outcomes are rarely communicated or integrated across industries.

Timber value chains impact interdependent challenges, from manufacturing employment to forest resilience.

In the U.S., timber value chains can be tightly linked, impacting regional economies and environments. While timber-based manufacturing can create employment opportunities with community benefits, interviewed stakeholders express that labor shortages are a key challenge across these value chains, from logging activities to wood product manufacturing and construction. Several manufacturers aim to address this shortage by increasing automation in timber-based industries. Automation promises to augment productivity in these industries, with the potential to reduce the labor required to perform dangerous manufacturing tasks. However, the effective integration of automated technologies into manufacturing lines may require workforce training to adapt to new tasks. An alternative approach to addressing the labor shortage used by small manufacturers is to focus on hyper-local manufacturing and construction aimed at providing other community benefits, such as forest resilience.

To ensure a sustainable wood supply in the long term, the resilience of forests must be safeguarded. However, there is often a disconnect between the types of trees that need to be removed from the forest and those that are economically viable as feedstock for wood product manufacturing. Adapting timber consumption habits to align more closely with forest needs necessitates a transformation in the way that designers and manufacturers make use of wood, requiring them to develop building methods that utilize wood with greater variation in dimensions and species.

Standardization is central to timber manufacturing value chains, but leaves much on the table.

The process of transforming harvested timber, a natural resource with variable characteristics, into engineering materials with reliable properties is one of finely tuned standardization. Roundwood logs harvested from the forest are sorted according to their economic potential and future structural use. Manufacturing processes are streamlined to produce standard building components, such as dimensional lumber, in widely available nominal sizes. Grading is used to characterize and group wood components by their properties, facilitating rapid engineering calculations and ensuring products meet performance requirements. These components form part of a simple, well-established constructive system: light wood framing leverages these standardized materials to create repeating units that can be assembled to frame a variety of layouts. This approach to standardization has enabled the construction of millions of homes in the United States and has created a market for consistent building components originating from many distinct sources. While it incentivizes harvesting and manufacturing practices based on reliable economic yields, it neither produces building components tailored to their structural role nor readily adapts to forest management needs. Furthermore, a consequence of this standardization process is the generation of substantial manufacturing waste.

Novel fabrication technologies and design tools facilitate construction with nonstandard materials and show potential to transform conventional ways of working with wood.

While standardization is central to building with wood materials, emerging design and fabrication tools are available that could support the use of diverse feedstocks for wood manufacturing and construction. These technologies could unlock the possibility of building with several untapped wood resources. The first of these resources includes trees that need to be removed from forests to maintain forest resilience, but cannot be profitably used to manufacture standard wood products. The second of these resources includes a major byproduct of wood manufacturing, construction, and demolition: wood waste. Tools are available to facilitate the use of these two non-standard construction materials, from design to construction. For instance, the geometric and mechanical properties of irregular wood inventories can be characterized using 3D scanning and non-destructive testing technologies. Integrated structural analysis tools can support quantitative performance assessments of designs with irregular geometries, such as structural round timber. Novel computational approaches, including inventory matching, can enable efficient design with wood inventories with naturally varying geometries (Amtsberg et al., 2020; Cousin, Marshall, et al., 2023). These diverse material resources can be assembled into building components or systems using automated fabrication and robotics. Further research and experimentation are needed to

understand how these techniques can be implemented efficiently in practice, ensuring that forest communities can gain economic benefits from their use.

Connecting timber manufacturing processes through digital technologies and data could promote the collaborative development of forest and design futures.

Examples of vertically integrated timber value chains from beyond the U.S. indicate the potential for improved efficiency through increased information exchange among harvesting practices, wood product manufacturing, and building design. Incorporating this level of integration at a large scale domestically would require substantial, disruptive changes to existing forest and manufacturing ownership models. An alternative approach to improve the efficiency of timber resource utilization involves connecting industries that are currently discrete through a common digital thread, enabling a flow of data between forests and housing production. Computational tools can enable this approach across both large-scale, distributed value chains and hyper-local partnerships that link forest management and design.

A key outcome of these digitally linked timber-producing systems is the design of building systems that can accommodate a broader range of wood resources. Developing new design and fabrication approaches for building with wood can impact the production of a range of housing typologies with the potential for ecological, sociological, and economic co-benefits. Future research needs include the development and evaluation of building system prototypes that make use of underutilized wood resources and a systemic assessment of the impacts of transformations in wood housing design on forest resilience.

1. Introduction

Timber has an important role in the U.S. housing stock. Contemporary light wood framing, the predominant method of residential construction, traces its origins to the balloon-framing technique developed in Chicago in the 1800s (Andersen et al., 2023). In 2024, 94% of single-family housing units constructed in the U.S. were wood-framed (U.S. Census Bureau, 2024a). As the U.S. confronts persistent housing challenges exacerbated by a shortage of affordable homes (Joint Center for Housing Studies of Harvard University, 2025), understanding the capacity of timber supply chains and their potential to support housing production is of increasing relevance.

Timber-producing forests generate substantial economic value while serving as critical carbon sinks that sustain ecosystems and communities. Their management must balance productivity with long-term ecological health. As climate change heightens risks to forests, adapting planting and harvesting practices to support forest resilience is essential. (Bousfield et al., 2025; Messier et al., 2022). In the U.S., residential construction is both a major driver of commercial forestry (Brandeis et al., 2021) and a significant source of embodied carbon emissions (Hu, 2022; Jungclaus et al., 2024). Developing strategies to use forest resources efficiently in housing is key to expanding the supply of affordable homes while ensuring the longevity of forests and reducing climate impacts. Emerging design tools and manufacturing technologies show promise in advancing these goals. This paper examines housing production methods and timber value chains to identify strategies for more efficient uses of wood in housing.

1.1 Enhanced manufacturing to meet affordable housing needs

Rising housing costs affect much of the U.S., due in part to a shortage of affordable housing units. Housing is becoming a cost burden for an increasing percentage of renters (Joint Center for Housing Studies of Harvard University, 2025). The National Low Income Housing Coalition estimates a shortage of 7.1 million affordable and available rental homes (National Low Income Housing Coalition, 2025). Potential homebuyers are also affected by the high cost of housing; the median price of a single-family home was five times the median household income in 2024 (Joint Center for Housing Studies of Harvard University, 2025). In Massachusetts alone, a housing needs assessment calls for the addition of 220,000 homes over the next decade (Executive Office of Housing and Livable Communities, 2025). Meeting the growing demand for homes requires efficient strategies for housing production.

To address affordability challenges, strategies have emerged that center manufacturing in the production of housing. Studies suggest the potential for factory-built housing to increase construction productivity (McKinsey Global Institute, 2017), improve affordability (Fu & Holland, 2024; Kaul & Pang, 2022; Pullen, 2022), and reduce the embodied carbon impact of new residential construction (Greer & Horvath, 2023). While

existing manufactured housing supply chains primarily focus on the production of single-family homes, wood can also be used in denser housing typologies, such as mid-rise or tall buildings, constructed with light wood framing or mass timber. As of 2021, the International Building Code allows mass timber construction up to 18 stories in height (International Code Council, 2024). This relatively new construction method relies on prefabrication, which can accelerate construction timelines and benefit regional economies in areas with tightly-linked wood value chains (Scouse et al., 2020). There is significant potential for prefabrication and manufacturing to play an expanded role in housing provision across multiple building types, discussed further in section 3.

1.2 Timber value chains: Supporting residential construction and forest communities

Throughout this paper, manufacturing is considered across timber value chains. These value chains extend from the forest to building frames, encompassing distinct manufacturing industries including harvesting operations, wood product manufacturing, prefabricated housing manufacturing, and site-built construction. Timber value chains deliver an important structural function in residential construction. In the U.S., wood is a widely available renewable building material. These properties, along with its high strength-to-weight ratio and ease of construction, make wood effective for framing a range of structures (Ramage et al., 2017). While wood construction is widespread due to these advantages, the properties and dimensions of wood vary among species, between individual trees, with the orientation of loading, and under changing conditions such as temperature and moisture content (R. Ross, 2021). Since the early 1900s, manufacturing methods have been honed to address this variability and consistently produce standardized building components that can easily be shipped and assembled to produce housing (Smith & Wood, 1964). Through interrelated but distinct industries, timber value chains promote standardization, from forest harvesting practices to the production and sale of finished wood products for homes. While the compartmentalization of wood-based industries allows each sector to operate cost-effectively, enhanced cross-sectoral communication could produce a range of benefits, as discussed further in sections 4 and 12. Furthermore, emerging tools that enable the use of non-standard building materials in construction could transform both the structure and flow of information through timber value chains.

These value chains also serve a significant economic role in the U.S., adding $288 billion per year to the economy and employing 950,000 people (*Forest Products | US Forest Service Research and Development*, 2025). Forest communities often feel the effects of fluctuations in wood product markets. Phenomena such as the closure of sawmills or the uptake of mass timber construction can have reverberating regional economic impacts (Lamsal et al., 2025; Scouse et al., 2020). Housing production levels also affect forest-based employment. For instance, 350,000 forest industry workers lost

their jobs following the housing market collapse linked to the 2007-2009 recession (Perry et al., 2022). Since that time, the forest products industry has recovered steadily (Brandeis et al., 2021). To maintain or grow the industry, a substantial workforce is required. However, employers struggle to find workers in the numbers needed across the value chain, as described in section 4.4. Since forest communities often bear the greatest economic and environmental impacts of forest-based industries, they should be actively involved in transitions in forest management or timber value chains to ensure their resilience and economic stability.

1.3 Managing forests for resilience

With its vast timber resources, the U.S. is a major consumer of wood products and the foremost producer of industrial roundwood globally (Brandeis et al., 2021; FAO, 2023a). To safeguard the long-term productivity of forests, it is essential to cultivate their resilience. Timber-producing forests are managed through a range of approaches, described in section 4.1. These approaches involve tradeoffs, for example, between nature conservation and timber production efficiency (Aggestam et al., 2020). While monoculture plantation forests yield substantial quantities of wood products, greater diversity can enable forests to fulfill multiple functions (Messier et al., 2022). Furthermore, forests which are diverse in species composition, age, and spacing are more resilient to disturbances such as insects or wildfire (Bousfield et al., 2025; Messier et al., 2022). Building designers can encourage forest diversity by shifting trends in demand for wood products (Messier et al., 2022), for instance through the design of building components or structural systems which accommodate a greater range of wood species or dimensions. While the time horizon for diversifying forests is long, transforming approaches for meeting housing demand could promote the sustainable production of building resources well into the future.

Incorporating a greater diversity of forest resources into wood products and housing could also provide an effective response to immediate forest health concerns. To mitigate the risk of wildfire, many forests can benefit from mechanical thinning and prescribed burning (Brodie et al., 2024). Thinning activities can be costly (Bukauskas et al., 2019; Chang et al., 2023). In some cases, harvested material yields can offset this cost (Skog & Barbour, 2006). More often, trees that need to be removed from the forest to reduce wildfire risk are small in diameter and difficult to utilize in conventional wood products (Bukauskas et al., 2019; Livingston, 2008). Developing a wood product market for small-diameter trees can incentivize their removal (Livingston, 2008). Designers can contribute to forest resilience by embracing these underutilized wood resources.

1.4 Data-driven design and advanced manufacturing: Tools to enable housing construction with underutilized wood resources

Design technologies and advanced manufacturing show significant potential to enable the efficient construction of affordable housing. These tools also make it possible to design with large inventories of non-standard building materials, including underutilized wood resources such as trees that must be thinned from forests to promote resilience and various untapped wood waste streams, discussed in section 4.6. Through the application of these technologies, it may be possible to simultaneously address the interrelated challenges of housing affordability, wood waste management, and forest resilience.

Throughout this paper, a survey of timber value chains in the U.S. is conducted through a literature review and a series of interviews with forest researchers, forest-based technology start-ups, sawmill operators, mass timber product manufacturers, and prefabricated wood component and home manufacturers. Digital technologies currently used in practice are identified. Challenges faced by each forest-based sector and opportunities for innovation are discussed. The current state of U.S. timber value chains is compared to examples of timber production systems from abroad. Through a series of manufacturing prototypes, concepts for adapting designs to make use of non-standard inventories of wood materials are explored.

To deploy these design and manufacturing approaches at scale, cross-sectoral communication is required. As discussed in sections 5 - 11, data-driven processes are increasingly used across timber value chains to collect, manage, and interpret information spanning forest management through to building design. Strategies for integrating this sector-specific data into cross-disciplinary decision-making are presented in section 12. Through this research, the following questions are addressed:

1. How are wood products currently used in housing production in the U.S.?
2. What is the state of timber manufacturing, and where are opportunities for automation or technological innovation?
3. What challenges does timber manufacturing face, and what are the implications for the labor force and forest communities?
4. How are forests currently managed, what interventions are required for increased resilience, and what technologies support these practices?
5. How can designers, manufacturers, and forest managers share data and collaborate to align housing designs with forest health needs and socio-economic benefits?

2. Methodology

To understand current challenges and opportunities for innovation across timber value chains, this research is informed by findings from three complementary methodological approaches: 1) interviews with timber value chain stakeholders, 2) a literature review, and 3) design and manufacturing prototypes. Interviews ranging between 30 minutes to one hour in length were conducted with stakeholders such as sawmill operators, mass timber manufacturers, forestry-focused organizations, and software companies geared toward forestry and the timber industry. Representatives from 29 companies in North America were interviewed, identified in Figure 1. Two companies based in Switzerland were also included in the study. Additionally, the research team made several visits to forests, sawmills, and wood product manufacturers.

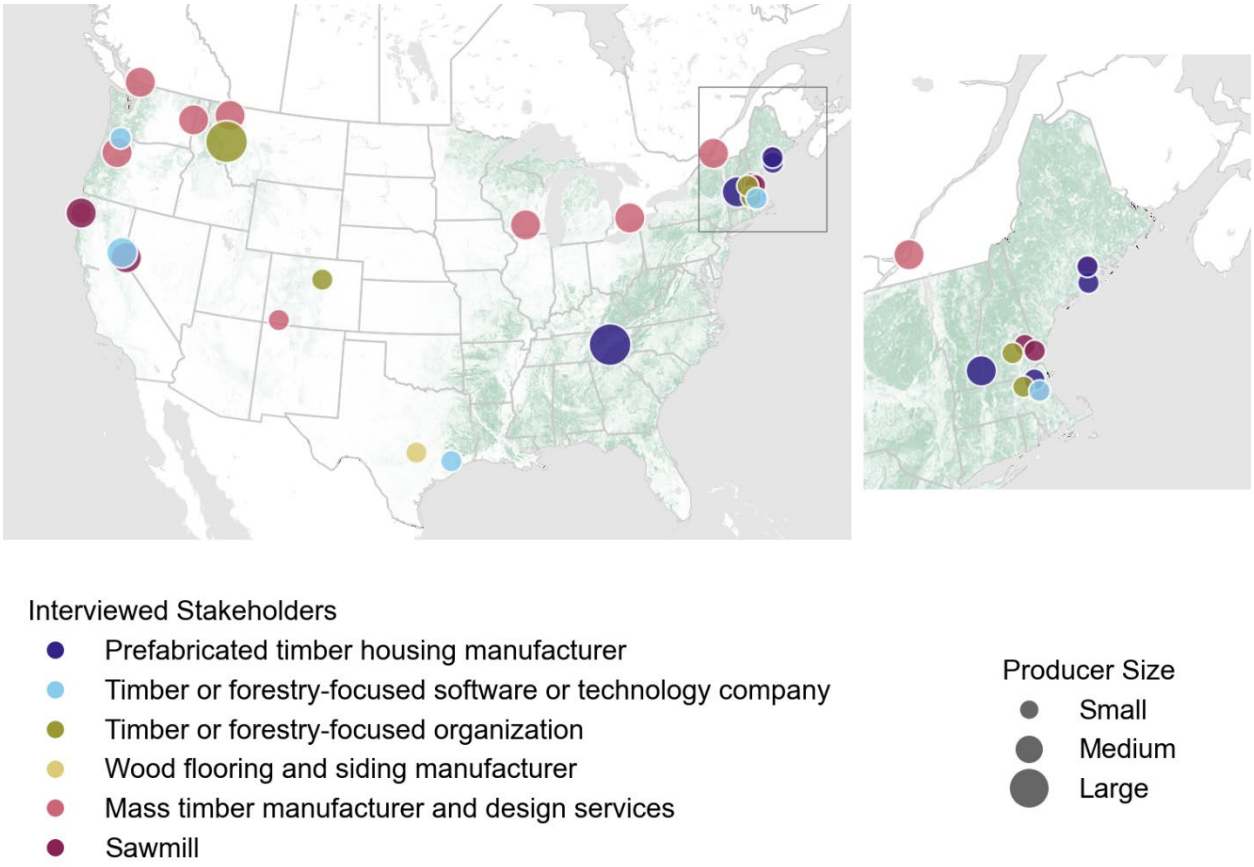


Figure 1. 29 interviewed timber-industry stakeholders in North America and forest cover of the United States.
Data source: Tree Canopy Cover Datasets, U.S. Forest Service (U.S. Department of Agriculture Forest Service, 2023)

The findings from these interviews and visits are supplemented by a literature review targeted at understanding the current state of timber value chains and the potential for digital technologies to enhance the link between timber manufacturing and housing

production. Scientific and government publications are reviewed to understand the impact of timber harvesting on forest resources. Government reports and publicly available housing data and forest product production and trade data are surveyed. Furthermore, novel digital technologies with applications in forestry, wood product manufacturing, design, and housing production are identified from scientific publications.

In collaboration with two timber value chain stakeholders, a sawmill and prefabricated home manufacturer, design and manufacturing prototypes are developed and explored. These prototypes are developed by identifying current wood waste streams and co-creating design solutions which enhance utilization of these resources with industry. Through this multipronged research approach, this research aims to provide an overview of current and emerging trends within the timber industry and housing production.

3. Affordable housing production: A wood manufacturing challenge

The United States faces challenges related to housing affordability. Both renters and homeowners are increasingly burdened by housing costs (Joint Center for Housing Studies of Harvard University, 2025). In 2023, roughly 50% of renters were cost-burdened, spending at least 30% of their income on housing (U.S. Census Bureau, 2024c). While homeownership remains a preference for most Americans (Herbert et al., 2023), homebuying is at its lowest rate since 1995, due in part to the high costs of housing (Joint Center for Housing Studies of Harvard University, 2025). In recent years, housing production has increased. However, a housing supply shortage persists, particularly affecting single-family homes. While a multi-family housing construction boom helped to fill gaps in the rental market, low-rent units remain limited in availability (Joint Center for Housing Studies of Harvard University, 2025). Researchers note that increasing the supply of housing alone is not enough to address housing affordability: other strategies such as policy initiatives and zoning changes are required to solve housing challenges, and particularly to narrow disparities in housing equity (Neal et al., 2024). However, increasing the supply of lower-cost housing is an important part of alleviating the housing affordability crisis.

While many studies of housing affordability focus on land-use reforms to allow denser construction and policy interventions to reduce costs for homeowners or renters (Rohe, 2017; Stacy et al., 2023), the cost of construction itself contributes substantially to new housing prices. The National Association of Home Builders (NAHB) finds that construction costs accounted for 64% of the sales price of new homes in 2024. These costs amounted to $162 per square foot, the highest recorded by the NAHB in a time series dating back to 1998. The influences of labor shortages and high building material prices are listed as contributors to these elevated costs. 84% of these construction

costs can be attributed to the building itself, including foundations, framing, exterior finishes, major systems rough-ins, and interior finishes (Lynch, 2025). While residential construction productivity increased in the United States in 2024 (*Construction Labor Productivity*, 2025), as a long-term trend, growth in construction productivity has lagged behind manufacturing (McKinsey Global Institute, 2017). As housing is constructed in much the same way as it has been for decades, there has only been a modest increase in the number of housing units which can be produced for a given amount labor in that time.

Understanding the impact of construction costs, one strategy builders are using to address affordability challenges is to reduce the size of new housing units or limit their amenities (Joint Center for Housing Studies of Harvard University, 2025). Another strategy proposed for reducing construction costs is to leverage efficiencies in off-site construction and manufactured housing (Kedir & Hall, 2021; Kaul & Pang, 2022). There is also a potential for efficiency gains from a greater adoption of technology in the construction industry (Wang et al., 2020). Advances in efficient, cost-effective approaches to housing production are needed to address affordability challenges.

3.1 Wood residential construction methods and timber product demand

Wood is the primary material used to frame housing in the U.S. For this reason, domestic sawnwood production is closely linked to housing production (Brandeis et al., 2021), as indicated in Figure 2. Other wood products, including plywood and oriented strand board (OSB) are also widely used in the construction of homes. Solid wood products are used in residential buildings of varied scales, from single-family homes and mid-sized multi-family complexes to large residential towers. This range of housing typologies is enabled by several distinct wood-construction methods: site-built, factory-built, and mass timber. Timber value chains and manufacturing are involved in the production of all wood housing. However, factory-built housing and mass timber leverage manufacturing to a greater extent than conventional construction. As a result of repeated, controlled manufacturing processes carried out in factories, these construction methods have been associated with increased production efficiency and reduced waste (Herbert et al., 2023; Fu & Holland, 2024). Furthermore, the use of premanufactured building components can limit on-site building requirements, resulting in accelerated construction timelines and a reduction in associated on-site building costs (Scouse et al., 2020; Fu & Holland, 2024). Despite the advantages of expanding the role of manufacturing in housing production, 91% of new single-family housing starts were site-built in 2024 (U.S. Census Bureau and U.S. Department of Housing and Urban Development, 2024).

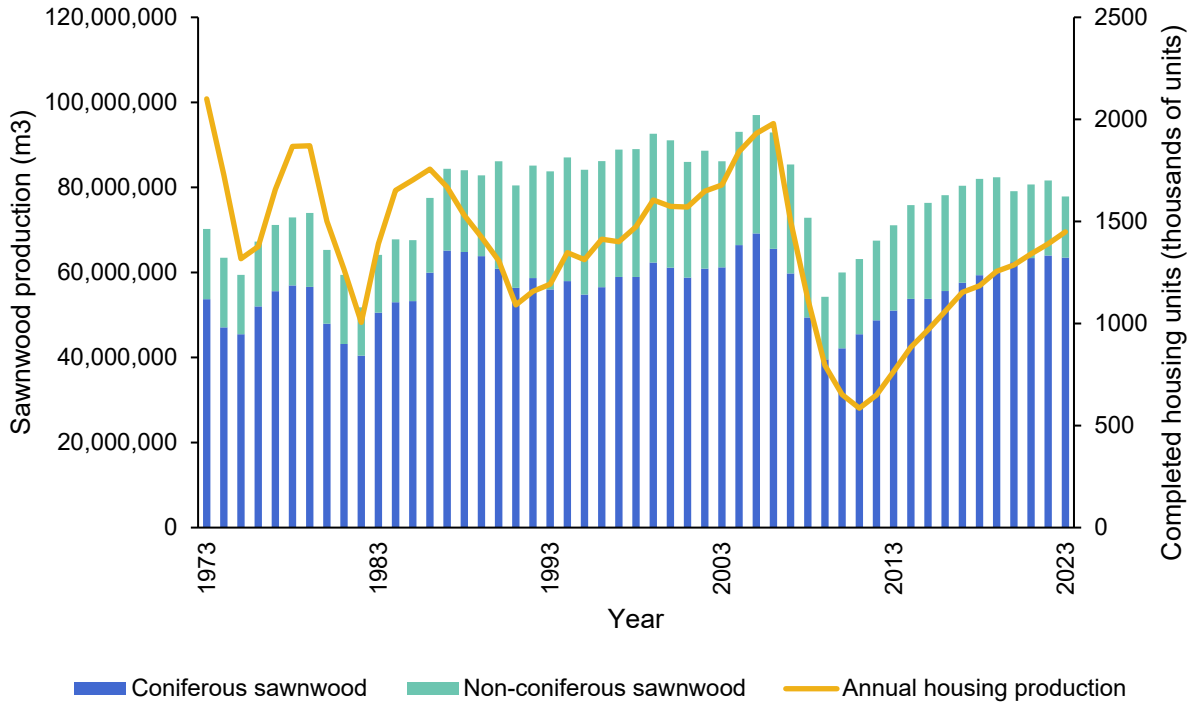


Figure 2. Annual sawnwood production is closely aligned with housing production in the United States, shown here over a fifty-year period.
Data sources: Food and Agriculture Organization of the United Nations (FAO, 2023a), United States Census Bureau (U.S. Census Bureau, 2024b).

3.2 Site-built housing

The most common approach for building housing in the United States is on-site light-frame wood construction (Brandeis et al., 2021). Dimensional lumber, produced by milling and processing roundwood to create standardized components, is the fundamental material unit that composes the structural framing of most homes. Lumber elements, widely available and easily modified on-site, can be assembled to frame a diversity of building plans and parts, including roof framing, stud walls, and floor joists. Panelized solid wood products such as plywood and oriented strand board (OSB) are also commonly used as sheathing elements, providing lateral load resistance and rigidity.

Light-frame wood construction is often used for single-family homes, which account for approximately 60% of new housing (U.S. Census Bureau, 2024b) and over 80% of solid wood products in new residential units (Brandeis et al., 2021). Denser housing typologies can also be built with light-frame construction, including multi-family units such as duplexes or apartment buildings. When built with lumber, these larger buildings are typically framed using Type III or Type V construction as defined in the International Building Code (International Code Council, 2024). Hybrid systems, including concrete

podiums or mass timber elements, may also be used to extend light-frame systems to additional stories (“Code Path and Requirements for Podium Projects,” 2025).

Site-built wood construction is not limited to new buildings. Residential repairs and renovations represent other important forms of site-built construction, and accounted for nearly half of solid wood product consumption in 2019 (Brandeis et al., 2021). Since dimensional lumber is easily worked on site, it is well-suited for modifying irregular as-built conditions in existing homes. As the Right to Repair movement has demonstrated for the technology sector, the ability for an owner to maintain and adapt their property can extend product lifespans and aid in facilitating a transition towards a circular economy (R. J. Hernandez et al., 2020). Given that the median age of housing was 43 years in 2023 (U.S. Census Bureau, 2023), on-site construction with solid wood products plays an important role in maintaining, repairing, and modifying the housing stock.

3.3 Factory-built housing

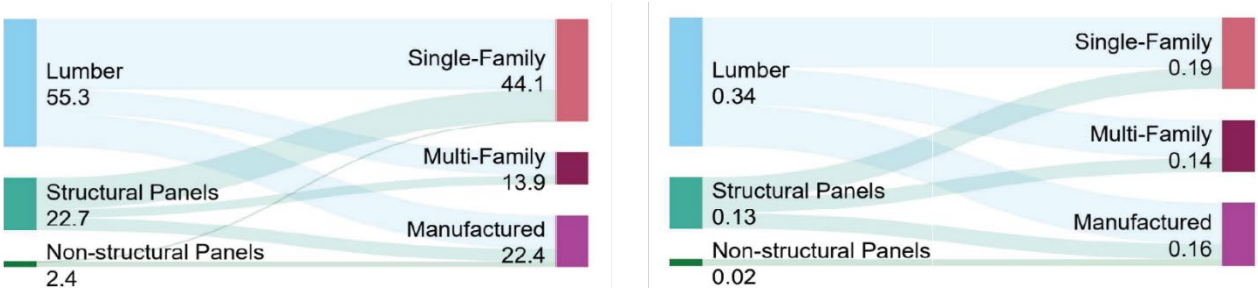
Compared with site-built construction, off-site factory-built housing centers the role of manufacturing in the production of homes. The prefabrication of building components or entire buildings can reduce on-site construction labor and project timelines (Pullen, 2022). There are two major categories of factory-built housing: manufactured housing, a form of housing with specific requirements corresponding to a federal building code, and other forms of factory-built housing that conform to local building requirements.

3.3.1 Manufactured housing

Manufactured housing is a distinct form of factory-built housing that is constructed according to regulations in the Manufactured Home Construction and Safety Standards implemented by the U.S. Department of Housing and Urban Development (HUD) (Fu & Holland, 2024). Constructed as modular units, these homes must be framed on a movable steel chassis. The HUD performance-based federal building code facilitates the mass production of manufactured housing across the United States, whereas other approaches to prefabrication must respond to regionally specific prescriptive building requirements. This mass production allows for economies of scale in the construction of housing: compared with site-built light wood framing, manufactured housing often involves less waste, faster construction times with fewer scheduling delays, and cost efficiencies (Fu & Holland, 2024).

In general, manufactured housing is less expensive than site-built housing. In 2024, the average cost per square foot of a new site-built single-family home was $168.86, excluding the cost of land (U.S. Census Bureau and U.S. Department of Housing and Urban Development, 2024). New manufactured homes cost roughly half that cost per square foot, at $86.71. In addition to the cost differences between site-built and manufactured housing, each housing typology consumes distinct amounts of wood

products. As Figure 3 shows, single-family housing units consumed roughly twice the volume of wood products that were used in the production of manufactured housing units in 2019 (Brandeis et al., 2021). This discrepancy is mainly due to the fact that manufactured housing units tend to be smaller than their site-built counterparts (U.S. Census Bureau and U.S. Department of Housing and Urban Development, 2024). When normalized by housing area, there is greater similarity in the consumption of wood products for site-built and manufactured homes, although manufactured homes use slightly smaller volumes of lumber and structural panels, and greater volumes of non-structural panels. Site-built multi-family housing consumes smaller volumes of wood products on both a per-unit and per-area basis. These figures point to the material efficiencies possible with denser housing typologies.



a) b)

Figure 3. Consumption of solid wood products a) per housing unit and b) per unit floor area of residential construction in 2019 suggests that denser housing typologies can support resource-efficient housing production.
Data source: U.S. Forest Service (Brandeis et al., 2021).

Despite the cost savings associated with manufactured housing, it currently accounts for less than 10% of new single-family home production (U.S. Census Bureau and U.S. Department of Housing and Urban Development, 2024). Historically, manufactured homes were produced in larger quantities, although production is steadily recovering following a steep decline during the late 2000s (Kaul & Pang, 2022). Recently, demand has increased as conventional site-built homes have become unattainable for many households. Kaul and Pang argue that manufactured housing could contribute significantly to the supply of affordable housing in the United States. They suggest that financing reforms could assist potential homebuyers, as it can be challenging for residents to secure financing since manufactured housing is ineligible for conventional mortgages unless it is sited on permanent foundations on owned land (Kaul & Pang, 2022; Herbert et al., 2023; Fu & Holland, 2024). In 2024, only 18% of manufactured homes were titled as real estate (U.S. Census Bureau and U.S. Department of Housing and Urban Development, 2024). The rest of manufactured homes were titled as personal property, often financed through chattel loans which have shorter repayment periods and higher interest rates than conventional home mortgages (Kaul & Pang,

2022; U.S. Census Bureau and U.S. Department of Housing and Urban Development, 2024).

Another challenge in the provision of manufactured housing is restrictive zoning (Kaul & Pang, 2022; Herbert et al., 2023; Fu & Holland, 2024). Despite the potential opportunity to enable homeownership for lower-income households, many municipalities prohibit manufactured homes or impose requirements such as a minimum lot size, which can reduce the cost advantage of this housing type (Herbert et al., 2023; Fu & Holland, 2024). Fu and Holland note that stigma may play a role in the resistance to manufactured housing. Prior to the implementation of the HUD code, manufactured homes, previously known as mobile homes, varied greatly in quality and were associated with increased fire risk (Fu & Holland, 2024). Past concerns about durability and safety have largely been addressed by HUD Code (Herbert et al., 2023). More recently, updates to the HUD code have also improved climate resilience and energy performance (Kaul & Pang, 2022).

The trade-off between standardization, which enables economies of scale in production, and site specificity affects the environmental performance of manufactured housing. Standardized designs produced in one region may not meet requirements for environmental loading in other regions, particularly in relation to extreme events such as wildfires or flooding (Stephen et al., 2018; Fu & Holland, 2024). Computational methods such as clustering can facilitate the design of standardized housing for grouped regions with similar climate loads (Stephen et al., 2018). Fu and Holland provide examples of community development organizations focused on the provision of affordable housing in climate-vulnerable areas that adapt manufactured housing through strategies such as elevating units at risk of sea-level rise or detailing roof elements for increased fire resistance (Fu & Holland, 2024). These strategies demonstrate that standardized factory-built construction can provide climate-responsive, resilient housing with modest modifications.

3.3.2 Other forms of factory-built housing

Alternate forms of factory-built housing are typically sited on permanent foundations and adhere to local building requirements rather than the HUD code (Fu & Holland, 2024). While the prescriptive requirements of local building codes may reduce some of the efficiencies gained from the opportunity for mass production across states, alternative forms of factory-built housing may still benefit from many of the advantages of off-site construction. Pullen identifies three approaches to off-site construction: kit-of-parts, flat-pack, and volumetric modular construction (Pullen, 2022). Kit-of-parts construction entails prefabricating individual building elements, such as prefabricated roof trusses, that can be assembled on-site. Flat-pack systems involve the construction of larger panelized assemblies, such as walls or floors, which are efficiently shipped to site where they are erected and connected. For example, GO Logic’s prefabricated housing

systems consist of flat-pack building panels, as shown in Figure 4 (GO LOGIC, 2025). For volumetric modular systems, entire building modules are constructed in a factory setting, substantially reducing on-site construction effort. Both manufactured housing and ERNE AG Holzbau's modular timber systems are examples of volumetric modular construction (ERNE AG Holzbau, 2025).

The use of factory-built housing in the United States is not new. In the post-war period, the Federal Housing Administration implemented a program to incentivize the development of pre-manufactured housing systems in an effort to meet housing needs. The short-lived nature of this program, along with a drop in housing demand and variability in the cost and quality of homes produced, led most of these manufacturing efforts to shut down (Kelly, 1951; Wilk, 2017). Any effort to expand factory-built housing must include strategies to ensure the quality and environmental performance of the buildings constructed, so that residents are not left with the cost burdens of high energy bills or expensive retrofits. Today, as housing demand is high and labor shortages slow project timelines, there is a renewed opportunity for factory-built construction to reduce project costs (Bertram et al., 2019). The barrier to becoming a producer of HUD manufactured housing is high, as the three major manufactured housing providers cover around 80% of market share (Kaul & Pang, 2022). Integrating advanced manufacturing and prefabrication in the production of other forms of housing could enhance construction productivity (McKinsey Global Institute, 2017).

Factory-built construction, also referred to as industrialized housing construction, has the potential for several benefits. This approach reduces project timelines, since scheduling is not impacted by weather delays, and labor productivity is higher in factory settings (Pullen, 2022). Additionally, while workplace safety requires further study, there is a potential for improved worker safety due to the controlled construction environment of a factory (Pullen, 2022). Kedir and Hall find that industrialized housing construction may lead to resource efficiency through value chain collaboration and the integration of strategies such as component-level and building system optimization, as well as waste management (Kedir & Hall, 2021). The authors emphasize that early-stage design is required to realize these resource efficiencies. In addition to material cost efficiencies, a modest reduction in embodied carbon may be possible with modular construction, depending on factors such as the distance of housing from its site of fabrication (Greer & Horvath, 2023). Interviews with wood product and prefabricated housing manufacturers indicate that they often prefer to locate factories near housing sites or regional wood baskets to reduce shipping costs. The cost savings and material efficiency associated with pre-manufacturing could enable the production of high-quality housing using regionally available materials.



Figure 4. Left: GO Logic panelized prefabricated wall system. Right: Mass timber post and beam system under construction.

3.4 Mass timber

While most homes are constructed with light wood framing, in recent years, mass timber has emerged as an alternative wood construction method for the production of housing. Mass timber makes use of large timber building elements with enhanced fire resistance and the capacity to support substantial structural loads. This construction method, categorized as Type IV in the International Building Code (IBC), can be used for taller buildings than light wood framing, enabling the construction of high-density housing, such as apartment buildings. Type IV construction can include both heavy timber elements with large cross-sections and prefabricated engineered mass timber products. These products encompass materials used for beams and columns, such as glulam, and panelized products used primarily for structural floors, such as cross-laminated timber (CLT), dowel-laminated timber (DLT), and nail-laminated timber (NLT) (WoodWorks, 2025). Mass timber products are implemented using several common structural framing approaches. In post-and-beam construction, beams support floor or roof panels in one-way or two-way spanning configurations, as shown in Figure 4. CLT panels, which have the capacity for two-way behavior, can also be used in a point-supported configuration without beams, where floors are supported directly by columns (Popovski et al., 2016). This construction method was used for the Brock Commons project, an 18-story student residence (Fast et al., 2016). A volumetric modular approach can also be taken for mass timber buildings, using panelized walls and floors as structural elements. In many cases, these approaches are employed in combination with concrete or steel lateral load-resisting systems. While mass timber currently accounts for a small percentage of buildings constructed in North America, demand for

mass timber buildings is growing and is projected to increase (Nepal et al., 2021; WoodWorks Wood Products Council, 2025).

Since mass timber is more materially-intensive than light-wood framing, it is generally used for mid-sized or tall buildings (Ahmed & Arocho, 2020; Ramage et al., 2017). However, in some cases, mass timber can be a sensible solution for single-family homes. For instance, the prefabricated home manufacturer Timber Age (Timber Age, n.d.) uses small-diameter trees that need to be thinned from the local forest to mitigate wildfire risk in CLT panelized home systems. As these forest resources are not suitable for producing the dimensional lumber required for light-wood framing, mass timber offers an alternative for constructing housing from regionally available materials.

In interviews, several mass timber manufacturers express interest in developing high-density housing built with wood that is cost-competitive with conventional construction using steel and concrete. While prefabrication is central to the manufacturing of many mass timber products and results in reduced construction timelines (Scouse et al., 2020), cost can still be a challenge, as mass timber is a relatively new building material in the United States (Ahmed & Arocho, 2020; Scouse et al., 2020). To address these costs, one interviewed mass timber manufacturer aims to implement their products in hybrid construction systems that use mass timber decking alongside more commonly used steel beams. In other cases, designers have managed to integrate mass timber more heavily in designs while providing affordable housing. Scouse et al. provide an example of a mixed-use CLT building in Oregon with 60 affordable units (Scouse et al., 2020). However, the authors suggest that government support through efforts such as wood encouragement policies (WEP) may be needed to make mass timber economically feasible as the industry grows. Another example of affordable housing that makes use of mass timber is the YWCA Supportive Housing project, which was assembled in only 20 days (*YWCA Supportive Housing - Mass Timber WIN Project*, 2025). The building materials for this project were produced using highly automated prefabrication methods. As mass timber is still in its early stages in North America, there is an opportunity to influence the adoption of this technology in the industry, with the potential to impact manufacturing productivity, material efficiency, and waste management practices.

4. Domestic timber value chain analysis

In North America, the primary framing materials used in housing are typically produced from fast-growing softwoods (R. Ross, 2021). Timber value chains are designed to extract timber from forests, a highly variable natural resource, and transform it into standardized building units with reliable, characterized dimensions and material properties. A range of stakeholders and industries are involved throughout timber value chains in the production of these building materials. Forest ecosystems and surrounding

communities are affected by both environmental and economic impacts of forestry. Landowners, planners, foresters, and loggers are engaged in forest management and harvesting activities. Sawmills transform harvested roundwood into standardized wood products and may sell these products directly to retailers, engineered wood product manufacturers, builders, or wholesalers. Engineered wood product manufacturers produce building products ranging from structural panels to mass timber products. Designers specify wood products for use in buildings. These products are purchased and assembled by prefabricated home manufacturers and construction companies to produce housing. Ultimately, timber value chains affect homeowners through the cost and long-term performance of the wood products in their homes.

As Figure 5 indicates, each stage of a timber value chain is linked to the next through the flow of wood products, yet a significant disconnect remains between the final product, housing, and the material's original source, the forest. There is an opportunity to strengthen the link between forest management and housing production through data, design, and digital technologies. Enhancing this link has the potential to transform how we extract and build with wood, impacting factors ranging from the characteristics of harvested trees to the types of homes constructed.

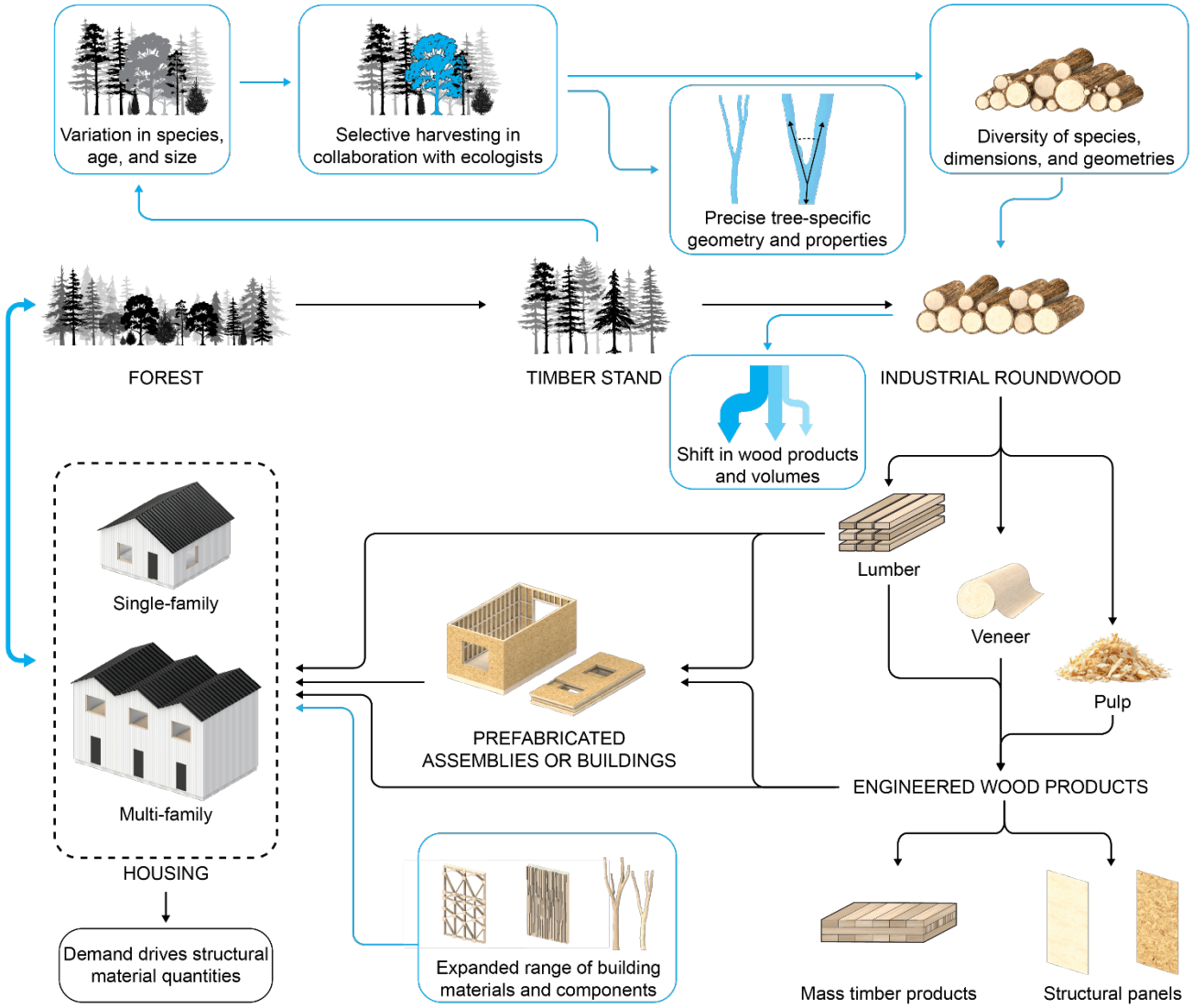


Figure 5. Timber flows originate in forests and facilitate housing production. While demand for housing drives the manufacturing of wood products, building design is often disconnected from forest management practices. Potential implications of enhancing the linkage between forests and housing design, such as using a broader range of wood species and sizes, are shown in blue.

4.1 Managing forest health and wood production

The forest is the starting point of domestic timber value chains. Forests provide a range of services, including ecosystem benefits, carbon sequestration, and economic value. Forest products are extracted from nearly 30% of forests globally (FAO, 2025). Within the U.S., around 79% of forest land is categorized as timberland (U.S. Department of Agriculture, 2023). Only a portion of this land is harvested; around 1% of timberland standing volume is removed each year (McGinley et al., 2023). Timber-producing forests fall into two principal categories: natural production forests and plantation forests (Bousfield et al., 2025). While both forest types are harvested for wood products,

plantation forests tend to comprise only one or two species and are intensively managed for rapid timber production cycles (Messier et al., 2022). In the U.S., around 13% of timberland was a plantation forest in 2017 (U.S. Department of Agriculture, 2023). Plantation forests are expanding, with 71% of planted forest area in the southern states (U.S. Department of Agriculture, 2023), where more than half of timber harvests occur (Perry et al., 2022). While 98% of plantation forests in the U.S. are composed of native species (Perry et al., 2022), plantation forests are less diverse than natural production forests (Bousfield et al., 2025).

As global demand for wood products is projected to increase substantially in the coming decades (Peng et al., 2023), a variety of strategies have been proposed to enhance the resilience of both forests and wood supply systems. These include adopting a sharing-sparing framework analogous to agricultural production systems (Betts et al., 2021), implementing integrated forest management to balance multiple objectives (Aggestam et al., 2020), and regenerative approaches (Löf et al., 2019). Some authors note that by serving as highly productive sources of timber, plantation forests can help alleviate the demand for wood products from natural forests (Betts et al., 2021; Bousfield et al., 2025; Perry et al., 2022). However, Messier et al. assert that both natural production forests and plantation forests can benefit from diversity (Messier et al., 2022). They suggest that developing wood products that can utilize a more diverse range of species can promote resilience.

Forest resilience is increasingly important as wildfires cause major losses in U.S. forests. (Bousfield et al., 2023). The U.S. Department of Agriculture Forest Service estimates that at least 50 million acres require treatment to mitigate this risk (U.S. Department of Agriculture, 2022). Forest management practices influence the extent of fire damage, as plantation forests have an increased risk of losses due to wildfires on a global scale (Bousfield et al., 2025). Ownership patterns also affect resilience; privately-managed industrialized timber-producing forests are at increased wildfire risk compared with publicly-owned forests (Levine et al., 2025). The stewardship of forests is an important consideration in the U.S., where 60% of forests are privately owned, often by families operating without formal management plans (U.S. Department of Agriculture, 2023).

Mechanical thinning, particularly when combined with prescribed burns, can reduce wildfire severity (Brodie et al., 2024; U.S. Department of Agriculture, 2022). However, these operations must be carefully planned, as removing large-diameter trees incurs a high carbon cost, whereas targeting smaller trees can reduce emissions from severe fires (Bartowitz et al., 2022). The removal of small-diameter trees is challenging because there is typically a misalignment between the trees prioritized for removal to promote resilience and those with the greatest potential to yield economic benefits (Livingston, 2008). The development of novel building strategies to use these trees in a

commercially viable manner could offset treatment costs and incentivize proactive forest management.

4.2 Overview of wood products and cascading principles

The initial product extracted from the forest through logging activities is roundwood. There are two distinct types of roundwood: industrial roundwood and fuelwood. Industrial roundwood is used for wood products or the pulp and paper industry, while fuelwood is involved in energy production (Ramage et al., 2017). Roundwood sawlogs can be used structurally as whole timber (Bukauskas et al., 2019). However, as Figure 5 illustrates, they are typically milled to produce standardized wood products, including dimensional lumber and timber. Timber denotes large sawn wood members measuring nominal 5 inches or more in the least dimension, while lumber consists of smaller wood members (U.S. Department of Commerce, 2020). Industrial roundwood also includes veneer logs and pulpwood, which are used to produce engineered wood products such as plywood and OSB. Engineered wood products are typically composed of layers or small elements of wood joined using adhesives or other connectors. These products often have favorable dimensional stability and strength, can be produced in a range of sizes, and distribute defects to limit their localized effects on performance (Wilk, 2017; Bergsagel et al., 2025). Beyond plywood and OSB, other common engineered wood products used in housing include structural framing elements such as laminated veneer lumber (LVL), I-joists, and mass timber products. These products expand the structural roles and spans that wood can accommodate in construction. However, while engineered wood products can efficiently make use of small wood elements, the processing and adhesives involved in their production contribute to their environmental impact (Ramage et al., 2017; Bergsagel et al., 2025).

Engineered wood products are also central to cascading, a concept aimed at improving the efficiency of wood utilization. Through this concept, wood resources are used in multiple sequential processes and products (Höglmeier et al., 2014, 2015). For instance, wood initially used as lumber could be reprocessed into OSB and ultimately combusted for energy after its secondary product life. Cascading of wood waste can have benefits in terms of environmental impact when compared with direct combustion, a common destination for wood waste (Höglmeier et al., 2014). While cascading is a well-established practice within pulp and paper value chains, it has been integrated to only a limited extent in solid wood product value chains (Bais-Moleman et al., 2018). To incorporate cascading more heavily in practice, comprehensive coordination across value chains will be required. The environmental impacts of this shift could be substantial (Bais-Moleman et al., 2018), and cascading shows potential for integration with circular design principles, which could also improve wood utilization (Jarre et al., 2020; Mair & Stern, 2017).

4.3 Domestic timber production and trade

While housing is mainly constructed locally in the U.S., timber value chains are globally linked. As shown in Figure 6, the majority of solid wood products used in construction in the U.S. are produced domestically. In addition to meeting the majority of domestic wood product demand, the U.S. is a major exporter of wood products, including hardwoods, fiber furnish, and paper products (FAO, 2023b, 2023a). Since the U.S. is a major global consumer of softwood lumber, significant quantities of coniferous sawn wood are imported to meet domestic demand. 93% of softwood lumber imports between 2000 and 2019 were sourced from Canada (Brandeis et al., 2021). Brandeis et al. suggest that Canadian lumber is cost-competitive with American lumber because it is harvested mainly from government-owned land rather than private land (Brandeis et al., 2021). Based on interviews with wood product manufacturers, it appears that timber imports may also be motivated by demand for species-specific properties. For instance, one manufacturer prefers to work with Black Spruce, which is mainly sourced from the Boreal Forest.

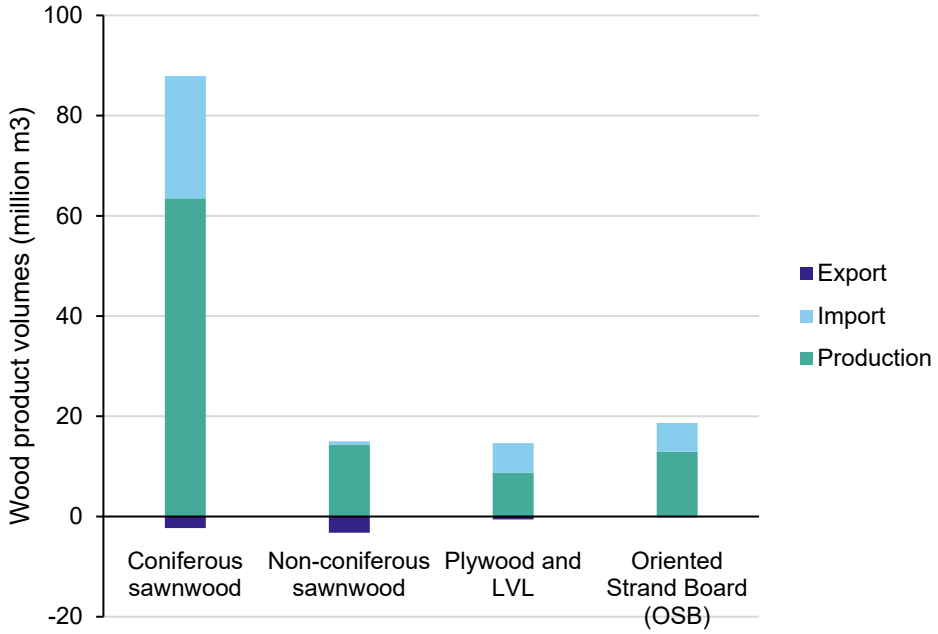


Figure 6. Production and trade of common wood products used in housing framing, 2023.
Data source: Food and Agriculture Organization of the United Nations (FAO, 2023a).

Solid wood products are largely consumed in the production of housing. Construction utilizes more solid wood products than other sectors in the U.S. Around 90% of wood products consumption in construction is related to residential building activities (Brandeis et al., 2021). Trends in the production and trade of wood products change over time, as illustrated by Figure 7. Domestically, production of softwood has increased since 1995, while imports have declined over the long term. Over the same time period,

there has been an increase in imports of both plywood and OSB. OSB production has also grown considerably over the past several decades. These trends in the production and trade of wood products reflect changes in their use in residential construction. The relative proportions of solid wood products used in housing have shifted as structural panels have become more widespread. The share of structural panels in wood product consumption in housing grew from 11% to 32% between 1962 and 2019 (Brandeis et al., 2021). Further changes in wood products consumption may be approaching. While the mass timber industry is still in its early stages in the US, it is expanding the types of buildings that can be constructed from wood. This will likely increase demand for solid wood products (Nepal et al., 2021).

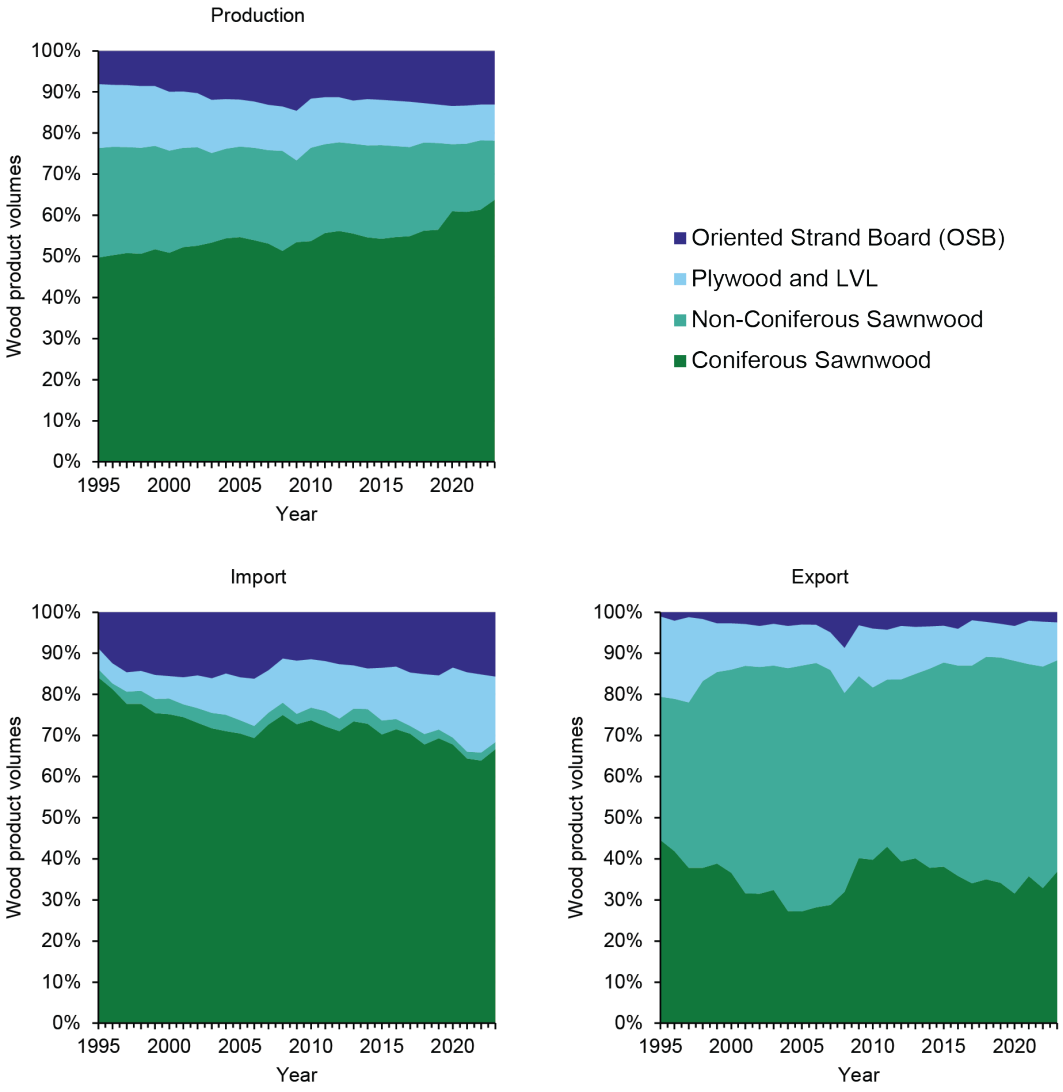


Figure 7. Trends in the relative production, import, and export of wood products commonly used in construction, 1995-2023.
Data source: Food and Agriculture Organization of the United Nations (FAO, 2023a).

4.4 Labor shortages across timber value chains

In interviews, several sawmill operators, mass timber manufacturers, and prefabricated home builders report challenges in finding labor to support timber supply chains. As transport costs can be significant (Ahmed & Arocho, 2020; Müller et al., 2019), sawmills and other wood product manufacturing facilities are often located near regional wood baskets to reduce shipping costs. These forested areas are frequently in rural or remote regions, where labor and workforce housing may be scarce. Beyond location, several industry stakeholders note that the perception of working in the wood products industry can deter youth from training in these areas. This perception may be linked to pay and workplace safety considerations. In the United States, wages in wood product manufacturing lag behind construction wages. While both industries comprise a broad range of roles and pay levels, wages can be higher in construction for comparable work. For instance, the median hourly wage for carpenters working in construction was $28.79 in 2024, surpassing the $21.09 earned by carpenters in wood products manufacturing (U.S. Bureau of Labor Statistics, 2025a, 2025b, p. 321). Furthermore, in 2023, the U.S. Bureau of Labor Statistics reported more injuries in wood products manufacturing than in construction, with rates of 4.8 and 2.3 cases per 100 full-time workers, respectively (U.S. Bureau of Labor Statistics, 2025a, 2025b, p. 321). Unionization might play a role in these discrepancies in pay and workplace safety. None of the interviewed wood products manufacturers replied that their employees were unionized when asked, while the construction industry has a rate of unionization near 10% (U.S. Bureau of Labor Statistics, 2025a). Researchers suggest that prefabrication can reduce workplace risks by increasing automation of dangerous tasks and shifting construction work to an indoor environment not subject to hazardous weather. However, this potential for improved workplace safety requires further study (Pullen, 2022).

Automation is already integrated in many large wood product manufacturing operations, including sawmills and mass timber manufacturers. One interviewed manufacturer anticipates that increased automation will not reduce the required workforce at their facility, but rather shift the type of tasks that need to be completed. Roles may transition from manual labor to operating automated machinery, such as CNCs. Currently, several interviewed manufacturers provide training for these roles on the job. Certain roles involved in timber supply chains, such as carpentry, have historically been oriented around craftsmanship. An interviewed timber framer expressed concern that the increasing adoption of technology could diminish the craft-based nature of their work by replacing the design and assembly of wood connections with standardized steel connectors. However, several studies and projects suggest that automated construction methods can build upon existing craft-based knowledge. For example, the structural performance of timber–timber joints can be evaluated using finite element modeling (Fang et al., 2019; Svilans et al., 2019; Brown, 2023), and digital fabrication techniques

can facilitate their physical construction (Svilans et al., 2019; Brown, 2023; Claus et al., 2024).

Several companies involved in timber supply chains have developed creative strategies to avoid or address labor shortages. Element5 (Element5, 2021), a mass timber manufacturer in southern Ontario, Canada, selected its location based on its proximity to an established skilled workforce and rail lines. The manufacturer uses kiln-dried lumber shipped by rail from a less densely populated region. Labor local to the manufacturing facility is involved in the production of value-added mass timber products such as CLT and glulam. This facility is also closer to many of the construction sites where the mass timber products are employed. Nordic Structures (Nordic Structures, n.d.), another mass timber manufacturer, is located in a region where housing is scarce. To attract employees in the midst of a tight labor market, the company provides language training to temporary foreign workers and workforce housing for its employees (Campbell, 2025). Another manufacturer, Timber Age (Timber Age, n.d.), takes a community-based approach to combining forest management with affordable housing production, with the goal of attracting employees by creating meaningful, rewarding work. These strategies demonstrate the multifaceted efforts being deployed to find and retain the workforce central to timber supply chains.

4.5 Embodied carbon and wood construction

While it is critical to build to meet housing needs, construction and demolition activities come with environmental costs. Embodied carbon in particular — the carbon related to extraction, manufacturing, transport, and construction activities associated with buildings — has an upfront cost (Y. C. for E. + A. United Nations Environment Programme, 2023). On a global scale, this embodied contribution is responsible for 18% of building-related carbon dioxide emissions (G. A. for B. and C. United Nations Environment Programme, 2025). For this reason, embodied carbon policies are being implemented for new construction at the municipal and national levels around the world (Feickert & Mueller, 2025).

Timber-based building systems can be very efficient in terms of embodied carbon (Feickert & Mueller, 2025). Compared with the other common building materials, steel and reinforced concrete, wood products are low in embodied carbon per unit mass (Feickert & Mueller, 2025; Waldman et al., 2025). However, when large quantities of wood are used, carbon impacts accumulate. For instance, Hu et al. find that wood-framed single-family detached homes are the largest contributor to the embodied carbon of the U.S. housing stock due to their prevalence (Hu, 2022). Although reinforced concrete used in foundations is the primary source of embodied carbon in these buildings (Jungclaus et al. 2024), developing materially efficient housing strategies remains important, as residential buildings are estimated to account for over 75% of floor space in the U.S. (Arehart et al., 2022).

Embodied carbon is generated at several stages in the production of wood building products. Considering dimensional lumber as an example, carbon emissions are first produced in the forest, during the cultivation and harvesting of trees. Transport emissions vary by shipping method and distance. Processing activities, including milling, drying, planing, and packaging, contribute most to the embodied carbon of lumber (American Wood Council & Canadian Wood Council, 2020). Kiln drying, a process used to control the moisture content and properties of wood, is often the largest source of these processing emissions (Ramage et al., 2017). The emission sources across the lumber production process suggest several strategies to reduce the embodied carbon of wood products. Emissions could be averted by reducing transport distances or by limiting processing requirements, for instance, by working with green wood, using a solar kiln for drying, or designing with minimally processed wood products such as round timber.

Wood buildings are often noted for their role in sequestering biogenic carbon. As trees grow, they absorb carbon dioxide from the atmosphere, storing carbon in their wood. A portion of this carbon remains locked in wood products as long as they are in service. For this reason, substantial amounts of biogenic carbon may be stored in wood-framed single-family homes (Jungclaus et al., 2024). However, this carbon is eventually released into the atmosphere following demolition and disposal. In the U.S., wood waste is typically landfilled or combusted as a fuel source (U.S. Environmental Protection Agency, 2020). Combustion generates significant immediate carbon emissions (Sterman et al., 2022), while landfilling generates methane, a potent greenhouse gas (R. Ross, 2021). Although the up-front carbon cost of wood construction is lower than that of many other building materials, end-of-life emissions must be carefully managed. Strategies to prolong carbon storage include extending the lifespan of wood products through reuse and reducing manufacturing waste by utilizing harvested wood more efficiently.

4.6 Untapped supply chain and manufacturing resources and circular design opportunities

The use of digital design tools and automated fabrication could enable the use of several untapped wood resources, including underutilized wood species and small-diameter trees, wood manufacturing waste, and wood construction and demolition (C&D) waste. These materials are often characterized by irregular geometries incompatible with conventional wood product manufacturing tools and processes. A transition toward design methods that engage computation could enable efficient production with these non-standard building materials.

Small-diameter trees and certain wood species go unused because their dimensions or characteristics do not provide economically viable yields of conventional wood products (Bukauskas et al., 2019; LeVan-Green & Livingston, 2001). The definition of small-

diameter products appears to vary by geographic region. For instance, an interviewed wood product manufacturer based in the Boreal Forest stated that their mill regularly uses 6-inch-diameter Black Spruce in lumber production, while another manufacturer based on the West Coast classifies trees with diameters below 9 inches as small-diameter. The economic viability of small cross-sections can be affected by wood quality, for example, when the proportion of juvenile wood is high (Bukauskas et al., 2019). A design approach that enables the use of small cross-sections is to incorporate them into mass timber products with composite structural capacity, such as CLT or glulam (R. Hernandez et al., 2005). Certain species or geometries of trees may also be underutilized. For instance, heavily branched trees, including many hardwoods, can be difficult to handle during wood processing (Bukauskas et al., 2019; Cousin, Alkhayat, et al., 2023). Another design approach for using underutilized wood is to take advantage of the entire available cross-section by using structural round timber. This approach can be advantageous, as it limits the required processing and maintains the fiber continuity of wood structural elements, thereby contributing to their strength (Bukauskas et al., 2019). Design approaches that broaden species and size tolerances could enable the use of a wider range of wood resources.

Wood waste is produced at several stages throughout wood manufacturing and during C&D activities. The process of converting roundwood logs to lumber has a recovery rate of around 50% (Ramage et al., 2017). The manufacturing of wood products generates a range of waste, including offcuts, wood chips, and sawdust. In interviews, several manufacturers stated that the estimated quantities of these waste materials can be vast, but that companies lack the incentive to reemploy them. There may be a market for larger waste, which could be used to produce finger-jointed studs or OSB. Often, small waste residues are burned for energy production (Brandeis et al., 2021). Additional waste is produced during the construction and demolition of buildings. Falk et al. estimated in 2013 that there may be as much as 4.0×10^6 m^3 of lumber in demolished housing each year (Falk et al., 2013). Despite the scale of this potential inventory of salvaged wood for construction, there are both economic and technical barriers to reuse. Wood waste supply chains are needed to effectively create markets for these materials (Garcia & Hora, 2017). Furthermore, grading reused lumber can pose challenges and often requires engineers to use their own judgment. Establishing a grade for reused lumber could address this barrier (Bergsagel & Heisel, 2023; Falk et al., 2013). Computational workflows and the optimization of structural form can address the complex task of designing with reused material inventories (Brütting et al., 2019; Huang et al., 2021). Furthermore, there is potential to incorporate wood waste into engineered wood products, including mass timber systems (Arbelaez et al., 2020; Bergsagel et al., 2025; Blowes et al., 2025; Giordano et al., 2023). Kedir and Hall suggest the potential to incorporate circular economy concepts into industrialized housing construction, as increased digitalization can enable the collection and tracking

of data required to facilitate building component reuse at a later date (Kedir & Hall, 2021). Employing design approaches and technologies that enable circular design with untapped waste wood resources could limit building-related embodied carbon (De Wolf et al., 2024) and reduce pressure on forests for wood production.

5. Current role of digital technologies in domestic timber manufacturing

Digital technologies are employed across timber value chains to characterize, monitor, and plan resource utilization in manufacturing, as shown in Figure 8. At each successive stage of timber value chains, wood resources undergo additional processing to achieve particular geometries or mechanical properties. Each forest-based industry has honed specific technologies, often to optimize the output of particular manufactured products. The use of computational approaches, such as optimization and automated tools, across the value chain indicates interest in adopting novel technologies. Given the current level of digitalization and openness to technology in practice, there is potential to share data across fragmented industries. In the following sections, current applications of digital technologies are discussed across timber value chains, along with the existing challenges and opportunities for linking these forest-based industries.

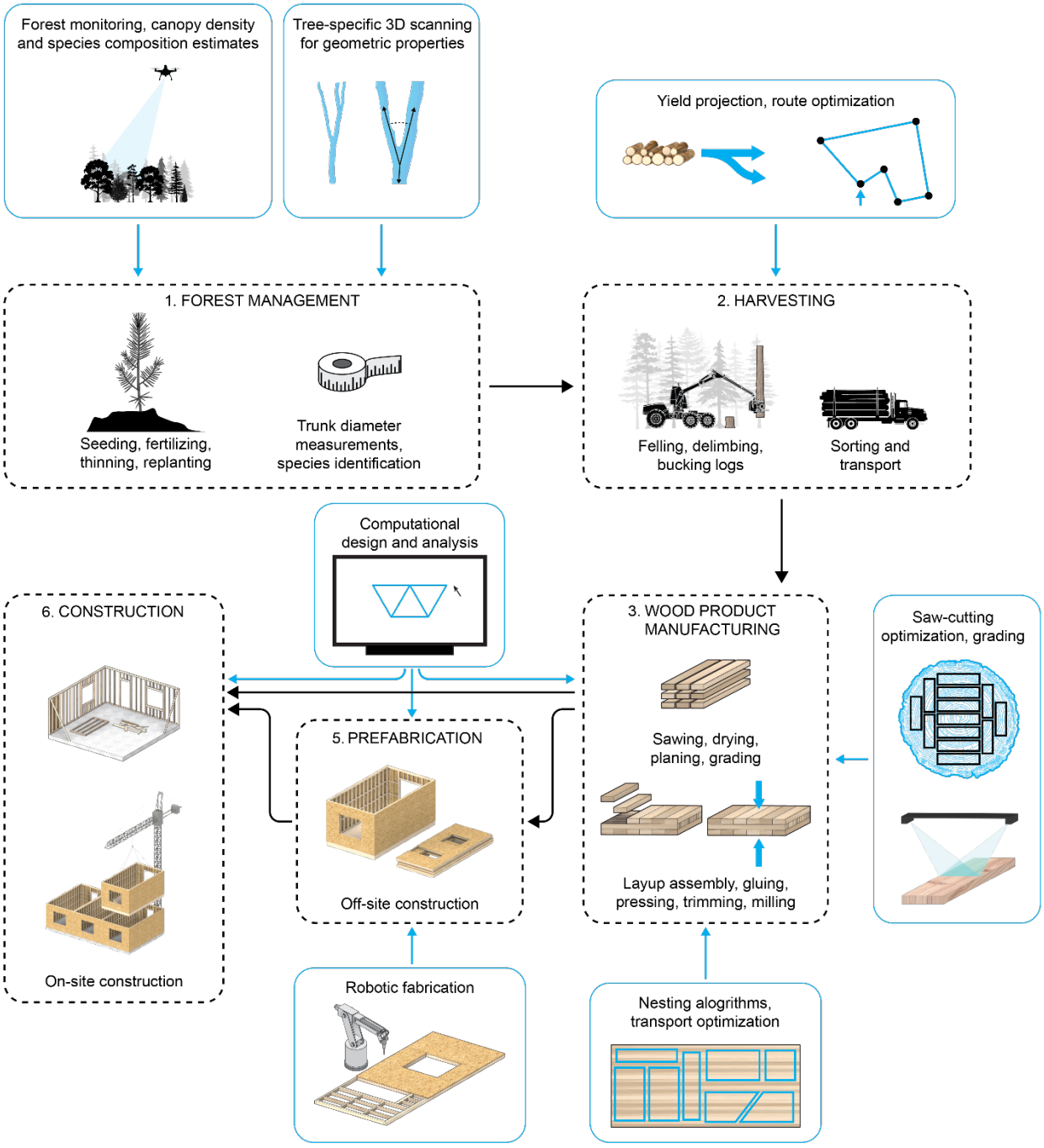


Figure 8. Digital technologies are engaged across timber value chains to enhance forest management, wood manufacturing processes, and housing construction.

6. Monitoring and modeling forest behavior: Digital forestry

Digital technologies are emerging and increasingly being implemented to monitor forests. Simultaneously, computational models are being developed to understand and project forest behavior. Müller et al. describe the concept of the ‘virtual forest’ (Müller et al., 2019), an informational twin of the existing forest with data that can be used by

foresters, planners, and mills to inform forest management practices. Data from the virtual forest can enable forest-level analyses, such as modeling wildfire risk, monitoring fire management impacts (Li et al., 2024; Vibrant Planet, n.d.), and assessing the status of forest carbon sinks (Silva et al., 2023).

To facilitate the concept of the virtual forest, extensive data must be collected. The U.S. Forest Service gathers substantial forest-level data through manual surveys of forest plots as part of the Forest Inventory and Analysis program. These surveys include detailed data such as records of observed species and tree diameter measurements, which are reported through the Nationwide Forest Inventory (NFI) (*Forest Inventory and Analysis | US Forest Service Research and Development*, 2023). While the Forest Service does not publish the geographic coordinates of surveyed plots, several research projects use computational approaches to link manual survey data to geospatial data, facilitating regional assessments of forest features (Riley et al., 2021; Service, 2024). Other data required to construct and monitor the virtual forest are often collected using remote sensing (Turner et al., 2004; Myeong et al., 2006; Allison et al., 2016; White et al., 2016; Chuvieco et al., 2020). These technologies, including satellite imagery and aerial LiDAR scanning, can be used to monitor forest features such as canopy density (Joshi et al., 2006) and species composition (Rocchini et al., 2016). Machine learning techniques, including computer vision, can support analyses of data obtained from remote sensing (Matiza et al., 2023; Vibrant Planet, n.d.). Terrestrial sensing data collection, including the use of autonomous sensing devices, is also being pursued with the goal of enabling more frequent and accurate surveys of forested areas (Malladi et al., 2024; *Gaia AI | Smarter Forest Management with AI-Powered Data & Insights*, 2025).

Data from the virtual forest can also be used for tree-specific studies, such as monitoring the growth conditions or strength properties of individual trees (Fitzgerald, 2016; Nocetti & Brunetti, 2024). The use of sensors to register tree dimensions could be useful for estimating harvest yields (Fitzgerald, 2016), and non-destructive testing can be used to measure the properties and quality of standing trees (R. J. Ross, 2015), which could inform log segregation decisions (Fitzgerald, 2016). Nocetti and Brunetti point to the current limitations of standing-tree wood quality assessments using laser-based and image-based methods. However, the authors assert that these assessments will have limited impact unless detailed tree surveys are linked to information about sawmill wood product yields, suggesting RFID as a method to trace the utilization of harvested logs (Nocetti & Brunetti, 2024). This approach could be impactful, as there is currently limited feedback between foresters and sawmills following timber sales. Improving communication and data transfer between foresters and sawmills could inform both harvesting and growing methods (Fitzgerald, 2016). Mass timber manufacturers, premanufactured home producers, and designers have even fewer

opportunities to interface with forest data. Connecting these wood-based industries could improve forest management and wood product utilization.

While the concept of digital forestry is often presented in a techno-optimistic light, Gabrys et al. argue that technologies which optimize the utilization, carbon sequestration, or commodification of forests may focus on a single driver of forest productivity at the risk of marginalizing other forest stakeholders (*The Forest Multiple: Composing and Digitalizing Wooded Worlds - Jennifer Gabrys, Michelle Westerlaken, Kate Lewis Hood, Yuti Fatimah, Trishant Simlai, 2025*, n.d.). The authors also point to the concern that forest monitoring could enable surveillance of forest communities. The impacts of digital technologies supporting the virtual forest must be broadly evaluated before implementation.

7. Technologies for harvest planning and operations: Roundwood extraction

Roundwood is extracted from the forest through harvesting activities. Harvesting is often carried out through either selective logging or clear-cutting. While both harvesting approaches have environmental consequences, several studies suggest that selective harvesting is less damaging to forest diversity than clear-cutting (Ding et al., 2017; Elliott et al., 2020). In addition to its environmental impacts, harvesting often generates substantial amounts of waste. The EPA estimates that 43% of wood resources are left in the forest as waste following harvests (United States Environmental Protection Agency, 2018). Digital technologies have the potential to improve harvesting efficiency and limit environmental impacts.

Müller et al. describe opportunities for digital technologies to inform harvest planning using data on forest characteristics, improve the execution of harvesting operations, enable the tracing of harvested roundwood, and guide the planning of roundwood transport (Müller et al., 2019). In practice, harvesting is primarily accomplished through manual harvesting or using mechanical timber harvesters to cut, delimb, and buck logs. While mechanical timber harvesters substantially improve harvest efficiency, they are most effective in clear-cutting scenarios, which are ideal for monoculture tree plantations (Ramage et al., 2017). Advances in technologies for locating, orienting, and optimizing the operations of harvesting machinery could enable autonomous harvesters or forwarders (Müller et al., 2019). Autonomous harvesters are actively being developed (*AORO*, n.d.; Jelavic et al., 2022; La Hera et al., 2024), and could eventually facilitate the targeted removals of specific trees. Once logs have been felled and processed, they must be transported to mills, often on logging trucks similar to the one shown in Figure 9. Route optimization can reduce the embodied carbon and environmental impact of trucking required to collect log piles post-felling and to transport roundwood to milling facilities (Müller et al., 2019; Holmström et al., 2023). While these technological solutions are promising, the U.S. logging industry faces more fundamental challenges in

value chain logistics and persistent labor shortages that must also be addressed (He et al., 2021; Dogru et al., 2024).

After extraction from the forest, roundwood can be used following this stage of the timber value chain with only minimal processing. While it is common to use roundwood for infrastructural applications such as utility poles (R. Ross, 2021), most roundwood used in buildings is further processed to produce solid wood products. In the U.S., only a few wood product manufacturers specialize in structural round timber products, such as WholeTrees Structures (*WholeTrees Structures*, n.d.). While using roundwood directly in buildings can reduce the embodied carbon associated with structural wood products (Bukauskas et al., 2019), working with the unique forms of roundwood elements falls outside conventional building design practices. However, as Figure 9 indicates, 3D scanning can precisely capture natural forms, and computational techniques can support design with non-standard roundwood geometry (Bukauskas et al., 2019; Lok et al., 2021; Cousin, Alkhayat, et al., 2023). The development of additional digital technologies that enable design using a broader range of wood resources can reduce wood processing requirements.



a) b)

Figure 9. a) Logging truck being loaded with roundwood. b) 3D scan of unique tree geometry. Source: WholeTrees Structures (*WholeTrees Structures*, n.d.).

8. Sensing and automation for quality control and optimized production: Primary manufacturing of solid wood products for housing

Interviews with wood manufacturers indicate that industrial roundwood is typically sourced for manufacturing locally to minimize transportation costs. Key processes involved in the manufacturing of wood products are designed to convert saw logs into products of standard dimensions with consistent quality and wood properties. While these processes are often optimized to achieve high wood product yields, substantial amounts of waste are generated throughout the manufacturing process. These

optimization strategies could benefit from coordination with harvest planning and structural design processes.

Roundwood is processed into solid wood products through primary manufacturing operations. This section focuses on the production of dimensional lumber. However, other common wood products, such as plywood and OSB, are produced through distinct operations. To transform roundwood logs into lumber, a series of steps is carried out to control wood properties throughout manufacturing, as shown in Figure 10. Prior to processing saw logs, it is common to spray them with water to prevent warping or shrinking due to changes in moisture content. Logs are then debarked and milled to green dimensions through a progression of sawing operations. Rough-sawn lumber is then typically kiln-dried and planed to ensure dimensional stability and accuracy. In some regions, such as California, interviewed manufacturers are able to air-dry lumber. It is common to dry lumber since wood has improved strength properties and durability compared with green lumber (Ramage et al., 2017). However, kiln-drying can contribute considerably to the embodied carbon of wood products (Ramage et al., 2017). Using more efficient kilns or using green lumber could address this carbon impact. During this process, lumber is graded and sorted, and ultimately shipped to wholesalers, retailers, or construction sites.



a)



b)



c)



d)



e)



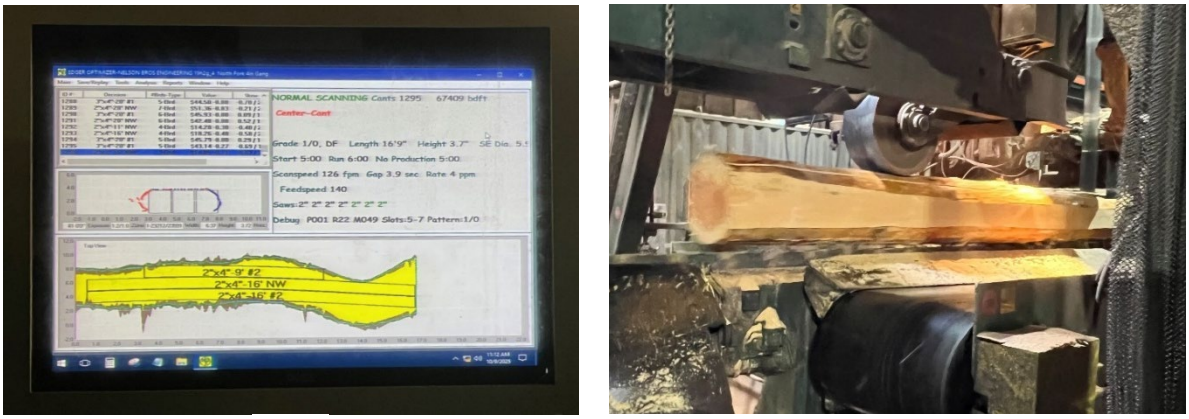
f)

Figure 10. During the primary manufacturing of dimensional lumber, roundwood is soaked to prevent cracking prior to processing (a), saw logs are sawn into cants (b), and cants are sawn into lumber (c). Sawdust and woodchips are produced as waste throughout this process (d). Lumber is air-dried (e) or kiln-dried prior to transport (f).

8.1 Saw cutting optimization and grading

Scanning technologies are central to the large-scale manufacturing of lumber products, enabling sawmills to extract the maximum yield of wood products from a given log. Laser-based methods are commonly used to evaluate the 3D geometry of logs as they enter the manufacturing line, as shown in Figure 11. These scans inform milling operations and can be integrated with machinery control systems to adjust the position of logs or cutting equipment throughout the manufacturing process. Several large mills that were interviewed make use of fully integrated systems such as those offered by JoeScan or Porter (*JoeScan Sawmill Optimization*, n.d.; *Porter Engineering*, n.d.). With these systems, scanning and cutting optimization occur at multiple stages along manufacturing lines, first informing bucking and merchandising as well as initial cuts to produce cants with the maximum potential for wood products. These processes are also often used to determine how to break down a log into dimensional lumber sizes to achieve the highest yield in the product mix. Improvements to saw optimization technologies and production workflows are active areas of research, along with potential applications for artificial intelligence in adaptive control systems (Nasir & Cool, 2020; Forghani et al., 2024). However, for small sawmills, these technologies can be cost-prohibitive. Instead, sawyers use their judgment based on visual assessments of logs to determine cutting patterns.

Grading is key to evaluating the quality of wood products, determining their potential structural applications, and economic value. Dimensional lumber products are graded according to the American Softwood Lumber Standard through visual grading or machine grading (R. Ross, 2021; U.S. Department of Commerce, 2020). Visual grading can involve manual or automated assessments of visible defects in lumber, while machine grading relies on non-destructive tests of wood properties (R. Ross, 2021). In one interviewed sawmill, automated visual grading informs lumber trimming to standard lengths, optimizing grade yield.



a) b)

Figure 11. a) Saw cutting optimization algorithms being used to identify the cutting pattern for a log. b) A log being positioned and sawn according to the algorithm output.

8.2 Opportunities to align wood product manufacturing with available wood resources

While sensors and scanning are widely used in sawmill operations to optimize milling processes and grading, these technologies remain largely disconnected from harvest planning, even though they are affected by wood fiber quality. Fitzgerald suggests that increased feedback between mills and loggers about wood quality and yield rates could improve the efficiency of wood product manufacturing (Fitzgerald, 2016). Sawing optimization is also disconnected from the final structural use of wood products. Structures can often benefit from non-uniform geometries of building components. For example, shape optimization can be used to align the form of building components with structural demands, and often results in unconventional geometries that are difficult to produce with dimensional lumber products (Haftka & Grandhi, 1986; Mayencourt, 2020). Through increased feedback between mills and structural designers, it could be possible to adjust milling operations to produce sawn lumber in sizes and shapes that more closely meet structural needs. Opportunities for informational exchange about structural performance exist even earlier in timber value chains. Historically, designers selected trees with specific geometries, such as natural curvature, for particular building applications. Computation could provide a pathway to resume this practice of incorporating natural structurally-efficient geometries in contemporary design at scale (Larsen et al., 2022).

Developing structural systems to accommodate the natural variation in wood geometries could also benefit small-scale sawmills. One interviewed sawmill, Timberdoodle Farm and Sawmill (*Timberdoodle Farm & Sawmill*, n.d.), finds that many trees which need to be removed for forest health do not occur in sizes which are readily marketable as dimensional lumber. For instance, the manufacturers often fell logs with lengths around 8 ft, which are difficult to sell. Through coordination with wood product

manufacturers, building designers could adapt their designs to make use of these available materials.

8.3 Biomass energy production and wood manufacturing waste

Wood biomass energy and related products are increasingly produced in the U.S. and are being integrated into global energy supply chains. Wood biomass used for fuel sources includes fuelwood combusted directly, residues from wood manufacturing, and manufactured products such as wood pellets (Brandeis et al., 2021). Substantial waste is generated during wood construction and demolition activities. As shown in Figure 12, much of this waste is landfilled or used as a fuel source. Interviews with manufacturers suggest that waste is also generated in large quantities during manufacturing. This waste ranges in dimensions and characteristics. Waste residues, mainly consisting of bark, are often combusted on-site at manufacturing facilities and used for energy generation (Brandeis et al., 2021). In some cases, interviewed manufacturers have found markets for sawdust and wood chips for use as soil amendments or in the pulp and paper industry. However, as pulp and paper demand has declined over the past two decades, facilities have shuttered in some regions, eliminating this waste destination. One interviewed wood products manufacturer, who had previously sold wood waste to the pulp and paper industry, purchased a biomass energy production facility as a means to dispose of their wood waste.

In recent years, the wood pellet industry, another consumer of wood residues, has grown in the southern U.S. Over just a three-year period, between 2016 and 2019, U.S. industrial wood pellet production increased by 42% (Brandeis et al., 2021). These pellets are largely shipped to the U.K. and the E.U., where policies incentivize the use of biomass as a renewable energy source (Sterman et al., 2022). Despite the emissions generated directly by their combustion, biomass energy sources are considered carbon-neutral in these regions, as in the U.S. (Sterman et al., 2022). While wood biomass energy is considered an alternative to fossil fuels, wood combustion is even less efficient than coal. Furthermore, wood manufacturing waste can be used to produce these pellets; however, 62% of wood pellet inputs are harvested directly for energy production (Brandeis et al., 2021). Trees sequester carbon dioxide as they grow, in theory, offsetting the emissions generated during their combustion. The argument for carbon neutrality implies that immediate emissions from burning wood will be offset by the emissions absorbed when trees are replanted. However, Sterman et al. demonstrate that it would take over a century for a replanted forest to absorb the carbon dioxide equivalent of the amount released during harvested wood combustion (Sterman et al., 2022). While the wood biomass industry has created economic viability for low-value and waste wood, wood combustion has immediate global warming impacts that cannot be ignored. Developing value-added building products from wood waste could

offer carbon benefits by disincentivizing the combustion of waste and sequestering carbon over their lifespans.

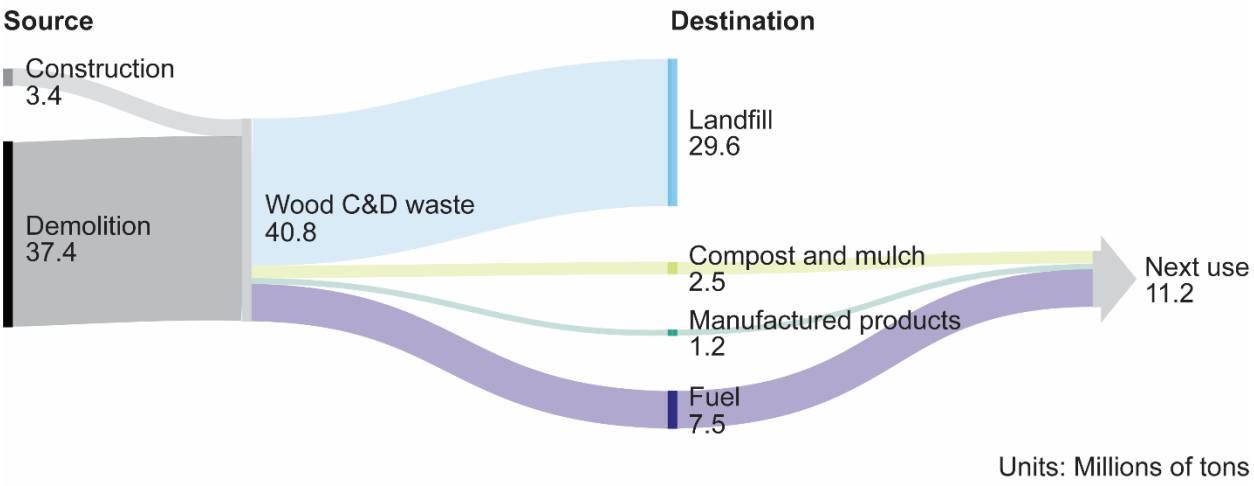


Figure 12. Destinations of wood construction and demolition waste in the United States in 2018. Reproduced from Blowes, Rachel, M. (2025). *Dowel-laminated timber from waste lumber offcuts: Towards structural component circularity* (Master's thesis, Massachusetts Institute of Technology). Data source: U.S. EPA (U.S. Environmental Protection Agency, 2020).

8.4 Wood durability and property modification

The porous cellular structure of wood enables efficient transport of water and nutrients within trees as they grow (R. Ross, 2021). This same feature makes long-term durability a key challenge of building with wood, particularly in exterior applications such as siding. As an organic material, wood is susceptible to biodegradation. Furthermore, both the dimensional and mechanical properties of wood are affected by moisture (R. Ross, 2021). To address the moisture resistance of wood, several approaches can be taken, including physical and chemical modifications (Ramage et al., 2017; Chen et al., 2020). Physical modification may be as simple as providing a protective coating for wood products. Other approaches include thermal modification and densification (Chen et al., 2020). These processes may increase strength properties in certain loading orientations but may reduce ductility and bending strength (Ramage et al., 2017). An emerging densified wood product is Superwood, which exhibits enhanced strength properties (*InventWood — Technology*, n.d.; Mims, 2025). Chemical modification includes a range of approaches, often designed to increase wood durability by limiting its tendency to absorb moisture (Chen et al., 2020; Ramage et al., 2017). Acetylation is a chemical process that can reduce the hydrophilic nature of wood without adversely affecting its strength and stiffness (Ramage et al., 2017). While acetylated wood is commercially available from the producer Accoya, (*Accoya Acetylated Wood | High Performance, Long Life Modified Wood*, 2025), one interviewed wood siding manufacturer noted that

the Accoya process in particular was developed for use on Radiata Pine sourced from New Zealand. The manufacturer suggested that adapting this process to North American species could expand the market for siding products with longer lifespans while leveraging locally available wood resources. While modification strategies show promise for the enhanced durability of wood products, their embodied carbon and environmental impacts must be evaluated, as certain wood treatments have historically posed challenges for end-of-life disposal (United States Environmental Protection Agency, 2018).

9. Automated precision and robotics-enabled customization: Secondary manufacturing of prefabricated wood building components and systems

Secondary manufacturing is required to produce prefabricated wood building components used in housing, including light wood framing elements, such as dimensional lumber trusses or stud wall panels, and mass timber elements, such as glulam beams or CLT floor panels. Entire building systems can also be pre-manufactured, as in manufactured housing. Interviews with secondary product manufacturers indicate varying degrees of automation are engaged in practice. Dedicated automated machinery capable of performing specific tasks, such as precisely cutting unique openings in mass timber panels, is commonly used on manufacturing lines. A small number of manufacturers use robotics capable of completing a wider range of tasks. Both of these approaches to automation facilitate the rapid production of customized building components.

9.1 Sourcing and grading primary wood product feedstocks

Wood product sourcing varies across prefabricated wood component manufacturers in North America. A few of the interviewed manufacturers are vertically integrated, producing wood products such as veneer or lumber that they use directly in the manufacturing of their own products. Other prefabricated building component manufacturers source feedstock from external suppliers for their manufacturing processes. Often, the material sourced is kiln-dried and graded lumber, which is required for manufacturing many mass timber products, as well as for prefabricated wall panels and truss systems. A consequence of this value chain structure is that the availability and quality of source materials for prefabricated wood components are sensitive to lumber prices (Adhikari et al., 2024). Mass timber manufacturers often regrade the wood they receive, since lumber must meet stringent requirements for moisture content and dimensional accuracy in order to meet the APA-PRG 320 standard that applies to CLT (Adhikari et al., 2024). Increasing coordination between primary wood product manufacturers and mass timber producers could simplify this requirement for additional grading and quality control.

9.2 Digital fabrication and robotics

Design software and digital fabrication tools are widely used by secondary wood product manufacturers in practice. These manufacturers link 3D design data from building information models (BIM) with software used to program the control of automated fabrication tools such as CNCs, as shown in Figure 13. Based on interviews, robots capable of adapting to many building tasks are not commonly used by secondary manufacturers in the U.S. One surveyed modular housing manufacturer based in Switzerland, ERNE AG Holzbau, uses robotics for the fabrication of panelized wall systems (ERNE AG Holzbau, 2025). Robots are used for tasks such as trimming lumber to specific lengths or nailing elements together. By coordinating computational design and robotic control, the company can produce unique façade panel designs using standard materials. Despite the potential benefits of incorporating robotics into the production of factory-built housing, this approach has been used only to a limited extent in North America. Ensuring that comprehensive process planning is undertaken and that the right mix of technologies is selected to enhance production appears to be key (Tommelein & Coelho, 2025).



Figure 13. Left: Reframe Systems robot building with dimensional lumber. Right: CNC machine being used to modify a CLT panel.
Source: Element5 (*Getting the Most from Every Panel - Element5*, 2021).

In interviews, mass timber manufacturers in North America describe heavily automated manufacturing lines in their facilities. These lines often incorporate processes for the scanning and quality assessment of feedstock materials. Automated processes are also commonly used to plane, trim, or finger-joint feedstock elements to achieve the required dimensions for use in mass timber components. Specialized machinery is also used for the gluing and layup of mass timber components. These components are often customized with CNC machinery to create unique openings for doors, windows, or connection details. The cost of such digital fabrication tools is prohibitive for small secondary manufacturers. Rather than investing up front in expensive automated

equipment, one small mass timber manufacturer, Timber Age (Timber Age, n.d.), focuses on manufacturing's potential to create rewarding employment opportunities and community benefits, and limits its projects to local housing production using nearby available resources.

A survey of manufacturers reveals two potential trajectories for the development of mass timber manufacturing in the U.S. One pathway involves large-scale manufacturing operations enabled by automation and robotics. These operations require workforce training to familiarize workers with the digital technologies used in manufacturing lines. A second pathway includes distributed small-scale manufacturing operations facilitated by localized workforces. These operations require lower start-up costs and less training related to automated technologies. While a greater portion of the tasks carried out by the workforce entails manual labor than in the previous manufacturing pathway, this manufacturing model has the potential to create employment opportunities in distributed rural areas directly linked to forests.

9.3 Optimization to reduce secondary processing waste and transportation impacts

From interviews, it appears that the characteristics of waste streams from secondary manufacturing depend heavily on the type of product being manufactured. For instance, small pieces of lumber, which would be considered waste by prefabricated housing manufacturers, can, in some cases, be incorporated into CLT layups. DLT production results in lumber offcuts, often with lengths set by the minimum length a finger jointer can process. According to one manufacturer, longer waste lumber elements can often be resold to produce finger-jointed studs, in some cases to markets found in Asia. Mass timber manufacturing also generates waste from the subtractive processes used to customize panelized products. For instance, waste is produced when openings are cut from panels or when building panels do not occupy the entire area of CLT blanks. These operations can produce large offcuts with irregular dimensions. Manufacturers of panelized building components often use nesting algorithms to cut openings in panels as efficiently as possible. Optimization is also used to coordinate shipments of mass timber products. As these products are often large in scale, transport can become a major expense for manufacturers. One interviewed mass timber manufacturer developed a custom optimization tool to limit the number of shipments required for each project.

9.4 Shifts in design processes required for efficiency gains from prefabrication

Mass timber and panelized housing systems are becoming more widespread (WoodWorks Wood Products Council, 2025). However, as markets for these materials continue to grow, designers and builders may be less accustomed to working with them. Several mass timber manufacturers and producers of pre-manufactured housing

emphasize that prefabrication requires shifts in project timelines, which may be unfamiliar to clients and collaborating designers. Compared with site-built construction methods, making late-stage design changes with prefabricated components is more challenging, since details for structural connections and penetrations for mechanical systems and plumbing must be defined before components are produced. Clear communication with clients and interdisciplinary coordination from the outset of projects can help mitigate this challenge.

Interviewed mass timber manufacturers face unique challenges that affect both their manufacturing processes and the feasibility of building designs using their products. One mass timber product manufacturer described challenges that emerge from adapting European fabrication tools to the North American context. In their experience, wood species in North America tend to be denser and have more frequent knots, requiring adjustments to machinery such as CNCs to accommodate local species. Additionally, the manufacturer believes that structural spans are generally larger in North America, requiring the fabrication of mass timber components with larger cross-sections. Another manufacturing concern shared by several mass timber producers is finding the workforce needed to operate large factories. Furthermore, many jobs in mass timber manufacturing, from design and engineering to production, require job-specific training. One manufacturer suggests an opportunity to expand education on mass timber in educational settings, from engineering schools to community colleges.

Mass timber manufacturers also encounter design challenges specific to their products. Several manufacturers express that both clients and designers are often inexperienced in working with mass timber, as it is a relatively new building material. Another manufacturer stated that designers often develop building plans with structural spans similar to conventional concrete or steel framing layouts, which may not be economical with mass timber. They express the need for rules of thumb or standard designs for architects to reference early in the design process for these wood products, as simple design changes, such as including an even number of bays in a structural framing plan, can improve structural efficiency and overall project costs.

10. Wood design tools and technologies

While the use of standardized wood products enables rapid design of homes using conventional construction methods, design tools with untapped potential exist to facilitate the widespread use of a broader assortment of wood resources with varied geometries and properties. Designers regularly employ 3D modeling software to develop building plans and construction documents. This software can represent complex geometry and, in many cases, track detailed information about individual building components, such as the species and grade of wood elements. It is increasingly common in contemporary design and construction to build with unique,

complex parts, tracking design data for their fabrication through BIM. Furthermore, 3D scanning can be used to measure geometric data, allowing designers to work with precision geometry in modeling software. For example, Amstberg et al. demonstrate how 3D scanning can enable the use of natural timber forms in design (Amtsberg et al., 2020). To assess the mechanical properties of wood inventories, non-destructive methods may be applied (R. J. Ross, 2015). With known properties, Finite Element Analysis tools can facilitate iterative structural design with complex geometry.

Emerging computational approaches can be implemented to facilitate working with large inventories of elements with distinct characteristics. For instance, inventory matching can be applied to match collections of building components with unique and varied properties to target designs (Cousin, Marshall, et al., 2023). Parametric modeling tools can also be used to adapt designs to accommodate non-standard components, such as reclaimed wood (Bergsagel & Heisel, 2023). Paired with the capabilities of robotics to support the fabrication of complex shapes, these design tools show potential to enable the efficient production of unique building components or systems using an expanded range of resources. Alternatively, computational approaches and additive manufacturing can be used to design structurally optimized building components with unique geometry and minimal waste (Mayencourt et al., 2025). However, to fully take advantage of the ability of these tools to facilitate design with diverse geometries, designers must develop novel approaches to employ these geometries in practice, addressing considerations ranging from constructability and serviceability to economic viability.

11. Comparison of domestic timber production to the global context

Forest ownership models and management practices vary globally (FAO, 2025; Lesiv et al., 2022; Messier et al., 2022; Whiteman et al., 2015), as does the structure of timber value chains. Examples of these value chains from abroad suggest that efficiencies can be gained from vertical integration. Timber products manufactured in the U.S. are also included in global value chains. To participate in international trade in wood products, manufacturers must meet traceability requirements. Technology is being deployed to enable detailed tracking and data collection for this purpose. Examples of timber-producing systems from abroad also demonstrate alternate approaches for managing the end-of-life of wood products (Garcia & Hora, 2017). While wood waste value chains are still emerging, these cases suggest the potential to integrate cascading and reuse at scale.

11.1 Vertical integration of timber value chains

A range of structures exists for timber value chains. Interviews with manufacturers in the U.S., Canada, and Europe indicate that varying degrees of vertical integration are possible. There are several examples in North America of manufacturers with vertically integrated primary and secondary wood product manufacturing operations. For

instance, Freres Engineered Wood produces veneer, which is subsequently used in the manufacturing of their mass ply products (*Freres Engineered Wood | Mass Ply - Timber Manufacturers*, n.d.). Vertical integration may also occur at the other end of timber value chains. For example, StructureCraft integrates secondary manufacturing of mass timber products with structural design expertise (*Structural Engineers. Master Builders.*, 2025). Full vertical integration of timber value chains is possible, as with Nordic Structures (Nordic Structures, n.d.). Through its integrated milling enterprise, Chantiers Chibougamau, the company negotiates the logging of small-diameter Black Spruce on publicly owned or Indigenous land in Quebec. They operate sawmills for the primary manufacturing of wood products and kraft pulp used in paper products. Their secondary manufacturing of solid wood products includes both mass timber and light wood framing elements, such as I-joists, which make use of small, stranded wood elements. Lastly, the firm provides structural design assistance to facilitate project delivery using its wood products.

There are both benefits and drawbacks of vertically integrated timber value chains. In the case of Nordic Structures, since the manufacturer produces a range of primary and secondary products, it can use wood resources that would be treated as waste by industries producing a single product. This vertically integrated structure offers benefits in terms of material efficiency. Conversely, one interviewed secondary product manufacturer asserts that obtaining primary wood products from a single source can pose challenges. They suggest that drawing from multiple sources makes their supply of manufacturing inputs less susceptible to impacts from threats to forests, such as fire or insects. The link between primary and secondary manufacturers appears to be important for ensuring the consistency of secondary processing inputs. As discussed in section 9.4, North American mass timber manufacturers regrade the wood they receive to meet the required standards for CLT (Adhikari et al., 2024). Austrian producers, who mass produce CLT blanks, experience fewer challenges posed by variable lumber quality than North American producers, who manufacture products on a project basis, due to the dedicated production of lumber for use in mass timber (Adhikari et al., 2024). Through this example, Adhikari et al. suggest that long-term partnerships between primary and secondary manufacturers can lead to production efficiencies without requiring vertical integration.

11.2 Domestic timber products in international markets

As differing forest management practices are employed globally, information about the sourcing of wood products is important to ensure their sustainable and ethical production. For this reason, manufacturers must track detailed information on the chain of custody for wood products to export them from the U.S. This information is required to obtain certifications that reflect the use of sustainable forest management practices, such as FSC certification (*Home | Forest Stewardship Council*, 2022). Additionally, the

EU requires detailed documentation of material sourcing and characteristics to deter illegal logging (Ramage et al., 2017). Certifiers and technology companies have developed tools to track information related to wood products to facilitate their trade. For example, Chainparency employs blockchain technology to track value chain information (Chainparency, n.d.). While transparency in timber harvesting and the wood product trade is important to monitor, one interviewed small manufacturer stated that collecting and managing the required data can be challenging. Ensuring that these certifications are attainable for timber product manufacturers at all scales is an important consideration.

11.3 Cascading and end-of-life scenarios

Examples from abroad demonstrate pathways for increasing the utilization of wood products through cascading or reuse. To encourage increased use, Sweden, Austria, and Germany have policies banning the landfilling of untreated wood waste (Ramage et al., 2017). Restricting the disposal of wood products creates a requirement for manufacturers and the C&D industry to find alternate uses for wood waste. In many cases, wood waste is combusted for energy production. However, extending the use of wood products or reusing waste in new building applications can prolong the carbon sequestration effect of wood (Ramage et al., 2017). Garcia and Hora identify several emerging wood waste supply chains in European countries. They point out that cascading and reuse are difficult to implement when the combustion of waste is incentivized. However, they identify a few scenarios where wood waste recovery rates are high, particularly in the case of Italy (Garcia & Hora, 2017). These wood waste value chains suggest that pathways to mitigate wood waste are feasible.

12. Design and manufacturing prototypes

In the following sections, two housing design case studies are described that make use of non-standard wood resources. These case studies demonstrate the potential of computational design and digital fabrication technologies for housing production. With these tools, it is possible to incorporate a broader range of wood resources in design.

12.1 GO Logic panelized systems

This case study explores how an existing prefabricated housing system could be adapted to include an inventory of non-standard building materials, namely wood manufacturing offcuts of varied lengths. GO Logic Design and Construction (*GO LOGIC*, 2025) is a home builder located in Maine focused on Passive House-certified prefabricated panelized homes. Using GO Logic structural framing panels as a point of departure, three non-normative wall and roof structural framing systems are developed below that leverage the irregular lengths of waste offcuts, as illustrated in Figure 14. The GO Logic 1100 house plan is modified to incorporate these panels, as shown in Figure 15.



a. b. c. d.

Figure 14. Wall panel structural framing systems, including: a. existing 2x6 wall panel, b. wall panel with sistered elements, c. truss panel, d. messy mass timber (MMT) panel.

12.1.1 Sistered 2x6 stud panel system

For this panel wall prototype, offcut lumber boards of irregular lengths are joined to create continuous sistered studs. Sistering is a conventional construction approach for rehabilitating structural elements. Through this approach, a new dimensional lumber joist or stud is typically nailed to an existing element to enable load sharing. The proposed wall panel system uses sistering to make use of short manufacturing offcuts that would otherwise become waste. Computational approaches can be employed to evaluate the structural performance of potential wall assemblies using this sistered technique, calibrating the joint locations between board ends as necessary. Figures 15-18 demonstrate how this panel system could be incorporated in a panelized house design.

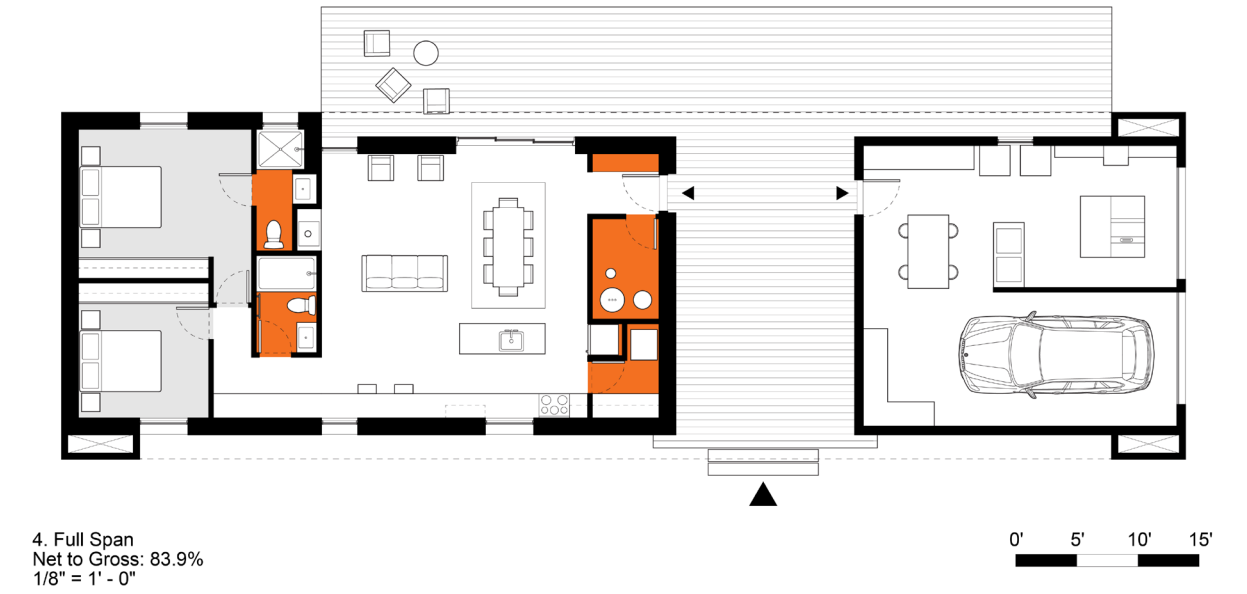


Figure 15. Adapted floor plan of a GO Logic house.

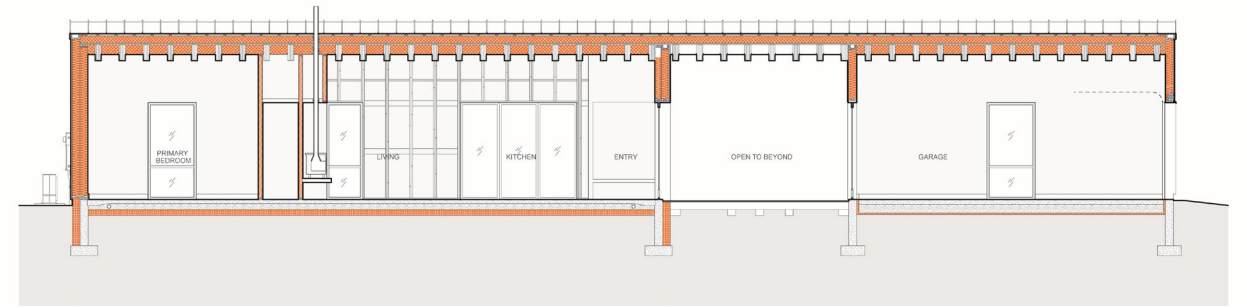


Figure 17. Longitudinal section, sistered panel system.

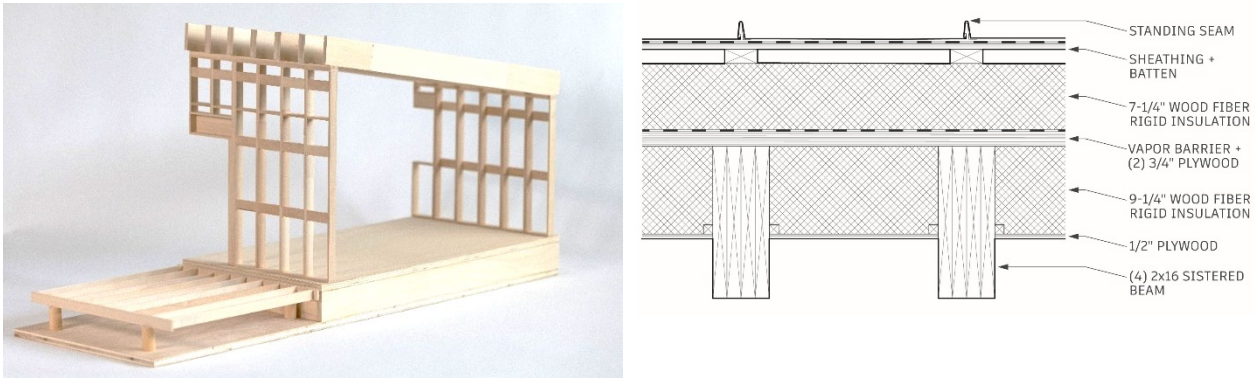


Figure 16. Left: Structural framing model of the sistered stud panel system. Right: Roof detail including sistered studs.



Figure 18. Interior rendering showing the sistered stud panel system.

12.1.2 Panelized truss system

A second concept for a non-normative panelized construction system makes use of offcut materials with irregular lengths as truss members in an expressive assembly, illustrated in Figures 19-21. Gusset plates are used as a simple connection strategy for joining truss elements. Through a computational workflow employing the Digital Circularity Toolkit (Lee, 2024), an inventory-matching approach is implemented which enables the optimal assignment of available stock material within a wall panel. Using this approach for an inventory of waste materials with varying lengths, wall panels can be design with unique geometries. To assist in the fabrication of these unique geometries, robotic assembly is proposed, as illustrated in Figure 22.

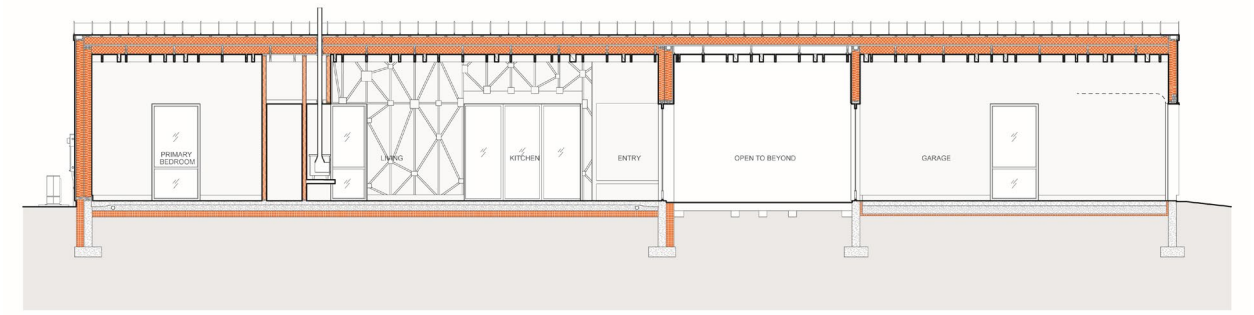


Figure 19. Longitudinal section, truss panel system.

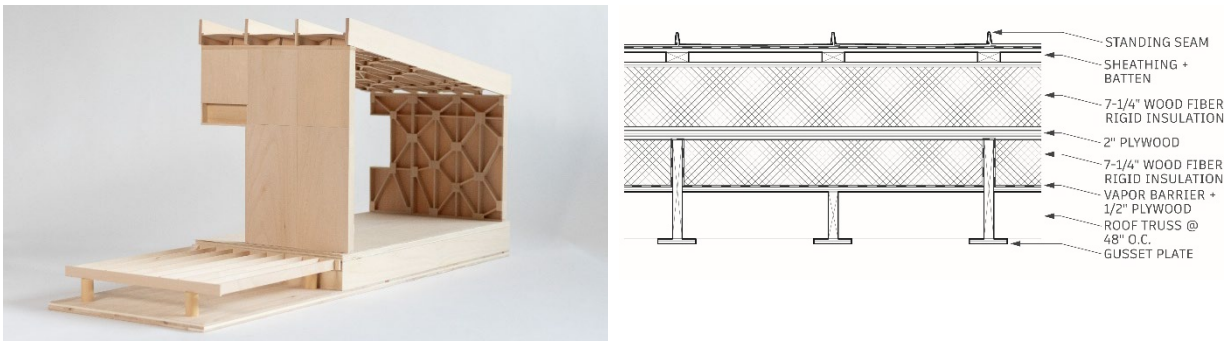


Figure 20. Left: Structural framing model of the truss panel system. Right: Roof detail including truss panels.



Figure 21. Interior rendering showing the truss panel system.

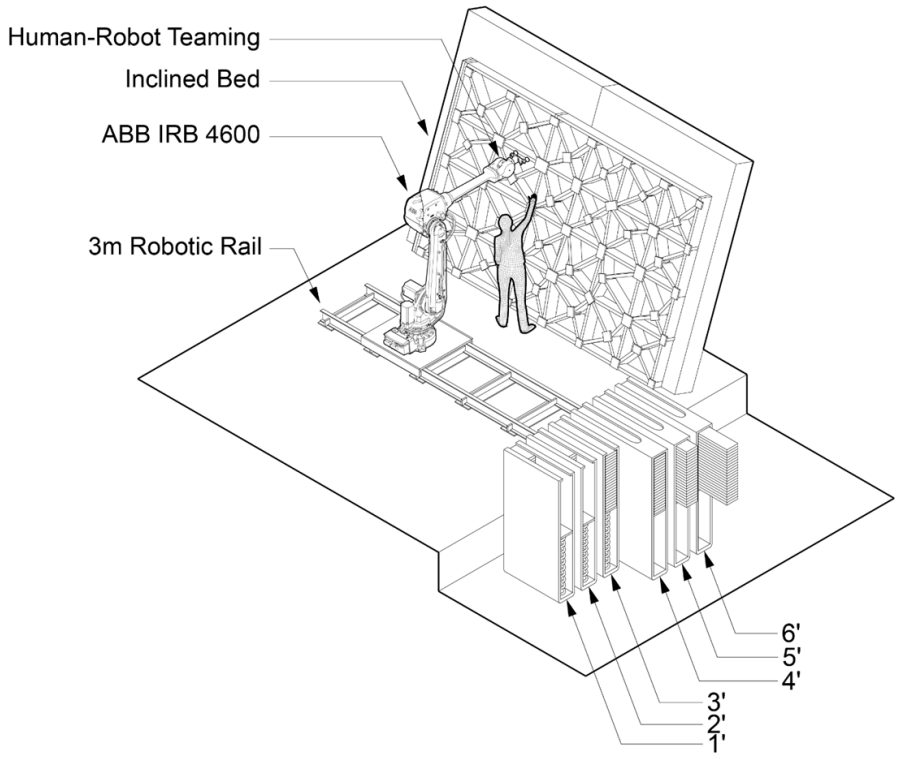


Figure 22. A proposal for the robotic assembly of truss panels. Robotics, an inclined vacuum work surface, and a binned inventory system can enable the production of truss panels with unique geometries.

12.1.3 Messy mass timber (MMT) panel system

This structural framing concept proposes using waste lumber offcuts in nail-laminated timber (NLT) panels, as shown in Figures 23-25. To construct these panels, nails are used to connect a series of adjacent lumber laminations, allowing load sharing across wood layers. A similar approach developed for the use of lumber offcuts in dowel-laminated timber (DLT) panels is illustrated in Figure 26. The performance of such panels is highly sensitive to the location of board ends. However, using a computational design approach, the structural performance of panel designs can be evaluated and optimized. Integrated inventory matching and Finite Element Analysis can be used to allocate material according to structural demand. While both NLT and DLT are mass timber products, NLT is proposed for this housing strategy given its relative ease of assembly. NLT panels can be fabricated using simple tools such as a nail gun. Alternatively, a proposal for the robotic assembly of these panels is illustrated in Figure 27. While mass timber is not typically used for single-story houses, it can be an effective strategy to use non-standard building materials, as in the case of Timber Age described in section 3.4.

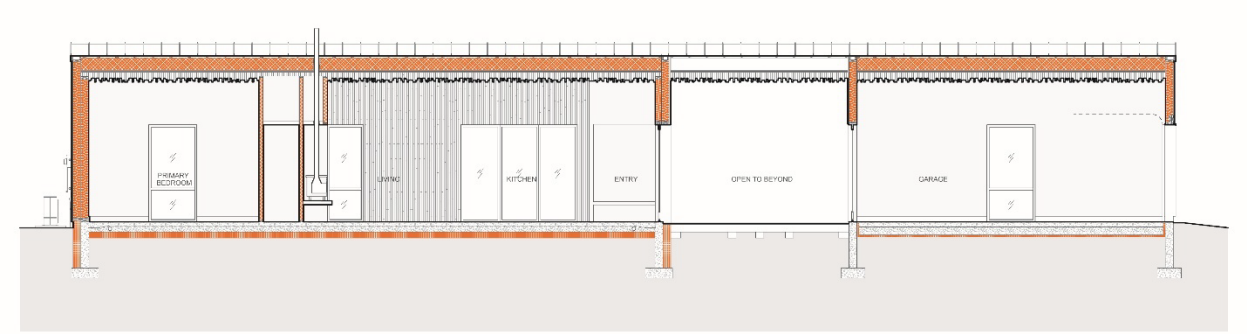


Figure 24. Longitudinal section, messy mass timber (MMT) panel system.

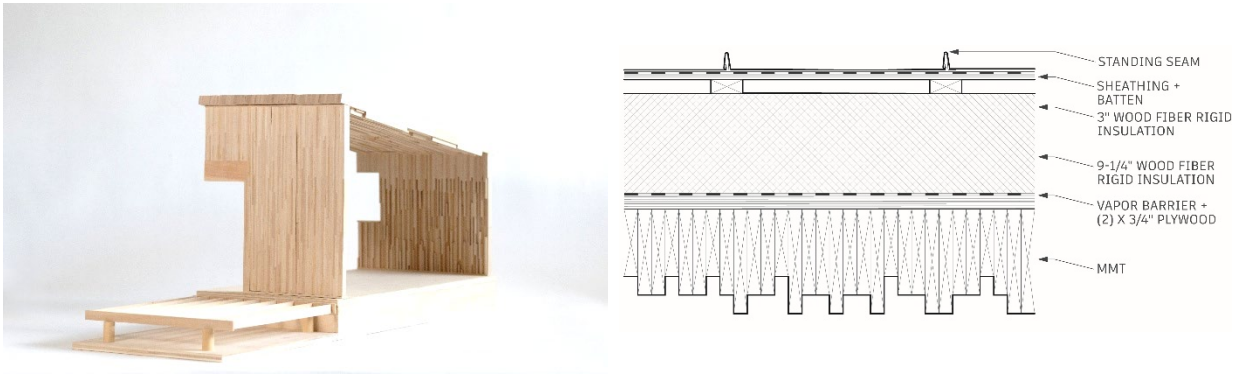


Figure 23. Left: Structural framing model of the messy mass timber (MMT) panel system. Right: Roof detail including MMT panels.



Figure 25. Interior rendering showing the messy mass timber (MMT) panel system.

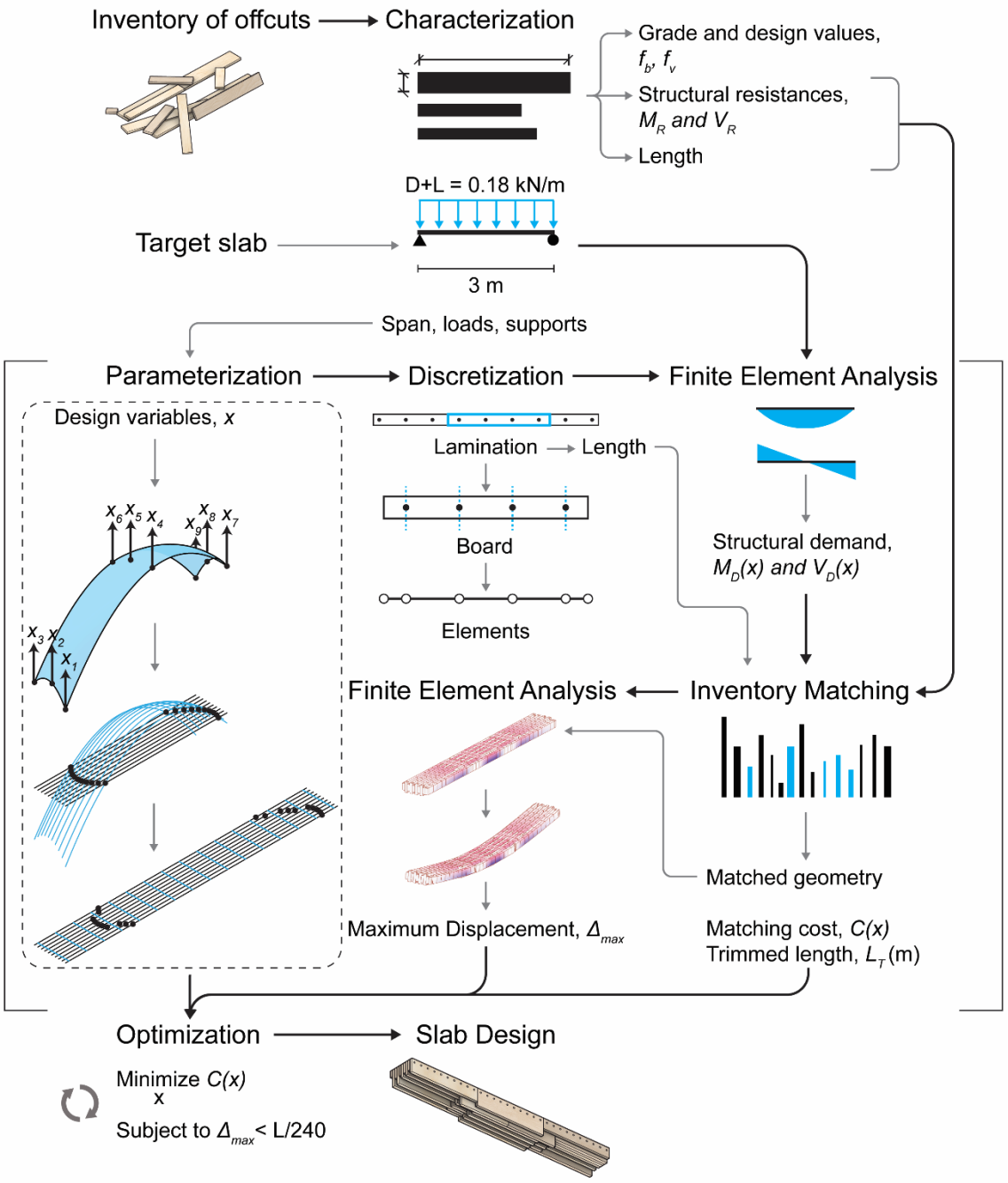


Figure 26. Computational design methodology for dowel-laminated timber structural floor panels using waste lumber offcuts. Reproduced from Blowes, Rachel, M. (2025). *Dowel-laminated timber from waste lumber offcuts: Towards structural component circularity* (Master's thesis, Massachusetts Institute of Technology) and *A digital circularity approach to leverage waste lumber in dowel-laminated timber slabs* (Blowes et al., 2025).

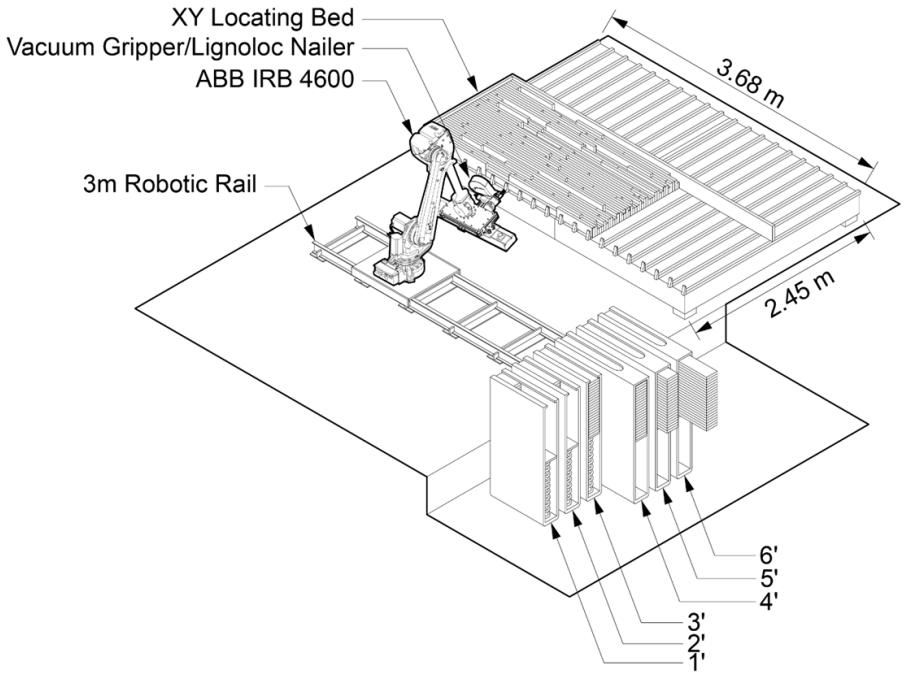


Figure 27. A proposal for the robotic assembly of nail-laminated timber panels. In addition to an automated bed and magazine system, multi-functional end-effectors can be implemented to maneuver material and nail boards together.

12.2 Forest-made cabin

This design case study is developed in response to discussions with a small sawmill and builder, Timberdoodle Farm and Sawmill (*Timberdoodle Farm & Sawmill*, n.d.). The sawmill owners prioritize selective harvesting of forests to support their resilience. In some cases, using this approach, they extract roundwood from the forest that is not commercially viable. Often, this harvested wood includes logs approximately 8 feet long, as shown in Figure 21. At this length, it is challenging for sawmill owners to produce standard-length dimensional lumber.

For this case study, a truss system is proposed for the structural framing of a cabin, composed of an inventory of wood elements with lengths less than or equal to 8 ft. This strategy is selected since trusses can benefit from variation in both element lengths and cross-sectional dimensions. Three logs were selected from the inventory shown in Figure 28, including two species: Red Pine and White Pine. 3D scanning was used to capture the geometry of these logs. Two selected logs were sawn using a Wood-Mizer mill, as shown in Figure 29. The geometry of the sawn boards was captured again using 3D scanning after milling. Combining an unconventional sawing strategy with edging allows boards with a single live edge and flat edges to be produced, creating both interesting architectural effects and variation in depth, which can be useful from a

structural perspective. Furthermore, leaving one edge of lumber boards unprocessed maintains fiber continuity, which can be beneficial for strength (Bukauskas et al., 2019).

Cabins built with Timberdoodle products are typically framed using heavy timber construction. This construction method uses wood elements with large cross-sectional dimensions and wooden connections. Timber frames are typically constructed green, using wood that has not been kiln-dried. For this case study, rough-sawn lumber was used instead of a heavier traditional timber frame. In practice, lumber is often kiln-dried to prevent warping and splitting that can occur when it is dried in place. In this case, green wood was used to fabricate a prototype doweled connection, shown in Figure 29. Elements are lapped to produce a simple connection that can join five truss elements. Further research is required to understand the long-term dimensional stability of elements composed in this matter, including the effects of using components with a single live edge.

An asymmetrical truss design is shown in Figure 30, featuring elements with differing structural demands. A structural finite element model is developed of this truss to assess the structural demands of each truss element. Using the 3D log scans, the irregular sawn lumber geometry is assembled to form a truss, allocating elements of greater depth in areas of higher structural demand. This approach demonstrates the potential to develop adaptable designs that accommodate wood elements of varying dimensions and species.



Figure 28. Typical harvested 8-foot logs that are not economically viable for the production of dimensional lumber.



Figure 29. Left: Reassembled sawn log. Right: Doweled and lapped truss connection.



Figure 30. Proposal for a truss system composed of minimally-processed wood elements of short lengths.

13. Potential models for improved utilization of timber in housing

In this section, timber production models are discussed that could improve the efficiency of existing value chains in terms of material consumption. Each of these models aims to increase feedback between forest resource management and design processes to meet housing needs. Through these models, plans for harvesting based on forest health can be communicated to designers, so that building designs can be adapted to the available inventory of materials. Conversely, designers can communicate the material requirements for housing to foresters so that only the required materials are harvested. Improving efficiency in timber value chains may involve rethinking current production models to better use wood resources in alignment with forest management needs, and to provide housing that meaningfully addresses affordability while minimizing

environmental impact. Furthermore, this shift should be considered with its potential to create impactful, engaging, and safe work with competitive compensation.

13.1 Model I – Vertically integrated value chain

The first model to increase material efficiency in timber value chains involves vertical integration. Through this approach, a single or limited number of entities manage wood resources —from the forest to building design. By integrating the value chain to include building design, the material demands of specific projects can drive the harvesting or processing of wood resources. This model appears to work well when a single or limited set of wood species is used, as in the example of Nordic Structures described in section 11.1. Working with a single wood species reduces the variation in dimensions and material properties that must be managed during manufacturing, allowing for a streamlined supply-specific production process. However, many forests across the U.S. are multi-species, requiring adaptable manufacturing processes to accommodate natural variability. Timberland ownership may also affect the feasibility of vertically integrated value chains. In the case of Nordic Structures, logging is often carried out on public land, which may have lower stumpage costs than privately-owned land (Brandeis et al., 2021). The full vertical integration of timber value chains in the U.S. would require a major shift away from standard ownership models, in which forests, sawmills, and secondary wood manufacturers are largely distinct, privately owned entities. This model may be feasible in the western states of the U.S., where much of the forest land is publicly-owned (Perry et al., 2022).

13.2 Model II.A – Digitally-linked dedicated industries

Given the potential challenge of vertically integrating timber value chains in the U.S., a second model is considered that maintains the current ownership trend of dedicated timber-based industries. This model entails the large-scale operation of dedicated industries, each producing standardized components, gaining efficiency through economies of scale. Each of these industries can be linked through data. A digital thread is proposed to allow communication between all branches of timber value chains. Through data sharing and increased use of adaptable digital technologies such as robotics, these industries may be able to leverage a broader range of wood resources with varied geometry and material properties.

13.3 Model II.B – Decentralized regionally-responsive forest design partnerships

Another model that is compatible with Model II.A involves distributed regionally-responsive operations. Through this model, hyper-local construction is produced from available materials at a smaller scale. Examples of this model in practice include the manufacturers Timberdoodle Farm and Sawmill, WholeTrees Structures, and Timber Age, described in earlier sections (Timber Age, n.d.; *Timberdoodle Farm & Sawmill*, n.d.; *WholeTrees Structures*, n.d.). These manufacturers make use of locally available

wood resources, allowing the properties of those materials to drive the design of the buildings and components in which they are used. As illustrated in section 12, computational design tools can enable the use of these non-standard wood resources.

14. Conclusion and recommendations

Augmenting the role of manufacturing in housing production could provide a cost-effective strategy to meet U.S. housing needs (Kaul & Pang, 2022). Prefabrication and the use of automated technologies and robotics show potential to increase construction productivity (McKinsey Global Institute, 2017). These manufacturing approaches have applications for multiple construction methods, including both light wood framing and mass timber. Furthermore, advanced manufacturing can be used to produce a range of housing typologies, including single-family and multi-family homes, as well as denser housing types such as residential towers.

The production of homes in the U.S. relies upon wood products sourced from forests through timber value chains that connect wood manufacturing outputs. These value chains play an important economic role through the creation of employment opportunities across the country (Perry et al., 2022). However, their current operations lead to inefficiencies in the use of wood resources. Examples of timber value chains from abroad indicate the potential for efficiency gains from the vertical integration of timber-based industries. As vertical integration may be difficult to undertake domestically, two distinct but compatible models, II.A and II.B, are proposed to enhance communication across timber value chains. Through these models, increased use of digital technologies and data sharing show potential to expand the range of wood resources used in the production of housing. To ensure the sustained production of wood resources for use in buildings, forest management must prioritize resilience (Messier et al., 2022). This management approach requires designers to shift their practices to use untapped forest resources, including wood that must be removed from forests to ensure forest health.

Design tools and technologies are available that could facilitate the use of a broader range of wood resources. These tools can enable design and manufacturing with underutilized forest resources, as well as with another category of non-standard wood resources generated by timber value chains: wood waste. Incorporating wood waste into value-added manufacturing processes could have positive embodied-carbon impacts. Providing designers with early data on forest health and waste inventories can influence design approaches. To fully leverage the capabilities of design technologies, broad collaboration is needed across timber value chains. Data communication could provide a digital thread to connect currently fragmented wood-based industries, enhancing material efficiency and productivity.

Further research is needed to fully evaluate potential synergies between forest management, advanced wood manufacturing, and housing production. Interdisciplinary studies that bring together forest ecologists, foresters, planners, manufacturers, and architects are required to identify key wood resources for use in construction to promote forest resilience. Funding and industry-research partnerships are required to further explore and implement a digital thread across timber value chains. Furthermore, capital investment in full-scale prototypes is required to evaluate the feasibility of using underutilized resources efficiently in housing. These prototypes can be used to assess and quantify potential efficiency gains from applying novel computational approaches and digital fabrication strategies in housing production. A broad systemic model and material flow analysis of the link between wood products and housing are needed to understand better how shifts in building design practices affect wood product consumption and forest resource demands. Furthermore, an evaluation of the availability of untapped resources, both in forests and in wood product stock models, would be beneficial. Through this research, opportunities can be identified to use technology to strengthen links within timber value chains and foster resource-efficient, cost-effective housing production.

References

Accoya Acetylated Wood | High performance, long life modified wood. (2025). Accoya. https://www.accoya.com/

Adhikari, S., Bond, B., Quesada, H., & Smith, R. (2024). *Lumber Supply-Chain Practice in Cross-Laminated Timber Industries in the United States: A Comparison with Austrian Producers*. https://doi.org/10.13073/FPJ-D-23-00018

Aggestam, F., Konczal, A., Sotirov, M., Wallin, I., Paillet, Y., Spinelli, R., Lindner, M., Derks, J., Hanewinkel, M., & Winkel, G. (2020). Can nature conservation and wood production be reconciled in managed forests? A review of driving factors for integrated forest management in Europe. *Journal of Environmental Management*, *268*, 110670. https://doi.org/10.1016/j.jenvman.2020.110670

Ahmed, S., & Arocho, I. (2020). Mass timber building material in the US construction industry: Determining the existing awareness level, construction-related challenges, and recommendations to increase its current acceptance level. *Cleaner Engineering and Technology*, *1*, 100007.

Allison, R. S., Johnston, J. M., Craig, G., & Jennings, S. (2016). Airborne Optical and Thermal Remote Sensing for Wildfire Detection and Monitoring. *Sensors*, *16*(8), 1310. https://doi.org/10.3390/s16081310

American Wood Council, & Canadian Wood Council. (2020). *Environmental Product Declaration: North American Softwood Lumber*.

Amtsberg, F., Huang, Y., Marshall, D. J. M., Gata, K. M., & Mueller, C. (2020). Structural upcycling: Matching digital and natural geometry. *Proceedings of Advances in Architectural Geometry*.

Andersen, P., Kelley, J., & Preissner, P. (2023). *American framing: The same something for everyone*. Park Books.

AORO: The world's first autonomous forest machine | Forsler.com. (n.d.). Retrieved October 30, 2025, from https://www.forsler.com/post/aoro-the-worlds-first-autonomous-forest-machine

Arbelaez, R., Schimleck, L., & Sinha, A. (2020). Salvaged lumber for Structural Mass Timber Panels: Manufacturing and Testing. *Wood and Fiber Science*, *52*(2), Article 2.

Arehart, J. H., Pomponi, F., D'Amico, B., & Srubar III, W. V. (2022). Structural material demand and associated embodied carbon emissions of the United States building stock: 2020–2100. *Resources, Conservation and Recycling*, *186*, 106583.

Bais-Moleman, A. L., Sikkema, R., Vis, M., Reumerman, P., Theurl, M. C., & Erb, K.-H. (2018). Assessing wood use efficiency and greenhouse gas emissions of wood product cascading in the European Union. *Journal of Cleaner Production*, *172*, 3942–3954. https://doi.org/10.1016/j.jclepro.2017.04.153

Bartowitz, K. J., Walsh, E. S., Stenzel, J. E., Kolden, C. A., & Hudiburg, T. W. (2022). Forest Carbon Emission Sources Are Not Equal: Putting Fire, Harvest, and Fossil Fuel Emissions in Context. *Frontiers in Forests and Global Change*, *5*. https://doi.org/10.3389/ffgc.2022.867112

Bergsagel, D., & Heisel, F. (2023). Structural design using reclaimed wood – A case study and proposed design procedure. *Journal of Cleaner Production*, *420*, 138316. https://doi.org/10.1016/j.jclepro.2023.138316

Bergsagel, D., Heisel, F., Owen, J., & Rodencal, M. (2025). Engineered wood products for circular construction: A multi-factor evaluation of lamination methods. *Npj Materials Sustainability*, *3*(1), 24. https://doi.org/10.1038/s44296-025-00067-7

Bertram, N., Fuchs, S., Mischke, J., Palter, R., Strube, G., & Woetzel, J. (2019). Modular construction: From projects to products. *McKinsey & Company: Capital Projects & Infrastructure*, *1*(1), 1–34.

Betts, M. G., Phalan, B. T., Wolf, C., Baker, S. C., Messier, C., Puettmann, K. J., Green, R., Harris, S. H., Edwards, D. P., Lindenmayer, D. B., & others. (2021). Producing wood at least cost to biodiversity: Integrating T riad and sharing–sparing approaches to inform forest landscape management. *Biological Reviews*, *96*(4), 1301–1317.

Blowes, R., Lee, K., Mayencourt, P., Kennedy, S., & Mueller, C. (2025). A digital circularity approach to leverage waste lumber in dowel-laminated timber slabs. In *Structures and Architecture* (pp. 59–66). CRC Press.

Bousfield, C. G., Lindenmayer, D. B., & Edwards, D. P. (2023). Substantial and increasing global losses of timber-producing forest due to wildfires. *Nature Geoscience*, *16*(12), 1145–1150.

Bousfield, C. G., Morton, O., Lindenmayer, D. B., Pellegrini, A. F., Hethcoat, M. G., & Edwards, D. P. (2025). Global risk of wildfire across timber production systems. *Nature Communications*, *16*(1), 4204.

Brandeis, C., Taylor, M., Abt, K. L., Alderman, D., & Buehlmann, U. (2021). *Status and Trends for the U.S. Forest Products Sector: A Technical Document Supporting the Forest Service 2020 RPA Assessment*. U.S. Department of Agriculture, Forest Service, Southern Research Station. https://doi.org/10.2737/srs-gtr-258

Brodie, E. G., Knapp, E. E., Brooks, W. R., Drury, S. A., & Ritchie, M. W. (2024). Forest thinning and prescribed burning treatments reduce wildfire severity and buffer the impacts of severe fire weather. *Fire Ecology*, *20*(1), 17. https://doi.org/10.1186/s42408-023-00241-z

Brown, N. (2023). *Mass Timber Joinery Design for Digital Fabrication and De-constructability*. University of Washington.

Brütting, J., Senatore, G., & Fivet, C. (2019). Form Follows Availability – Designing Structures Through Reuse. *Journal of the International Association for Shell and Spatial Structures*, *60*(4), 257–265. https://doi.org/10.20898/j.iass.2019.202.033

Bukauskas, A., Mayencourt, P., Shepherd, P., Sharma, B., Mueller, C., Walker, P., & Bregulla, J. (2019). Whole timber construction: A state of the art review. *Construction and Building Materials*, *213*, 748–769. https://doi.org/10.1016/j.conbuildmat.2019.03.043

Campbell, S. (2025, January 22). This northern Quebec business pulls out all the stops to recruit and retain foreign workers. *CBC News*. https://www.cbc.ca/news/canada/montreal/chantiers-chibougamau-foreign-workers-1.7437470

Chainparency. (n.d.). *Chainparency—High Fidelity Data for Transparent & Accountable Supply Chains*. Chainparency - High Fidelity Data for Transparent & Accountable Supply Chains. Retrieved November 1, 2025, from https://chainparency.com/

Chang, H., Han, H.-S., Anderson, N., Kim, Y.-S., & Han, S.-K. (2023). The Cost of Forest Thinning Operations in the Western United States: A Systematic Literature Review and New Thinning Cost Model. *Journal of Forestry*, *121*(2), 193–206. https://doi.org/10.1093/jofore/fvac037

Chen, C., Kuang, Y., Zhu, S., Burgert, I., Keplinger, T., Gong, A., Li, T., Berglund, L., Eichhorn, S. J., & Hu, L. (2020). Structure–property–function relationships of natural and engineered wood. *Nature Reviews Materials*, *5*(9), 642–666. https://doi.org/10.1038/s41578-020-0195-z

Chuvieco, E., Aguado, I., Salas, J., García, M., Yebra, M., & Oliva, P. (2020). Satellite Remote Sensing Contributions to Wildland Fire Science and Management. *Current Forestry Reports*, *6*(2), 81–96. https://doi.org/10.1007/s40725-020-00116-5

Claus, T., Ehrhardt, K., Michalski, A., Lienhard, J., Stute, P., & Burger, S. (2024). A Paradigm in Digital Detail Design for a Complex Timber Framework. *Proceedings of the IASS 2024 Symposium: Redefining the Art of Structural Design*. IASS 2024.

Code Path and Requirements for Podium Projects. (2025). *WoodWorks | Wood Products Council*. https://www.woodworks.org/resources/code-path-and-requirements-for-podium-projects/

Construction Labor Productivity: U.S. Bureau of Labor Statistics. (2025, September 24). Bureau of Labor Statistics. https://www.bls.gov/productivity/highlights/construction-labor-productivity.htm

Cousin, T., Alkhayat, L., Pearl, N., Dewart, C. B., & Mueller, C. (2023). Wild Wood Gridshells: Mixed-Reality Construction of Nonstandard Wood. *Technology|Architecture + Design*, *7*(2), 216–231. https://doi.org/10.1080/24751448.2023.2245725

Cousin, T., Marshall, D., Pearl, N., Alkhayat, L., & Mueller, C. (2023). Integrating irregular inventories: Accessible technologies to design and build with

nonstandard materials in architecture. *Journal of Physics: Conference Series*, *2600*(19), 192004. https://doi.org/10.1088/1742-6596/2600/19/192004

Ding, Y., Zang, R., Lu, X., & Huang, J. (2017). The impacts of selective logging and clear-cutting on woody plant diversity after 40 years of natural recovery in a tropical montane rain forest, south China. *Science of The Total Environment*, *579*, 1683–1691. https://doi.org/10.1016/j.scitotenv.2016.11.185

Dogru, A. K., Elmadag, A. B., Gong, K., Travers, J. M., & Meng, C. (2024). Examination of upstream supply chain and logistics issues in the US logging industry. *Transportation Journal*, *63*(2), 74–97. https://doi.org/10.1002/tjo3.12009

Element5. (2021, February 25). *Element5 CLT and Glulam Mass Timber Manufacturers*. https://elementfive.co/

Elliott, K. J., Miniat, C. F., & Medenblik, A. S. (2020). The long-term case for partial-cutting over clear-cutting in the southern Appalachians USA. *New Forests*, *51*(2), 273–295. https://doi.org/10.1007/s11056-019-09731-y

ERNE AG Holzbau. (2025). *Construction modulaire en bois*. https://www.erne.net/fr/prestations/systemes/construction-modulaire-en-bois/

Executive Office of Housing and Livable Communities. (2025, February). *A Home for Everyone: Statewide Housing Needs Assessment*. Commonwealth of Massachusetts.

Falk, R. H., Cramer, S., & Evans, J. (2013). Framing Lumber from Building Removal: How do We Best Utilize This Untapped Structural Resource? *Forest Products Journal*, *62*, 429–499. https://doi.org/10.13073/0015-7473-62.7.492

Fang, D., Moradei, J., Brütting, J., Fischer, A., Landez, D. K., Shao, B., Sherrow-Groves, N., Fivet, C., & Mueller, C. (2019). Modern timber design approaches for traditional Japanese architecture: Analytical, experimental, and numerical approaches for the Nuki joint. *Proceedings of IASS Annual Symposia*, *2019*(20), 1–8.

FAO. (2023a). *Forestry Production and Trade* [Dataset]. https://www.fao.org/faostat/en/#data/FO

FAO. (2023b). *Global forest products facts and figures 2023* (p. 36). https://doi.org/10.4060/cd3650en

FAO. (2025). *Global Forest Resources Assessment 2025* (p. 210). FAO. https://doi.org/10.4060/cd6709en

Fast, P., Gafner, B., Jackson, R., & Li, J. (2016). Case study: An 18 storey tall mass timber hybrid student residence at the University of British Columbia, Vancouver. *Proceedings of the World Conference on Timber Engineering (WCTE2016), Vienna, Austria*, 22–25.

Feickert, K., & Mueller, C. T. (2025). Policy and design levers for minimizing embodied carbon in United States buildings: A quantitative comparison of current and

proposed strategies. *Building and Environment*, *270*, 112485. https://doi.org/10.1016/j.buildenv.2024.112485

Fitzgerald, M. (2016). Will the Internet of Trees Be the Next Game Changer? *MIT Sloan Management Review*, *57*(3).

Forest Inventory and Analysis | US Forest Service Research and Development. (2023, January 13). [Text]. https://research.fs.usda.gov/programs/fia

Forest Products | US Forest Service Research and Development. (2025, August 1). [Text]. U.S. Department of Agriculture Forest Service. https://research.fs.usda.gov/forestproducts

Forghani, K., Carlsson, M., Flener, P., Fredriksson, M., Pearson, J., & Yuan, D. (2024). Maximizing value yield in wood industry through flexible sawing and product grading based on wane and log shape. *Computers and Electronics in Agriculture*, *216*, 108513. https://doi.org/10.1016/j.compag.2023.108513

Freres Engineered Wood | Mass Ply—Timber Manufacturers. (n.d.). Retrieved November 1, 2025, from https://frereswood.com/

Fu, S., & Holland, N. (2024). *Can Factory-Built Housing Contribute to Greater Affordability and Climate Resiliency?: A Housing Innovation Program Case Study*. Urban Institute.

Gaia AI | Smarter Forest Management with AI-Powered Data & Insights. (2025). https://www.gaia-ai.eco/

Garcia, C. A., & Hora, G. (2017). State-of-the-art of waste wood supply chain in Germany and selected European countries. *Waste Management*, *70*, 189–197.

Getting the Most from Every Panel—Element5. (2021, December 21). https://elementfive.co/getting-the-most-from-every-panel/

Giordano, L., Derikvand, M., & Fink, G. (2023). Bending Properties and Vibration Characteristics of Dowel-Laminated Timber Panels Made with Short Salvaged Timber Elements. *Buildings*, *13*(1), Article 1. https://doi.org/10.3390/buildings13010199

GO LOGIC. (2025). GO LOGIC. https://www.gologic.us

Greer, F., & Horvath, A. (2023). Modular construction's capacity to reduce embodied carbon emissions in California's housing sector. *Building and Environment*, *240*, 110432. https://doi.org/10.1016/j.buildenv.2023.110432

Haftka, R. T., & Grandhi, R. V. (1986). Structural shape optimization—A survey. *Computer Methods in Applied Mechanics and Engineering*, *57*(1), 91–106.

He, M., Smidt, M., Li, W., & Zhang, Y. (2021). Logging Industry in the United States: Employment and Profitability. *Forests*, *12*(12), 1720. https://doi.org/10.3390/f12121720

Herbert, C., Reed, C., & Shen, J. (2023). *Comparison of the Costs of Manufactured and Site-Built Housing*. Harvard University, Joint Center for Housing Studies.

Hernandez, R., Green, D. W., Kretschmann, D. E., & Verrill, S. P. (2005). Improved utilization of small-diameter ponderosa pine in glulam timber. *Res. Pap. FPL-RP-625. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 38 p.*, *625*. https://doi.org/10.2737/FPL-RP-625

Hernandez, R. J., Miranda, C., & Goñi, J. (2020). Empowering Sustainable Consumption by Giving Back to Consumers the 'Right to Repair.' *Sustainability*, *12*(3), 850. https://doi.org/10.3390/su12030850

Höglmeier, K., Weber-Blaschke, G., & Richter, K. (2014). Utilization of recovered wood in cascades versus utilization of primary wood—A comparison with life cycle assessment using system expansion. *The International Journal of Life Cycle Assessment*, *19*(10), 1755–1766. https://doi.org/10.1007/s11367-014-0774-6

Höglmeier, K., Weber-Blaschke, G., & Richter, K. (2015). Evaluation of Wood Cascading. In *Sustainability Assessment of Renewables-Based Products* (pp. 335–346). John Wiley & Sons, Ltd. https://doi.org/10.1002/9781118933916.ch22

Holmström, E., Nikander, J., Backman, J., Väätäinen, K., Uusitalo, J., & Jylhä, P. (2023). A multi-objective optimization strategy for timber forwarding in cut-to-length harvesting operations. *International Journal of Forest Engineering*, *34*(2), 267–283. https://doi.org/10.1080/14942119.2022.2149003

Home | Forest Stewardship Council. (2022, August 17). https://fsc.org/en

Hu, M. (2022). Embodied Carbon Emissions of the Residential Building Stock in the United States and the Effectiveness of Mitigation Strategies. *Climate*, *10*(10), 135. https://doi.org/10.3390/cli10100135

Huang, Y., Alkhayat, L., De Wolf, C., & Mueller, C. (2021). Algorithmic circular design with reused structural elements: Method and Tool. *Proceedings of the International Fib Symposium on the Conceptual Design of Structures*, *55*, 457–468. https://doi.org/10.35789/fib.PROC.0055.2021.CDSymp.P056

International Code Council. (2024). *International Building Code*.

InventWood—Technology. (n.d.). Retrieved March 1, 2026, from https://www.inventwood.com/technology

Jarre, M., Petit-Boix, A., Priefer, C., Meyer, R., & Leipold, S. (2020). Transforming the bio-based sector towards a circular economy-What can we learn from wood cascading? *Forest Policy and Economics*, *110*, 101872.

Jelavic, E., Kapgen, T., Kerscher, S., Jud, D., & Hutter, M. (2022). Harveri: A small (Semi-) Autonomous precision tree harvester. *Innovation in Forestry Robotics: Research and Industry Adoption, ICRA 2022 IFRRIA Workshop*.

JoeScan Sawmill Optimization: 3D Scanners For Sawmills. (n.d.). JoeScan. Retrieved October 30, 2025, from https://joescan.com/

Joint Center for Housing Studies of Harvard University. (2025). *The State of the Nation's Housing 2025*. https://www.jchs.harvard.edu/state-nations-housing-2025

Joshi, C., Leeuw, J. D., Skidmore, A. K., Duren, I. C. van, & van Oosten, H. (2006). Remotely sensed estimation of forest canopy density: A comparison of the performance of four methods. *International Journal of Applied Earth Observation and Geoinformation, Perspectives on Modelling and Managing Geospatial Data*, *8*(2), 84–95. https://doi.org/10.1016/j.jag.2005.08.004

Jungclaus, M. A., Grant, N., Torres, M. I., Arehart, J. H., & Srubar III, W. V. (2024). Embodied carbon benchmarks of single-family residential buildings in the United States. *Sustainable Cities and Society*, *117*, 105975.

Kaul, K., & Pang, D. (2022). *The Role of Manufactured Housing in Increasing the Supply of Affordable Housing*. Urban Institute. https://www.urban.org/research/publication/role-manufactured-housing-increasing-supply-affordable-housing

Kedir, F., & Hall, D. M. (2021). Resource efficiency in industrialized housing construction – A systematic review of current performance and future opportunities. *Journal of Cleaner Production*, *286*, 125443. https://doi.org/10.1016/j.jclepro.2020.125443

Kelly, B. (with Albert Farwell Bemis Foundation). (1951). *The prefabrication of houses: A study by the Albert Farwell Bemis Foundation of the prefabrication industry in the United States*. Andesite Press.

La Hera, P., Mendoza-Trejo, O., Lindroos, O., Lideskog, H., Lindbäck, T., Latif, S., Li, S., & Karlberg, M. (2024). Exploring the feasibility of autonomous forestry operations: Results from the first experimental unmanned machine. *Journal of Field Robotics*, *41*(4), 942–965. https://doi.org/10.1002/rob.22300

Lamsal, B., Poudel, J., & Pokharel, R. (2025). Regional economic and employment impacts of industrial decline in the forest sector: Evidence from sawmill closures in Michigan. *Forest Policy and Economics*, *178*, 103601.

Larsen, N. M., Aagaard, A. K., Hudert, M., & Rahbek, L. W. (2022). Timber structures made of naturally curved oak wood: Prototypes and processes. *Architecture, Structures and Construction*, *2*(4), 493–507. https://doi.org/10.1007/s44150-022-00046-9

Lee, K. J. (2024). *DigitalCircularityToolkit* (Version v0.2) [Computer software]. Zenodo. https://doi.org/10.5281/zenodo.10724610

Lesiv, M., Schepaschenko, D., Buchhorn, M., See, L., Dürauer, M., Georgieva, I., Jung, M., Hofhansl, F., Schulze, K., Bilous, A., Blyshchyk, V., Mukhortova, L., Brenes, C. L. M., Krivobokov, L., Ntie, S., Tsogt, K., Pietsch, S. A., Tikhonova, E., Kim, M., … Fritz, S. (2022). Global forest management data for 2015 at a 100 m resolution. *Scientific Data*, *9*(1), 199. https://doi.org/10.1038/s41597-022-01332-3

LeVan-Green, S. L., & Livingston, J. (2001). Exploring the uses for small-diameter trees. *Forest Products Journal. Vol. 51, No. 9 (Sept. 2001).:P. 10-21 : Ill.* https://research.fs.usda.gov/treesearch/5832

Levine, J. I., Collins, B. M., Coppoletta, M., & Stephens, S. L. (2025). Extreme Weather Magnifies the Effects of Forest Structure on Wildfire, Driving Increased Severity in Industrial Forests. *Global Change Biology*, *31*(8), e70400. https://doi.org/10.1111/gcb.70400

Livingston, J. (2008). Small-diameter success stories III. *General Technical Report FPL-GTR-175. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 31 Pages.*, *175*. https://doi.org/10.2737/FPL-GTR-175

Löf, M., Madsen, P., Metslaid, M., Witzell, J., & Jacobs, D. F. (2019). Restoring forests: Regeneration and ecosystem function for the future. *New Forests*, *50*(2), 139–151. https://doi.org/10.1007/s11056-019-09713-0

Lok, L., Samaniego, A., & Spencer, L. (2021). Timber de-standardized. *Proceedings of the 41st Annual Association for Computer Aided Design in Architecture Conference*.

Lynch, E. (2025, January 20). *Cost of Constructing a Home—2024*. National Association of Home Builders. https://www.nahb.org/news-and-economics/housing-economics-plus/special-studies/special-studies-pages/cost-of-constructing-a-home-in-2024

Mair, C., & Stern, T. (2017). Cascading Utilization of Wood: A Matter of Circular Economy? *Current Forestry Reports*, *3*(4), 281–295. https://doi.org/10.1007/s40725-017-0067-y

Malladi, M. V., Guadagnino, T., Lobefaro, L., Mattamala, M., Griess, H., Schweier, J., Chebrolu, N., Fallon, M., Behley, J., & Stachniss, C. (2024). Tree instance segmentation and traits estimation for forestry environments exploiting LiDAR data collected by mobile robots. *2024 IEEE International Conference on Robotics and Automation (ICRA)*, 17933–17940.

Matiza, C., Mutanga, O., Peerbhay, K., Odindi, J., & Lottering, R. (2023). A systematic review of remote sensing and machine learning approaches for accurate carbon storage estimation in natural forests. *Southern Forests: A Journal of Forest Science*, *85*(3–4), 123–141. https://doi.org/10.2989/20702620.2023.2251946

Mayencourt, P. (2020). *Mass reduction: Opportunities and structural optimization methods to reduce material use in mass timber buildings* [Thesis, Massachusetts Institute of Technology]. https://dspace.mit.edu/handle/1721.1/129890

Mayencourt, P., Cousin, T., Ganeles, S., & Mueller, C. (2025). Zero-waste fabrication methodology for structurally optimized mass timber beams. *Journal of Cleaner Production*, *490*, 144518. https://doi.org/10.1016/j.jclepro.2024.144518

McGinley, K., Murray, L., Robertson, G., & White, E. M. (2023). National report on sustainable forests, 2020. *FS-1217. Washington, DC: U.S. Department of Agriculture, Forest Service, Washington Office*, *1217*. https://doi.org/10.2737/FS-1217

McKinsey Global Institute. (2017, February). *Reinventing Construction: A Route to Higher Productivity*. https://www.mckinsey.com/~/media/mckinsey/business%20functions/operations/our%20insights/reinventing%20construction%20through%20a%20productivity%20revolution/mgi-reinventing-construction-a-route-to-higher-productivity-full-report.pdf

Messier, C., Bauhus, J., Sousa-Silva, R., Auge, H., Baeten, L., Barsoum, N., Bruelheide, H., Caldwell, B., Cavender-Bares, J., Dhiedt, E., Eisenhauer, N., Ganade, G., Gravel, D., Guillemot, J., Hall, J. S., Hector, A., Hérault, B., Jactel, H., Koricheva, J., … Zemp, D. C. (2022). For the sake of resilience and multifunctionality, let's diversify planted forests! *Conservation Letters*, *15*(1), e12829. https://doi.org/10.1111/conl.12829

Mims, C. (2025, June 28). It's Bulletproof, Fire-Resistant and Stronger Than Steel. It's Superwood. *Wall Street Journal*. https://www.wsj.com/tech/inventwood-superwood-material-engineered-wood-f7f558e9

Müller, F., Jaeger, D., & Hanewinkel, M. (2019). Digitization in wood supply–A review on how Industry 4.0 will change the forest value chain. *Computers and Electronics in Agriculture*, *162*, 206–218.

Myeong, S., Nowak, D. J., & Duggin, M. J. (2006). A temporal analysis of urban forest carbon storage using remote sensing. *Remote Sensing of Environment*, *101*(2), 277–282. https://doi.org/10.1016/j.rse.2005.12.001

Nasir, V., & Cool, J. (2020). A review on wood machining: Characterization, optimization, and monitoring of the sawing process. *Wood Material Science & Engineering*, *15*(1), 1–16.

National Low Income Housing Coalition. (2025). *The Gap: A Shortage of Affordable Homes*. https://nlihc.org/gap

Neal, M., Sawo, M., Balakrishnan, C., & Lal, A. (2024). Can Increasing Housing Supply Advance Racial Equity in Homeownership? *Urban Institute*.

Nepal, P., Johnston, C. M., & Ganguly, I. (2021). Effects on global forests and wood product markets of increased demand for mass timber. *Sustainability*, *13*(24), 13943.

Nocetti, M., & Brunetti, M. (2024). Advancements in Wood Quality Assessment: Standing Tree Visual Evaluation—A Review. *Forests*, *15*(6), 943. https://doi.org/10.3390/f15060943

Nordic Structures. (n.d.). *Nordic Structures | nordic.ca | Engineered Wood*. Retrieved October 15, 2025, from https://www.nordic.ca/en

Peng, L., Searchinger, T. D., Zionts, J., & Waite, R. (2023). The carbon costs of global wood harvests. *Nature*, *620*(7972), 110–115. https://doi.org/10.1038/s41586-023-06187-1

Perry, C. H., Finco, M. V., & eds..Wilson, B. T. (2022). Forest Atlas of the United States. *FS-1172*, *1172*. https://research.fs.usda.gov/treesearch/64468

Popovski, M., Chen, Z., & Gafner, B. (2016). Structural behaviour of point-supported CLT floor systems. *Proc. 14th World Conference on Timber Engineering (WCTE2016), Vienna, Austria*.

Porter Engineering. (n.d.). Porter Engineering. Retrieved October 30, 2025, from https://portereng.com/

Pullen, T. (2022). *Scaling up off-site construction in Southern California: Streamlining production of affordable and supportive housing*. Terner Center for Housing Innovation. https://ternercenter. berkeley. edu/research-and-policy/off-site-construction-southern-california

Ramage, M. H., Burridge, H., Busse-Wicher, M., Fereday, G., Reynolds, T., Shah, D. U., Wu, G., Yu, L., Fleming, P., Densley-Tingley, D., & others. (2017). The wood from the trees: The use of timber in construction. *Renewable and Sustainable Energy Reviews*, *68*, 333–359.

Riley, K. L., Grenfell, I. C., Finney, M. A., & Wiener, J. M. (2021). TreeMap, a tree-level model of conterminous US forests circa 2014 produced by imputation of FIA plot data. *Scientific Data*, *8*(1), 11. https://doi.org/10.1038/s41597-020-00782-x

Rocchini, D., Boyd, D. S., Féret, J.-B., Foody, G. M., He, K. S., Lausch, A., Nagendra, H., Wegmann, M., & Pettorelli, N. (2016). Satellite remote sensing to monitor species diversity: Potential and pitfalls. *Remote Sensing in Ecology and Conservation*, *2*(1), 25–36. https://doi.org/10.1002/rse2.9

Rohe, W. M. (2017). Tackling the Housing Affordability Crisis. *Housing Policy Debate*. (world). https://www.tandfonline.com/doi/abs/10.1080/10511482.2017.1298214

Ross, R. (2021). Wood handbook: Wood as an engineering material. *FPL-GTR-282*, *282*, 1–543.

Ross, R. J. (2015). *Nondestructive Evaluation of Wood: Second Edition*. U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. https://doi.org/10.2737/fpl-gtr-238

Scouse, A., Kelley, S. S., Liang, S., & Bergman, R. (2020). Regional and net economic impacts of high-rise mass timber construction in Oregon. *Sustainable Cities and Society*, *61*, 102154. https://doi.org/10.1016/j.scs.2020.102154

Service, T. W., USDA Forest. (2024, February 1). *BIGMAP*. ArcGIS StoryMaps. https://storymaps.arcgis.com/stories/c710684b98f54452804e8960d37905b2

Silva, J. R., Artaxo, P., & Vital, E. (2023). Forest Digital Twin: A Digital Transformation Approach for Monitoring Greenhouse Gas Emissions. *Polytechnica*, *6*(1), 2. https://doi.org/10.1007/s41050-023-00041-z

Skog, K. E., & Barbour, R. J. (2006). Estimating woody biomass supply from thinning treatments to reduce fire hazard in the US West. *In: Andrews, Patricia L.; Butler, Bret W., Comps. 2006. Fuels Management-How to Measure Success:*

Conference Proceedings. 28-30 March 2006; Portland, OR. Proceedings RMRS-P-41. Fort Collins, CO: US Department of Agriculture, Forest Service, Rocky Mountain Research Station. p. 657-672, *41*.

Smith, L. W., & Wood, L. W. (1964). *History of yard lumber size standards*. USDA, Forest Service, Forest Products Laboratory.

Stacy, C., Davis, C., Freemark, Y. S., Lo, L., MacDonald, G., Zheng, V., & Pendall, R. (2023). Land-use reforms and housing costs: Does allowing for increased density lead to greater affordability? *Urban Studies*. (Sage UK: London, England). https://doi.org/10.1177/00420980231159500

Stephen, C. P., Brown, N. C., Mayencourt, P. L., & Mueller, C. T. (2018). Clustering analysis of structural loading for post-disaster housing design. *Proceedings of IASS Annual Symposia*, *2018*(2), 1–8.

Sterman, J., Moomaw, W., Rooney-Varga, J. N., & Siegel, L. (2022). Does wood bioenergy help or harm the climate? *Bulletin of the Atomic Scientists*, *78*(3), 128–138.

Structural Engineers. Master Builders. (2025). StructureCraft. https://structurecraft.com

Svilans, T., Tamke, M., Thomsen, M. R., Runberger, J., Strehlke, K., & Antemann, M. (2019). New workflows for digital timber. In *Digital wood design: Innovative techniques of representation in architectural design* (pp. 93–134). Springer.

The Forest Multiple: Composing and digitalizing wooded worlds—Jennifer Gabrys, Michelle Westerlaken, Kate Lewis Hood, Yuti Fatimah, Trishant Simlai, 2025. (n.d.). Retrieved August 8, 2025, from https://journals.sagepub.com/doi/full/10.1177/26349825251323100

Timber Age. (n.d.). *The Timber Age Modular Building System*. Retrieved October 15, 2025, from https://www.timberage.com/Approach

Timberdoodle Farm & Sawmill. (n.d.). Timberdoodle Farm & Sawmill. Retrieved October 30, 2025, from https://www.timberdoodlesawmill.com

Tommelein, I. D., & Coelho, R. V. (2025). *What is your Rationale and Approach for Investing in Industrialized Construction?*

Turner, D. P., Guzy, M., Lefsky, M. A., Ritts, W. D., Van Tuyl, S., & Law, B. E. (2004). Monitoring Forest Carbon Sequestration with Remote Sensing and Carbon Cycle Modeling. *Environmental Management*, *33*(4), 457–466. https://doi.org/10.1007/s00267-003-9103-8

United Nations Environment Programme, G. A. for B. and C. (2025). *Not just another brick in the wall: The solutions exist—Scaling them will build on progress and cut emissions fast. Global Status Report for Buildings and Construction 2024/2025*. https://wedocs.unep.org/20.500.11822/47214

United Nations Environment Programme, Y. C. for E. + A. (2023). *Building Materials and the Climate: Constructing a New Future*. https://wedocs.unep.org/20.500.11822/43293

United States Environmental Protection Agency. (2018). *Wood Waste Inventory Final Report* (No. 600R18262; p. 94). National Service Center for Environmental Publications. https://nepis.epa.gov/Exe/ZyPURL.cgi?Dockey=P1012VIQ.txt

U.S. Bureau of Labor Statistics. (2025a, October 1). *Construction: NAICS 23*. Industries at a Glance. https://www.bls.gov/iag/tgs/iag23.htm

U.S. Bureau of Labor Statistics. (2025b, October 1). *Wood Product Manufacturing: NAICS 321*. Industries at a Glance. https://www.bls.gov/iag/tgs/iag321.htm

U.S. Census Bureau. (2024a). *Characteristics of New Housing* [Dataset]. https://www.census.gov/construction/chars/current.html

U.S. Census Bureau. (2024b). *New Residential Construction, Historical Time Series* [Dataset]. https://www.census.gov/construction/nrc/data/series.html

U.S. Census Bureau. (2024c, September 12). *Nearly Half of Renter Households Are Cost-Burdened, Proportions Differ by Race*. Census.Gov. https://www.census.gov/newsroom/press-releases/2024/renter-households-cost-burdened-race.html

U.S. Census Bureau and U.S. Department of Housing and Urban Development. (2024). *Cost & Size Comparisons: New Manufactured Homes and New Single-Family Site-Built Homes* [Dataset]. https://www.census.gov/construction/chars/; https://www.census.gov/construction/nrc/xls/starts_cust.xls.

U.S. Census Bureau, U. S. D. of C. (2023). *Median Year Structure Built*. https://data.census.gov/table/ACSDT5Y2023.B25035

U.S. Department of Agriculture, F. S. (2022). *Confronting the Wildfire Crisis: A 10-Year Implementation Plan* (General FS–1187b).

U.S. Department of Agriculture, F. S. (2023). *Future of America's Forest and Rangelands: Forest Service 2020 Resources Planning Act Assessment* (p. 348) [Gen. Tech. Rep. WO-102.]. U.S. Department of Agriculture, Forest Service. https://doi.org/10.2737/wo-gtr-102

U.S. Department of Agriculture Forest Service. (2023). *Tree Canopy Cover Datasets* [Dataset]. https://data.fs.usda.gov/geodata/rastergateway/treecanopycover/#docref

U.S. Department of Commerce. (2020). *American Softwood Lumber Standard* (Version PS 20-20) [Voluntary Product Standard]. National Institute of Standards and Technology.

U.S. Environmental Protection Agency. (2020). *Advancing Sustainable Materials Management: 2018 Fact Sheet*.

Vibrant Planet. (n.d.). *Vibrant Planet | Wildfire & Landscape Resilience*. Retrieved October 30, 2025, from https://www.vibrantplanet.net

Waldman, B., Habchi, R., & Palmeri, J. (2025). *2025 CLF North American Material Baselines Report*. Carbon Leadership Forum. https://carbonleadershipforum.org/2025-clf-north-american-material-baselines/

Wang, M., Wang, C. C., Sepasgozar, S., & Zlatanova, S. (2020). A Systematic Review of Digital Technology Adoption in Off-Site Construction: Current Status and Future Direction towards Industry 4.0. *Buildings*, *10*(11), 204. https://doi.org/10.3390/buildings10110204

White, J. C., Coops, N. C., Wulder, M. A., Vastaranta, M., Hilker, T., & Tompalski, P. (2016). Remote Sensing Technologies for Enhancing Forest Inventories: A Review. *Canadian Journal of Remote Sensing*, *42*(5), 619–641. https://doi.org/10.1080/07038992.2016.1207484

Whiteman, A., Wickramasinghe, A., & Piña, L. (2015). Global trends in forest ownership, public income and expenditure on forestry and forestry employment. *Forest Ecology and Management, Changes in Global Forest Resources from 1990 to 2015*, *352*, 99–108. https://doi.org/10.1016/j.foreco.2015.04.011

WholeTrees Structures. (n.d.). Timber Search. Retrieved January 22, 2025, from https://timbers.wholetrees.com/m/search

Wilk, C. (with Bisley, E. & Victoria and Albert Museum). (2017). *Plywood: A material story*. Thames & Hudson.

WoodWorks. (2025). What is mass timber? *WoodWorks | Wood Products Council*. https://www.woodworks.org/resources/what-is-mass-timber/

WoodWorks Wood Products Council. (2025). *Mass Timber Projects in Design & Constructed—WoodWorks*. https://www.woodworks.org/resources/mapping-mass-timber/

YWCA Supportive Housing—Mass Timber WIN Project. (2025, June 8). Woodworks Innovation Network. https://www.woodworksinnovationnetwork.org/projects/ywkw