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Multi-criteria decision analysis for mass timber sourcing for construction in the United States

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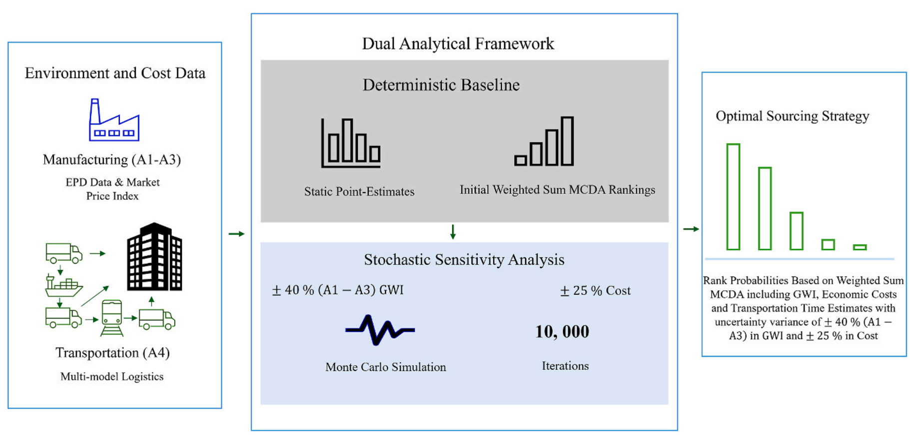
HIGHLIGHTS

- MCDA framework developed to evaluate U.S. mass timber sourcing options.
- Deterministic baseline assesses upfront GWI, total cost, and delivery time.
- Stochastic analysis captures parametric uncertainty in A1-A3 GWI and costs.
- Domestic sourcing minimizes A4 transport GWI, total costs, and delivery time.
- Probabilistic MCDA maps optimal sourcing based on stakeholder priorities.

GRAPHICAL ABSTRACT



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ABSTRACT

Mass timber (MT) is among the most sustainable construction materials for building structures. While U.S. building codes facilitate MT construction up to 18 stories of height, the frequent international sourcing of MT raises sustainability concerns regarding transportation emissions. Previous research relies primarily on deterministic whole building life cycle assessment (WBLCA), which lacks the mechanisms to balance environmental impacts with competing economic and logistical factors under uncertainty. To address this, we developed a multi-criteria decision analysis (MCDA) framework that employs a Weighted Sum Model (WSM) to establish a deterministic baseline integrating upfront global warming impacts (GWI) (Modules A1–A4), material and transportation costs, and transportation times. To account for data ambiguity, this baseline is then expanded into a stochastic Monte Carlo sensitivity analysis (10,000 iterations) using parametric uncertainties (±40% for GWI and ±25% for costs). This framework was applied to four diverse U.S. cities, evaluating eight domestic and four international suppliers across multi-modal networks under three weighting cases (prioritizing GWI, Cost, or

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Time). Probabilistic results indicate that when prioritizing GWI, Canadian imports generally achieve the highest probability of optimality due to lower manufacturing emissions. Conversely, domestic U.S. manufacturers consistently emerge as optimal options when prioritizing economic costs or delivery times. These findings demonstrate that geographic proximity does not guarantee the highest sustainability, and MCDA often yields different optimal selections than WBLCA alone. Ultimately, this robust, customizable framework optimizes MT supply chain decisions and identifies areas where domestic infrastructure must improve for the local MT industry to outcompete the global marketplace.

1. Introduction

Mass timber (MT) has emerged as a viable solution for improving the safety, resiliency, and sustainability of building construction. U.S. building code standards (International Code Council, 2020, 2024) facilitate construction of MT buildings up to 18 stories of height, largely based on the performance demonstrated in full-scale compartment fire tests (Zelinka et al., 2018) and other supporting fire safety research (Bøe et al., 2024). MT seismic lateral-force-resisting systems have been developed to rigorous qualification standards (Van de Lindt et al., 2022) and have proven capable of sustaining 88 consecutive historical earthquakes, replicated on the world's largest shake-table, without damage (Pei et al., 2024). While this high level of seismic performance is critical to improving the safety and resiliency of many communities, sustainability affects every project, even in areas of low seismic risk, because energy consumption and emissions of each construction add to global challenges. The production of construction materials accounts for approximately 10% of total annual global carbon dioxide emissions (UNEP, 2022). These emissions, known as *embodied carbon*, represent a quarter of total environmental impacts of the construction industry, and the use of low embodied carbon materials is critical to achieving zero-carbon building objectives (Brashaw, 2021; Duan et al., 2026; Greer and Horvath, 2023; Kremer et al., 2025).

Using the standard framework of whole building lifecycle analysis (WBLCA) (ISO 21930: 2017), many studies highlight the sustainable attributes of MT construction that drastically reduce the embodied carbon of building structures relative to conventional benchmarks (Duan et al., 2022). The main advantage of wood building materials is storage of biogenic carbon, the CO_2 absorbed during tree growth that remains sequestered within wood throughout a building's lifespan and beyond through recycling or long-term storage in landfills (Chen et al., 2020; Gu et al., 2021; Hernandez et al., 2018; Prestemon et al., 2022). MT products, such as cross-laminated timber (CLT), glue-laminated timber (glulam), and laminated veneer lumber (LVL), achieve robust sizes of panels and framing (Mayencourt et al., 2025) by assembling and gluing renewable wood resources from sustainably managed forests. These forests are harvested in a manner that promotes regeneration and continuous carbon sequestration within living trees and soil (Andersen et al., 2024; Cordier et al., 2022; Nepal et al., 2024). MT building products resemble precast concrete in form and utility but with typically less energy consumption and emissions of manufacturing (Ahmad et al., 2023; Gu et al., 2021; Kumar et al., 2024a; Pierobon et al., 2019) and physical mass. Lighter weight MT structures typically lessen foundation requirements, which in turn lowers emissions and construction costs (Chen et al., 2020; Kumar et al., 2024a). Prefabrication of MT components facilitates modularity and faster on-site erection of structures, which enhances sustainability of the construction installation process (Alotaibi, 2024; Scouse et al., 2020).

Despite the benefits of biogenic carbon storage (Lim et al., 2025; Ouellet-Plamondon et al., 2023), renewability of trees, and efficient manufacturing and construction, questions about the transportation emissions loom, because many MT products are transported internationally. One of the tallest MT building structures in the United States, for example, is constructed of imported glulam framing and CLT panels from Austria (Fernandez et al., 2020). To properly evaluate these impacts, we must review definitions of the standard life cycle assessment (LCA) boundaries. Upfront embodied carbon encompasses the product stage (Modules A1–A3, which include resource extraction, transport to the factory, and manufacturing) (Highlighted in blue; Fig. 1) and the construction process stage (Module A4, transportation to the building site (Highlighted in blue; Fig. 1), and Module A5, on-site installation). Because the magnitude of cradle-to-gate emissions (Modules A1–A3) for MT products is generally low, the magnitude of emissions generated by transportation (Module A4) typically amounts to a large proportion of the total upfront embodied carbon for United States. Several prior studies have addressed emissions generated by transporting MT products Liang et al. (2021), for instance, showed that MT buildings in the Pacific Northwest have transportation (module A4) accounting for 4.6% of the total upfront embodied carbon (excluding module A5), represented as the ratio A4/(A1+A2+A3+A4). Hemmati et al. (2022) similarly reported a wide range of transportation-related emissions for various sources of MT from Austria and various domestic producers of CLT for a building on the University of Arkansas campus. Puettmann et al. (2021) reported that transportation-related emissions contributed between 4.7% and 11.7% to the total upfront embodied carbon (A1 through A4, excluding module A5) in MT buildings across the Pacific Northwest, Northeast, and Southeast U.S. regions.

At first glance, sourcing MT from nearby production centers seems optimal and obvious, because locally sourced MT has much lower transportation emissions than imported MT (Hemmati et al., 2022, Kumar et al., 2024). While applications of WBLCA framework critically highlight environmental impacts of material selection and sourcing in construction, conventional and deterministic WBLCA methodology lacks the mechanism to account for competing logistical, economic, and environmental priorities and the uncertainty associated with each factor. The globalized marketplace, presents a multitude of supply chain options that further complicate selection, a challenge that other industries have confronted (Sarkar et al., 2025, 2026). A study of greenhouse gas emissions (GHG) of tomato production, for example, found that locally grown tomatoes are not necessarily the most sustainably grown (Zhu and Miller, 2025). To better manage the complexity of supply chains, this study uses a greater portion of the WBLCA framework to examine transportation emissions and a more comprehensive framework of multi-criteria decision analysis (MCDA) (Cegan et al., 2017; Wątróbski et al., 2019). In this study, domestic and international MT sourcing options for construction sites in four U.S. cities: Seattle, WA; Madison, WI; Austin, TX; and Boston, MA are compared. These four cities were selected as destinations due to their growing adoption of MT in construction and their representation of diverse geographical regions within the U.S., ensuring the analysis captures regional variations in logistics, environmental impacts, and costs. The sources of MT represent major manufacturers in the U.S., Canada, Finland, and Austria. The emissions of multiple modes and routes of transportation (maritime, rail, and road) are accounted for in the model for appropriate comparisons among MT supply chains.

The main goal of this set of case studies is to illustrate the value of WBLCA and MCDA frameworks in evaluating various MT supply chains. We hypothesized that local and domestic MT sources would minimize upfront embodied carbon emissions but found that some regions of the country lack a nearby domestic producer. In addition, we found a U.S. manufacturing site had up to 86% higher manufacturing emissions (module A1-A3) than respective counterparts in Austria and QC, Canada. Greater manufacturing emissions of domestic producers generally offset transportation-related emissions savings realized by local sourcing of MT. Sometimes, the most sustainable source of MT was neither domestic nor local, because manufacturing and transportation mode efficiencies can make up for greater distances. To capture these complex trade-offs, we first established a baseline deterministic MCDA framework that evaluated global warming impact (GWI), economic costs, and delivery times using a static weighted sum of 50%, 40%, and 10%, respectively. Then, to ensure robust decision-making under parameter uncertainty, we then extended this baseline into a stochastic Monte Carlo sensitivity analysis. This stochastic model evaluates supply chains across three distinct weighting scenarios (prioritizing GWI, costs, or time). The primary contribution and novelty of this study is this robust, customizable framework, which mathematically addresses data ambiguity and demonstrates how optimal MT sourcing strategies shift based on distinct stakeholder priorities over GWI, cost and time.

Section 2 details the methodological framework, beginning with the deterministic MCDA baseline integrating GWI, economic costs, and transportation time and its subsequent expansion into a stochastic Monte Carlo sensitivity analysis. Section 3 presents result of the analyses with comparisons of following six metrics:

(i) Cradle-to-gate GWI,
(ii) Transportation-related GWI,
(iii) Economic costs, including MT market price and transportation expenses,
(iv) Transportation time estimates
(v) Deterministic MCDA outcome, and
(vi) Probabilistic MCDA outcomes (rank stability) derived from the stochastic Monte Carlo sensitivity analysis with parametric uncertainty (±40% GWI (A1-A3) and ±25% economic costs).

Section 4 summarizes key findings, which are a snapshot of current market conditions, and proposes areas of domestic infrastructure that need to improve for local MT suppliers to outcompete international suppliers environmentally and economically.

2. Methodology

2.1. Overview of analysis frameworks

The analysis considers MT supply from eight U.S. domestic manufacturing facilities located in Alabama, Arkansas, Illinois, Montana, New York, Oregon, Texas, and Washington, and four international sites located in Canada, Austria, and Finland (Table S1), incorporating three intermodal transportation routes including sea, rail, and road. Fig. 2 highlights the transportation phases (module A4) within the WBLCA. This study evaluates global and domestic MT supply chains for four cities, representing regional U.S. construction hubs, with three main criteria that serve as inputs in a broad MCDA framework. Ahmed et al. (Ahmad et al., 2023) utilized MCDA to compare MT and steel structural systems, balancing GWI against project costs. Expanding the scope to circular economy principles, Balasbaneh and Sher (2024) used MCDA to evaluate various MT wall assemblies, including Cross-Laminated Timber (CLT), Nail-Laminated Timber (NLT), and Dowel-Laminated Timber (DLT). Their model optimized for Global Warming Potential (GWP), embodied energy, and total cost, providing a framework for selecting timber products that align with both environmental and economic performance goals. Ahmed et al. (Ahmed and Arocho, 2022) applied the Choosing by Advantages method to identify and evaluate the critical success factors for the adoption of MT building materials within the United States. Several authors have applied MCDA methods to support decision-making across various areas of the construction sector (Bianchi et al., 2024; Nagy et al., 2026; Sánchez-Garrido et al., 2022; Theilig et al., 2025).

Our MCDA framework incorporates environmental, economic, and delivery times as inputs. Environmental impacts are derived from a WBLCA focusing on modules A1–A4 (Fig. 1), while economic costs

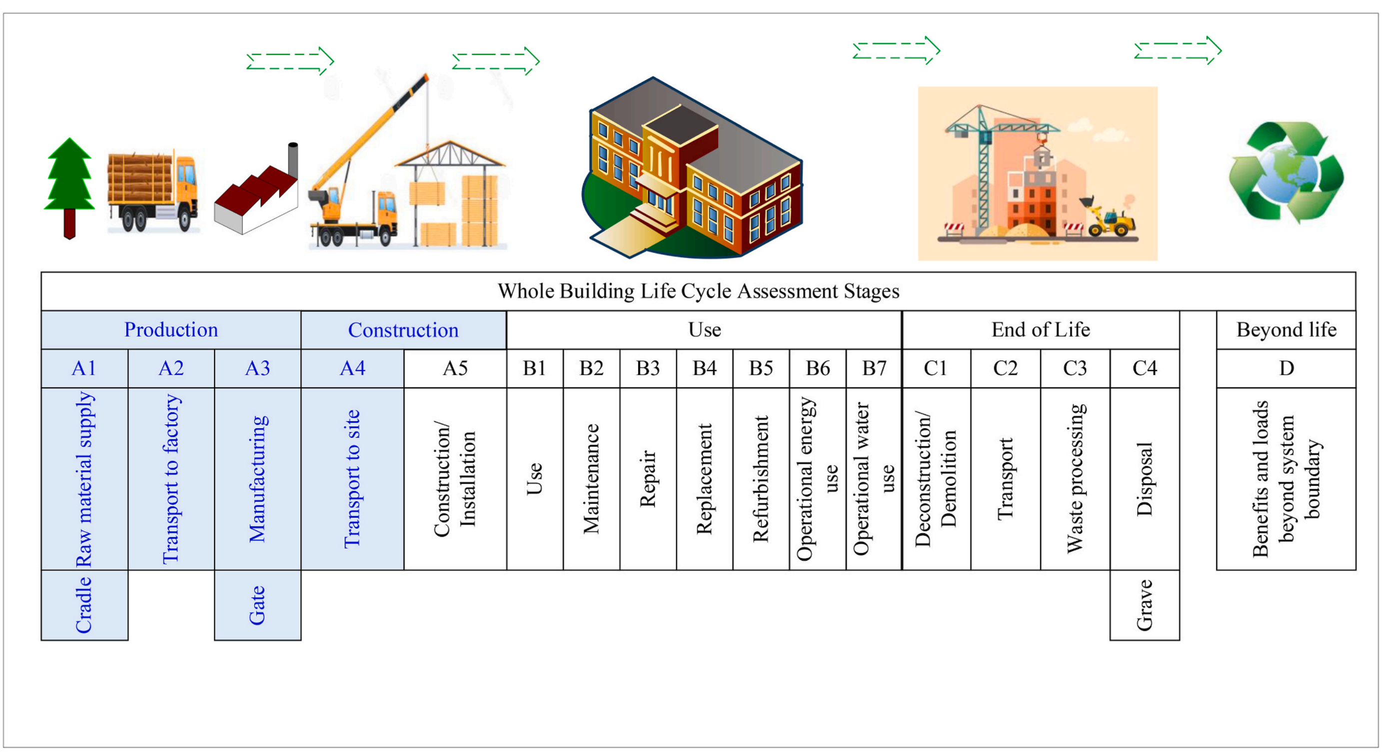

Fig. 1. System boundary for whole building life cycle assessment (WBLCA) adapted from ISO 21930:2017. Present study focuses on modules A1–A3 (production) and A4 (transportation) of MT sourced from eight domestic and four international manufacturing facilities located in Canada, Austria, and Finland for supplying MT for construction in four U.S. cities (Seattle, WA; Madison, WA; Austin, TX; and Boston, MA).

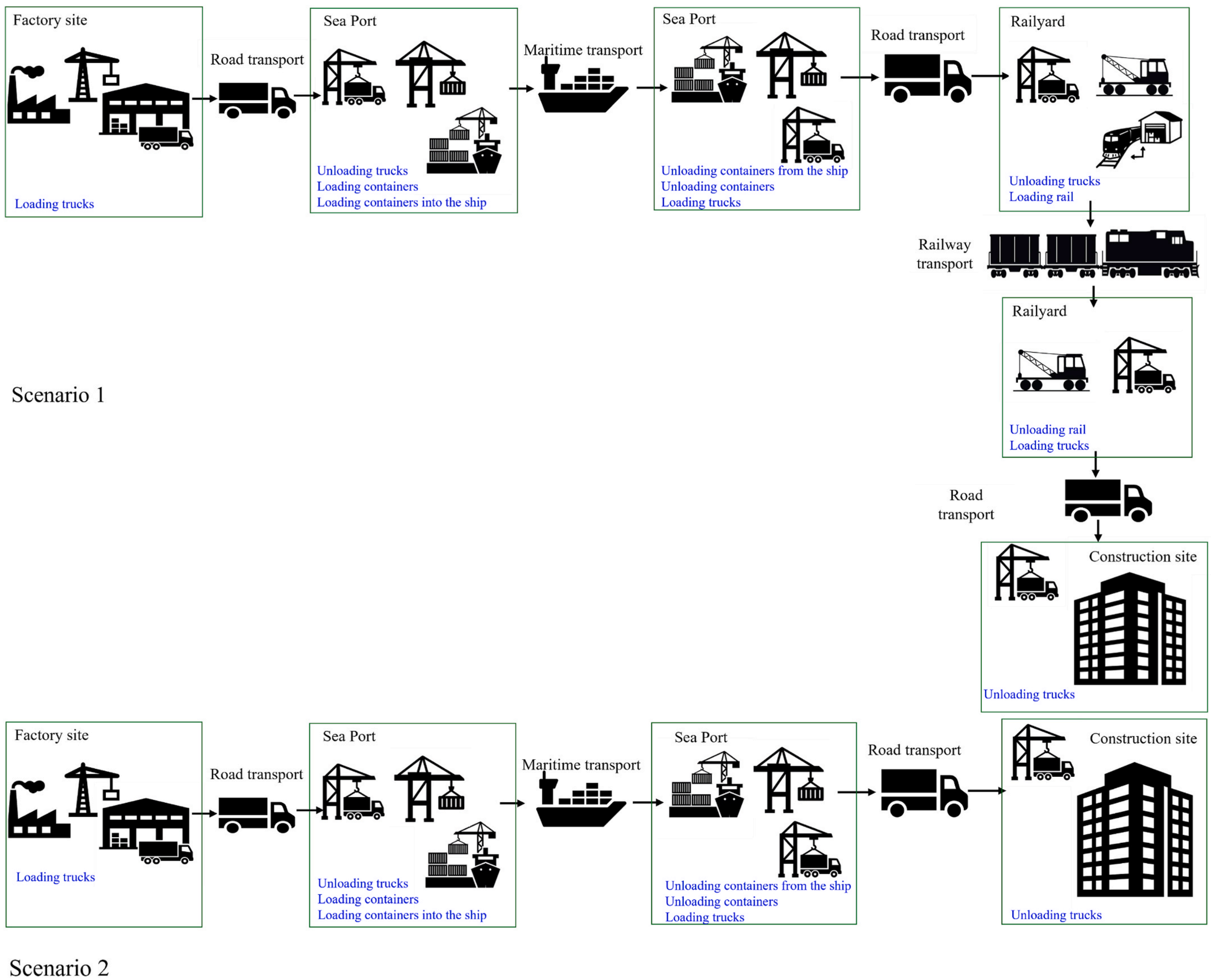

Fig. 2. Transportation routes and activities related to transporting MT products to construction sites in four U.S. cities (Seattle, WA; Madison, WI; Austin, TX; and Boston, MA) from eight domestic and four international manufacturing sites in Canada, Austria, and Finland. Scenario 1 represents intermodal transport (road-maritime-railroad), while Scenario 2 (road-maritime-road) represents road only ground transport.

(comprising MT market prices and transportation expenses) and delivery times are calculated based on the activities illustrated in Fig. 2 and detailed in Supplementary Tables S2 and S3. By integrating these data points, the analysis provides an evaluation of the trade-offs between sustainability, cost, and schedule for MT construction in four U.S. cities (Seattle, Madison, Austin, and Boston) in respective Pacific Northwest, Midwest, Southwest, and New England regions.

Given the significant variations in energy consumption, GHG emissions, and costs across transportation modes, this study quantifies their cumulative impacts to enable a robust comparison of life-cycle environmental performance, economic costs, and delivery timelines across various sourcing strategies and routes. To capture real-world logistical variability, this study evaluated two distinct transportation scenarios. Scenario 1 models a comprehensive intermodal transport network integrating maritime, rail, and road freight. Under this route, MT materials are transported from the manufacturing facility to a foreign export seaport, shipped to a U.S. port of entry, conveyed by truck to an origin railyard, transported via rail to another terminal, and finally delivered by truck to the construction site. All nodal activities associated with this supply chain including loading, unloading at manufacturing site, seaport, and railyard operations are illustrated in Fig. 2 (Scenario 1). Conversely, Scenario 2 reflects a streamlined maritime and road-only network for North American routes. This scenario bypasses the rail network and its associated railyard activities entirely, utilizing direct long-haul trucking from the U.S. seaport to the final construction site (Fig. 2, Scenario 2).

2.2. System boundary and functional unit

The most heavily weighted criterium of the MCDA is GWI, which is quantified according to the standard WBLCA framework, depicted in Fig. 1 (Nurdiawati et al., 2025). WBLCA modules encompass the full building life cycle, from raw material extraction (module A1) and transportation to manufacturing facilities (module A2), material processing (module A3), transportation to construction sites (module A4), installation (module A5), use (module B1-B7), demolition (module C1), and end-of-life options (module C4) such as landfilling, recycling, or energy recovery (Fig. 1) (ASTM, 2022; EN 15978, 2011; Marsh et al., 2023). To make practical comparisons among construction materials, using only ‘A’ modules is common to address focused questions. *Cradle-to-gate* modules (A1, A2, and A3) account for raw material extraction, transportation of raw materials to manufacturing facilities, and processing materials into construction products ready for shipment (Highlighted in blue; Fig. 1). Module A4 accounts for transportation of construction materials from the manufacturing facility to the construction site (Fig. 1). The installation module A5 accounts for onsite erection and construction of the building (Fig. 1). The sum of GHG associated with modules A1 through A5 is known as *upfront carbon emissions* (Fig. 1).

The scope of WBLCA applied in this study ranges from A1 to A4 (modules highlighted in blue: Fig. 1), because we seek only to compare embodied emissions of MT sourced from 12 different suppliers and delivered via multimodal transport routes to 4 U.S. cities. Although variations in sizes of components and rates of production among MT manufacturers could affect emissions of the A5, we assume that each manufacturer can supply a complete set of MT components for equivalent building structures. Hence, only the A1 to A4 portion of upfront embodied carbon needs comparison to evaluate the environmental impacts among MT supply chains.

The A1 to A4 system boundary of this study covers the manufacturing and transportation activities involved to deliver MT materials needed to build 8-, 12-, and 18- story buildings in each of four U.S. destination cities from eight domestic manufacturing facilities in the U.S. and four international MT manufacturing facilities (Supplementary Table S1). It encompasses the environmental impacts associated with MT manufacturing (modules A1–A3), as well as transportation-related activities (module A4), such as loading and unloading operations, intermodal transportation via road, rail, and sea routes, and the market prices per tonne, transportation costs per tonne, and transportation times. The functional unit is defined as 1 tonne of MT delivered to the construction site, providing a consistent and standardized basis for comparing GWI, material and transport costs, and delivery timelines across diverse sourcing scenarios and intermodal transportation routes.

2.3. Analysis and modeling intermodal transport activities

This section briefly explains the methodology details on the estimation of MT quantity transported along with the distances, modes, and transportation activities for four MT construction locations in U.S. The sub-sections 2.3.4 to 2.3.6 describe three international supply locations and section 2.3.7 describes all domestic supply locations. One construction location, Madison, WI, described in more detail exemplifies logistics adaptable to other three U.S. cities (Seattle Austin, and Boston) with regional adjustments.

Emissions, costs, and transportation times are influenced by factors such as transportation mode, distance, and regional logistics infrastructure. Maritime shipping, while efficient per tonne-kilometer, contributes significantly to emissions over long international distances, whereas rail and trucking, used for initial and final transport legs, adds further emissions, particularly for sites distant from ports or rail hubs (Hemmati et al., 2022). Intermodal transportation, combining maritime, rail, and road modes, can reduce emissions compared to single-mode transport (Gandhi et al., 2024; Heinold and Meisel, 2018; Pinto et al., 2018).

2.3.1. Estimated quantities of MT materials by building heights

For an IBC construction type IVC 8-story building, approximately 3215 m^3 of MT materials are required, including CLT panels for floors, walls, and roofs, glulam for beams and columns, and miscellaneous small-dimension softwood lumber for other structural uses (Kumar et al., 2024b). Similarly, 5181 m^3 are required for IVB-12-story, and 7630 m^3 are required for IVA-18-story buildings (Kumar et al., 2024b). The average tonnes of MT materials required are 1511, 2435, and 3585 for the respective 8-, 12-, and 18-story buildings, based on an average oven dry density value of 470 kg/m^3. Throughout this study, the volume of MT and wood materials are assumed constant, regardless of source, but variations in average density are accounted for because mass of MT materials impact transport from manufacturing sites to the building construction site. Fig. 2 shows all transportation supply chains and routes considered in this study.

2.3.2. Analysis of the environmental impacts

For this study, environmental impacts with a focus on GWI associated with the manufacturing of MT products were evaluated using EPDs developed from manufacturer-reported data. The original EPD data, provided on a per cubic meter (m^3) basis, was converted to a per-tonne basis using MT product density values (e.g., CLT, Glulam) to ensure consistency with the study's functional unit of 1 tonne of MT delivered. This conversion facilitates a standardized comparison of manufacturing-related GHG emissions (modules A1–A3) across domestic and international manufacturing sites, aligning with the assessment of transportation impacts (module A4) and material and transport costs.

2.3.3. Modeling intermodal transport activities

The transportation activities associated with MT sourcing to four U.S. construction cities from eight domestic and four international manufacturing sites (Supplementary Table S1) are modeled using intermodal transport routes (Fig. 2, Supplementary Fig. S1a–S1d). In Europe, the initial leg of A4 transportation typically involves trucks, followed by container ships for maritime transport. In the United States, freight trains are used for rail transport, with the final delivery leg completed by trucks (Fig. 2, Supplementary Fig. S1a–S1d). For road transport, trucks with a maximum capacity of 32 tonnes are assumed (PRe Consultants, 2024; Smart Lam North America, 2020), requiring 112 trucks to transport 3586 tonnes of MT for an 18-story building. Loading and unloading operations require 40 min per truck with two workers (Hemmati et al., 2022), totaling 112 trucks. Additionally, 144 containers (12.2 m length, 25-tonne capacity) are loaded and unloaded at ports by two workers (Hemmati et al., 2022). Comparable equipment and resource requirements (trucks, containers, and machine hours) apply to 12- and 8-story buildings (IVB-12 and IVC-8). Detailed modeling specifications are provided in Supplementary Tables S2–S4.

Environmental impacts for the A4 transportation module are modeled using SimaPro (PRe Consultants, 2024) with the DATASMART 2023; LTS, 2023) and Ecoinvent 3.9.1 databases (ecoinvent, 2022). Impacts are quantified using the Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI) method (Bare et al., 2012), which provides characterization factors for Life Cycle Impact Assessment (LCIA). These factors quantify environmental impacts of inputs and emissions across standardized categories, expressed in common equivalence units, ensuring consistent evaluation of GHGs and other environmental metrics.

The study evaluates various intermodal transportation routes for both international and domestic MT sourcing (Fig. 2), considering geographic proximity to the construction sites in the four U.S. cities. All production facilities are assumed capable of supplying MT for 8-, 12- and 18-story buildings compliant with the 2021 and 2024 International Building Codes (ICC-International Code Council, 2024); Route selection prioritizes proximity and efficiency to minimize transportation times, costs, including MT sales prices and transportation costs, and environmental impacts.

2.3.4. MT import from Graz-Styria, Austria

Austria, a landlocked country, utilizes the Port of Hamburg, Germany, as the nearest seaport for exporting MT. The process starts with a road journey from the Graz-Styria production site to Hamburg, employing trucks with a maximum capacity of 32 tonnes. From Hamburg, MT is shipped by sea to U.S. ports, initiating two supply chain scenarios upon U.S. port arrival in New York. In Scenario 1, MT is transported by truck to a railyard, followed by rail to another railyard, with the final leg via truck to the construction site, forming an intermodal route. In Scenario 2, MT is directly trucked from the maritime port to the construction site.

For the Madison destination, the journey begins with road trip to Hamburg, followed by a maritime shipping to the Port of New York. In Scenario 1, materials are then moved by truck to a railyard followed by rail trip to the Chicago railyard, and a final leg to Madison is completed by truck. In Scenario 2, a truck route from New York delivers directly to Madison. This exemplifies logistics adaptable to the other three U.S. cities (Seattle, Austin, and Boston) with regional adjustments. The transportation route, including all associated activities such as loading, unloading, and mode transfers, is detailed in Supplementary Fig. S2(a) for a construction site located in Madison.

For Seattle and Boston, the process starts with a road trip to Hamburg, followed by maritime shipping to the Port of Seattle, and Boston. In both scenarios, a truck trip from the port completes delivery to the construction sites in Seattle and Boston, reflecting Seattle, and Boston unique coastal access.

For Austin, the process starts with a road trip to Hamburg, followed by a maritime shipping to the Port of Houston, similar to the earlier routes. In both scenarios, a truck trip from the Port of Houston completes delivery to the construction site in Austin.

2.3.5. MT import from Kuhmo, Finland

Finland, with its extensive forested regions, exports MT from the production site in Kuhmo, relying on the Port of Oulu as the nearest seaport. The process commences with a road journey from Kuhmo to Oulu, utilizing trucks with a maximum capacity of 32 tonnes. From Oulu, MT is shipped to the Port of New York.

After arriving at the Port of New York by sea, on route to the Madison construction destination, two supply chain scenarios are initiated. In Scenario 1, upon arrival in New York, MT is first transported by truck to a railyard, then moved by rail to another railyard, with the final leg completed by truck to the construction site, forming an intermodal route. In Scenario 2, MT is trucked directly from the port to the construction site in Madison, streamlining the process. The complete transportation route from Kuhmo, Finland to Madison, WI, U.S. including all loading, unloading, and transportation modes, is detailed in Supplementary Fig. S2(b).

For Seattle and Austin, the maritime route extends from Oulu to the Ports of Seattle and Houston, respectively. In contrast, for Boston, the maritime distance is shorter, running from Oulu to the Port of Boston. In all cases Seattle, Austin, and Boston, final delivery to the construction sites is completed by truck from the respective ports, highlighting regional logistics variations across these locations.

2.3.6. MT import from Canada

Unlike imports from Austria and Finland, MT imports from Canada eliminate the need for sea transportation due to its proximity to the U.S. The study considers two manufacturing facilities, one located in Chibougamau, QC, and the other located in South Slocan, BC. The Quebec facility serves construction sites in Boston, Madison, and Austin, via transport through Montreal, while South Slocan delivers to Seattle. Two supply chain scenarios are evaluated. In Scenario 1, the process combines road and rail transport, because truck transport is most often necessary to reach freight rail transfer stations. Scenario 2 relies solely on road transport via trucks with a maximum capacity of 32 tonnes.

For Madison, in Scenario 1, the journey begins with a truck haul from the Chibougamau facility to a railyard in Montreal, followed by a rail transport to the Chicago railyard. The final leg is completed by truck from Chicago to Madison, finalizing the intermodal route. Supplementary Fig. S2(c) illustrates this route, including all associated activities such as loading and unloading. In Scenario 2, MT is transported directly by truck from Chibougamau to Montreal to Madison, simplifying the supply chain. These routes are also adaptable to Boston and Austin, and reflect regional logistics, with distances and modes adjusted based on proximity and infrastructure, ensuring efficient delivery across the target U.S. cities.

2.3.7. Domestic MT supply from within the United States

This study evaluated eight domestic MT manufacturing facilities distributed across the United States from east to west (Table S1), which produce MT products (e.g., CLT and glulam). These facilities are selected based on geographical proximity to the four selected construction destination cities. For Madison, MT, sourcing from manufacturers in Columbia Falls, MT, and Phoenix, IL was considered, and their transportation routes are detailed in Supplementary Fig. S2d–2f.

Transportation routes to supply MT from Montana to Madison (Fig. S2d) encompass all related activities such as loading and unloading. In Scenario 1, the process begins with trucks transporting MT from the Montana production site to a local railyard, followed by rail journey to the Chicago railyard, IL. The final leg mirrors routes from Austria, Finland, and Canada, completed by truck to Madison. In Scenario 2, MT is transported directly by truck from Columbia Falls, MT to Madison, WI, simplifying the supply chain.

Additionally, the transportation route from Phoenix, IL to Madison (Fig. S2e) was modeled to represent a regional supply scenario. In both Scenario 1 and Scenario 2, MT were transported directly by truck from the sourcing site to the destination construction site. This short-haul route demonstrates efficient domestic logistics and can be adapted to other regional pairings such as from sourcing sites in Colville and Spokane to Seattle; Lufkin to Austin; or Sidney to Boston, based on proximity and infrastructure.

Finally, for Austin, TX (domestic supply from Dothan, AL) and Boston, MA (domestic supply from Conway, AR) in Scenario 1, the process begins with trucks transporting MT from the production site to a local railyard. From there, MT transported by rail to another railyard near the destination, followed by final delivery by truck to the construction sites in Austin and Boston.

2.4. Cost estimation

2.4.1. Market price index

To estimate the market price of MT (USD per tonne) for this study, we used the 2025 Mass Timber Performance Index data for consistency and accuracy (Anderson and Spiritos, 2025). The original cost data, expressed in dollars per cubic foot ($\$/ft^3$), were converted to a per-tonne basis using Equation (1). This conversion ensured consistency with the study's functional unit of 1 tonne of MT delivered to construction sites. This conversion used the average oven-dry density values (kg/m^3) of the various MT products, as reported in Supplementary Table S8, to ensure a consistent and comparable analysis across both domestic and international sourcing scenarios. For globally sourced materials, a flat 10% tariff rate was applied, based on the new U.S. requirement that sets a standardized 10% tariff on most imported goods (Avalara, 2026).

$$Market\ Price_{tonne} = \frac{Price_{ft^3} \times 35.314667}{Density_{kg/m^3}} \times 1000 \quad (1)$$

2.4.2. Transportation

Cost estimates for transporting MT are influenced by several key factors, including the selection of service providers, regional variables such as labor costs, the chosen mode of transport, and current market conditions. The cost data was originally available on a U.S. ton per km basis, which was converted to a metric tonne per km format for consistency with the LCA results.

2.4.2.1. Loading and unloading. Loading and unloading costs can vary widely based on the region and specific requirements. In vehicle logistics, for instance, loading costs can range from $30 to $300 per vehicle, depending on factors such as labor intensity and regional labor costs (Kar-tainer.com, 2020). However, specific per-minute rates for loading/unloading in general freight are not readily available. For estimation purposes, we assumed an average labor cost of $50 per hour (approximately $0.83 per minute) per worker. Assuming that loading/unloading a truck requires two workers, the cost would be about $1.66 per minute per truck.

2.4.2.2. Road transportation. Road transportation costs via truck vary significantly across regions. For European routes, an estimated €2 per kilometer for a 22-tonne load translates to roughly $ 0.107 per tonne-kilometer (IRU, 2025). In the United States, the average cost is approximately 19.6 cents per ton-mile, which converts to about 12 cents per ton.km (Boleneus, 2024a). Based on these data, transportation costs were estimated at 11 cents per tonne.km for European routes and 13.5 cents per tonne.km for U.S. routes.

2.4.2.3. Maritime transportation. Maritime shipping costs for MT transportation vary depending on routes and fluctuating market conditions, with specific per tonne.km rates often unavailable. Based on estimates from Heavy Haulers (2023), shipping a 12.2 m (40 ft) container from Hamburg, Germany to New York costs approximately $1056. Assuming such a container accommodates 25–28 tonnes of MT, this data serves as a baseline for extrapolation across other sea routes within the MCDA framework for supplying MT to construction destinations. Similarly, the route from Oulu, Finland, to New York, United States, is estimated at $1314 per 12.2 m container. These extrapolated costs, adjusted for distance and container capacity, support the assessment of transportation costs (module A4) from domestic and international MT manufacturing facilities, though variations in fuel prices and port fees may influence the accuracy.

2.4.2.4. Rail transportation. Rail transport is typically more cost-effective for long-distance freight movement. In the United States, the average rail transport cost in 2023 was approximately $0.160 per ton per mile, equivalent to about $0.110 per tonne.km (Boleneus, 2024b). For this study, we applied the 2023 estimates to derive a cost of $0.11 per tonne per km.

2.5. Transportation time estimates

To estimate transportation times for shipping MT materials from various manufacturing facilities to construction destinations, we adopted specific speed assumptions for each transportation mode. Road transportation was modeled at 60 km per hour, rail at 40 km per hour, and maritime transport at 10 knots (approximately 18.5 km per hour), consistent with typical operational speeds. To account for intermodal transfer logistics, a 24-h layover was assumed at each intersection (e.g., road to ship at ports and road to rail at railyards), covering potential transfer times, equipment availability, and delays due to scheduling or customs. This layover duration reflects real-world variability, such as port congestion or rail scheduling constraints, ensuring a conservative time estimate. For instance, the 1000 km road leg from Graz-Styria, Austria, to Hamburg is estimated at 16.7 h, plus a 24-h layover, totaling 40.7 h before sea transport begins. Similarly, the 2414 km rail leg from Montana to Chicago is calculated at 60.4 h, with an additional 24-h layover, aligning with observed transport delays. These estimates, integrated with distances from domestic and international manufacturing sites, support the assessment of delivery times across intermodal routes, though variations in weather or infrastructure may require further refinement.

2.6. Multi criteria decision analysis using the weighted sum method

MCDA provides a structured and transparent framework for decision-making, enabling reproducible, defensible, and stakeholder-inclusive outcomes that go beyond intuition or reliance on a single metric. In this study, a Weighted Sum Model (WSM) was employed within the MCDA framework to capture and evaluate three competing logistical factors to identify the optimal solution for sourcing MT: GWI (Modules A1–A4), material and transport costs, and transportation time.

For the initial deterministic baseline analysis, a weighting scheme of 50% GWI, 40% cost, and 10% time was established. Given the primary adoption of MT for its sustainability benefits, the highest weight (50%) was assigned to GWI to reflect its environmental significance in the marketplace. Economic considerations, including MT market sales prices and multi-modal transportation costs, were allocated a 40% weight due to their critical role in project viability and procurement decisions. Transportation time, a key factor in supply chain efficiency, received the remaining 10% weight to optimize delivery schedules across intermodal routes.

However, because stakeholder value systems are inherently subjective, relying solely on a single static weighting assumption risk limiting the generalizability of the optimal sourcing selections. To overcome this limitation and provide robust decision-support, the baseline WSM is subsequently expanded into a stochastic Monte Carlo sensitivity analysis. Within this probabilistic framework, the supply chain networks are evaluated across three distinct, extreme weighting cases to observe how rank stability shifts under different value systems: prioritizing environmental impact (70% GWI, 20% cost, 10% time), prioritizing economic impact (70% cost, 20% GWI, 10% time), and prioritizing logistics and scheduling (70% time, 15% cost, 15% GWI). By systematically varying weights alongside the parameter uncertainties, this multi-scenario approach removes the bias of a single weighting assignment and mathematically demonstrates how optimal sourcing strategies shift depending on specific stakeholder priorities.

2.7. Sensitivity analysis based on variations in GWI and cost

While the preceding sections present fixed (deterministic) estimates for three parameters (GWI, material and transport costs, and transportation time), real-world supply chain logistics are subject to inherent parametric uncertainty. For instance, GWI values based on EPDs from North America and Europe may not reflect regional differences in manufacturing efficiency or energy mixes. Similarly, assuming constant transportation emission factors ignores variation in fuel types, vehicle performance, and seasonal logistics constraints. Deterministic cost estimates also overlook economic volatility, such as fluctuating fuel prices, taxes, and tolls, which can affect the actual project costs.

To address these limitations and mitigate point-estimate bias, a stochastic approach using a Monte Carlo simulation was integrated into our MCDA framework (Lahdelma et al. 1998, 2003; Durbach and Stewart, 2012). The baseline A1-A3 GWI estimates were varied by $\pm$ 40% and the market prices by $\pm$25% using a triangular distribution across a 10,000-iterations. The $\pm$40% range follows established LCA pedigree matrix methodologies (e.g., Weidema et al., 2013; Lloyd and Ries, 2007; Igos et al., 2019) and captures the geographical, temporal, and technological variability in background LCA data. Furthermore, transportation impacts were modeled as a continuous uniform distribution bounded by Scenario 1 and Scenario 2, accounting for logistical variability. The $\pm$25% cost range (AACE International, 2020) reflects typical taxation and market price volatility.

Instead of generating statistical confidence intervals around a mean MCDA score, this stochastic approach applies these deterministic variance bounds to estimate the probability of optimality (rank stability). By evaluating each weighting case probabilistically across the 10,000 Monte Carlo iterations and tracking how often a site ranks first, the final rankings account for regional manufacturing variations, logistical variability, and economic fluctuations. This yields more robust decision-support results despite underlying data uncertainty.

3. Results and discussion

3.1. GWI estimates

In this study, GWIs, expressed in kg CO_2 eq, measured the warming effect of GHG emissions over a 100-year time horizon, a widely accepted metric for evaluating climate impact. Each GHG is assigned a unique GWP based on its radiative efficiency and atmospheric lifetime, with CO_2 as the reference gas, assigned a GWP of 1. For example, the TRACI impact category method assigns methane (CH_4) a GWP of 25 and nitrous oxide (N_2O) a GWP of 298 for the 100-yr time horizon (Greenhouse Gas Protocol, 2024; Solomon, 2007).

3.1.1. GWI estimates for manufacturing of MT (modules A1–A3)

The GWIs associated with manufacturing MT (modules A1–A3) are presented in Table 1 and Supplementary Table S7 as absolute values (kg CO_2-eq per tonne) and illustrated as relative percentages in Fig. S3. Their contribution to the total GWI (modules A1–A4) is shown in Fig. 3. The analysis reveals significant variations in A1-A3 GWIs across domestic and international MT manufacturing processes. United States manufacturing exhibits the highest GWI, with values ranging from 38% to 86% above those of Austrian production. This disparity is primarily attributed to the reliance on comparatively less sustainable energy sources within the U.S. manufacturing process (Özkan et al., 2023). In contrast, one Canadian manufacturer reports a 26% lower GWI than an Austrian producer, reflecting efficient hydroelectric energy infrastructure among other factors (Laurent et al., 2013), whereas another Canadian facility shows a 42% higher GWI, indicating regional variability in manufacturing emissions. These findings emphasize the need for targeted improvements in domestic energy infrastructure that will generally improve all manufacturing, including MT manufacturing, to compete with lower international emissions benchmarks.

3.1.2. GWI estimates for transportation of MT (module A4)

The estimated GWI associated with transporting MT (module A4) is detailed in Table 1. These impacts, represented in kg CO_2e per tonne, are estimated using intermodal transportation models for MT sourcing from eight domestic and four international manufacturing sites (Table S1). Scenario 1 represents intermodal transport (maritime, rail, and road), while Scenario 2, utilizes maritime with road transport for North American routes, to capture a range of logistical variations. Relative percentage results for Scenarios 1 and 2 are also shown in Supplementary Fig. 5a–d. The analysis highlights that domestically sourced MT offers the greatest potential to reduce transportation GWI.

For instance, sourcing from Phoenix, IL, U.S. to construction destination in Madison, WI, U.S., reduces GWI by approximately 91% compared to imports from Austria (Supplementary Fig. 5b; scenario 1), owing to shorter distances and efficient logistics. Despite a longer total transportation distance, MT imports from Finland exhibit a lower GWI than those from Austria, with reductions of up to 19% for Madison and Seattle, 23% for Austin, and 31% for Boston. This advantage stems from Finland's shorter 300 km European road leg versus Austria's 1000 km, as road transport contributes four to five times higher GWI than maritime transport. The maritime distances to the port of New York are 8345 km from Finland and 6704 km from Austria (Hamburg, Germany), resulting in relatively lower A4 GWI for sourcing MT from Finland. Findings further indicate that other domestic sources can also reduce GWI. For example, MT sourcing from Montana to Madison results in 37% and 22% lower A4 GWI compared to imports from Austria and Finland, respectively. However, this domestic option yields 2% and 42% higher GWI than imports from Quebec, Canada, and Phoenix, IL, U.S., due to the extended 2414 km rail leg from Columbia Falls, MT, U.S. (Supplementary Fig. 5b; Scenario 1).

Similar trends were observed for the other three construction destinations, Seattle, Austin, and Boston, in Scenario 1 (Supplementary Fig. 5a, c, d). Notably, Boston benefits from its proximity to the eastern Canadian supplier in Quebec, Canada. However, the domestic supply route from Conway, AR to Boston exhibits a higher GWI compared to imports from Austria, Finland, and Canada.

3.1.3. Combined GWI (modules A1–A4) estimates

Relative comparisons for combined GWI (A1–A4) estimates of sourcing MT from different sourcing locations are illustrated in Fig. 3. The estimated module A4 GWIs indicates that regionally sourced domestic MT has significant potential to reduce transportation-related GWI. However, this benefit is substantially offset by higher A1–A3 manufacturing emissions in the United States compared to Europe and Canada.

With Scenario 1, for instance, for Madison construction sites, domestic sourcing from Phoenix, IL reduces module A4 GWI by 91% compared to Austrian imports (Supplementary Fig. S5b; Table 1), yet the overall GWI across modules A1–A4 decreases by only 22% (Fig. 3). This result is attributed to the dominant influence of U.S. manufacturing emissions (module A1-A3) on total GWI.

Notably, for Boston, sourcing from Canada, Finland, and Austria yields lower A1-A4 GWI than domestic options, (e.g., Conway, AR) attributed to geographical proximity to Canada and Europe, coupled

Table 1
Estimated GWI (kg CO_2 eq per tonne) for module A1-A3 and transportation module A4 of sourcing MT from U.S. domestic and international manufacturing locations. Scenario 1 represents intermodal transport (road-maritime-rail-road), while Scenario 2 (road-maritime-road) represents road only transport for North American routes, reflecting variations in logistics from domestic and international sourcing.

MT sourcing sites	GWI (module A1-A3) kg CO_2 eq per tonne	Building construction sites in the U.S.							
		GWI (module A4) kg CO_2 eq per tonne							
		Seattle, WA, U.S.		Madison, WI, U.S.		Boston, MA, U.S.		Austin, TX, U.S.	
		Scenario 1	Scenario 2	Scenario 1	Scenario 2	Scenario 1	Scenario 2	Scenario 1	Scenario 2
Graz Styria, Austria	181.5	274	274	278	326	168	168	229	229
Kuhmo, Finland	179.0	222	222	225	274	116	116	176	176
Chibougamau, QC, Canada	133.8	-	-	169	186	103	113	277	374
South Slocan, BC, Canada	258.5	73	66	-	-	-	-	-	-
Columbia Falls, MT, U.S.	316.8	-	-	174	234	-	-	-	-
Phoenix, IL, U.S.	333.6	-	-	25	25	-	-	-	-
Dothan, AL, U.S.	268.3	-	-					100	134
Colville, WA, U.S.	307.6	42	42	-	-	-	-	-	-
Spokane, WA, U.S.	337	49	49	-	-	-	-	-	-
Conway, AR, U.S.	290	-	-	-	-	150	230	-	-
Lufkin, TX, U.S.[a]	333.6	-	-	-	-	-	-	40	40
Sidney, NY, U.S.[b]	250	-	-	-	-	47	47	-	-

[a] Phoenix, IL, U.S. (Source EPD, as the corresponding EPD is not available)
[b] North American Glulam. (Source EPD, as the corresponding EPD is not available)

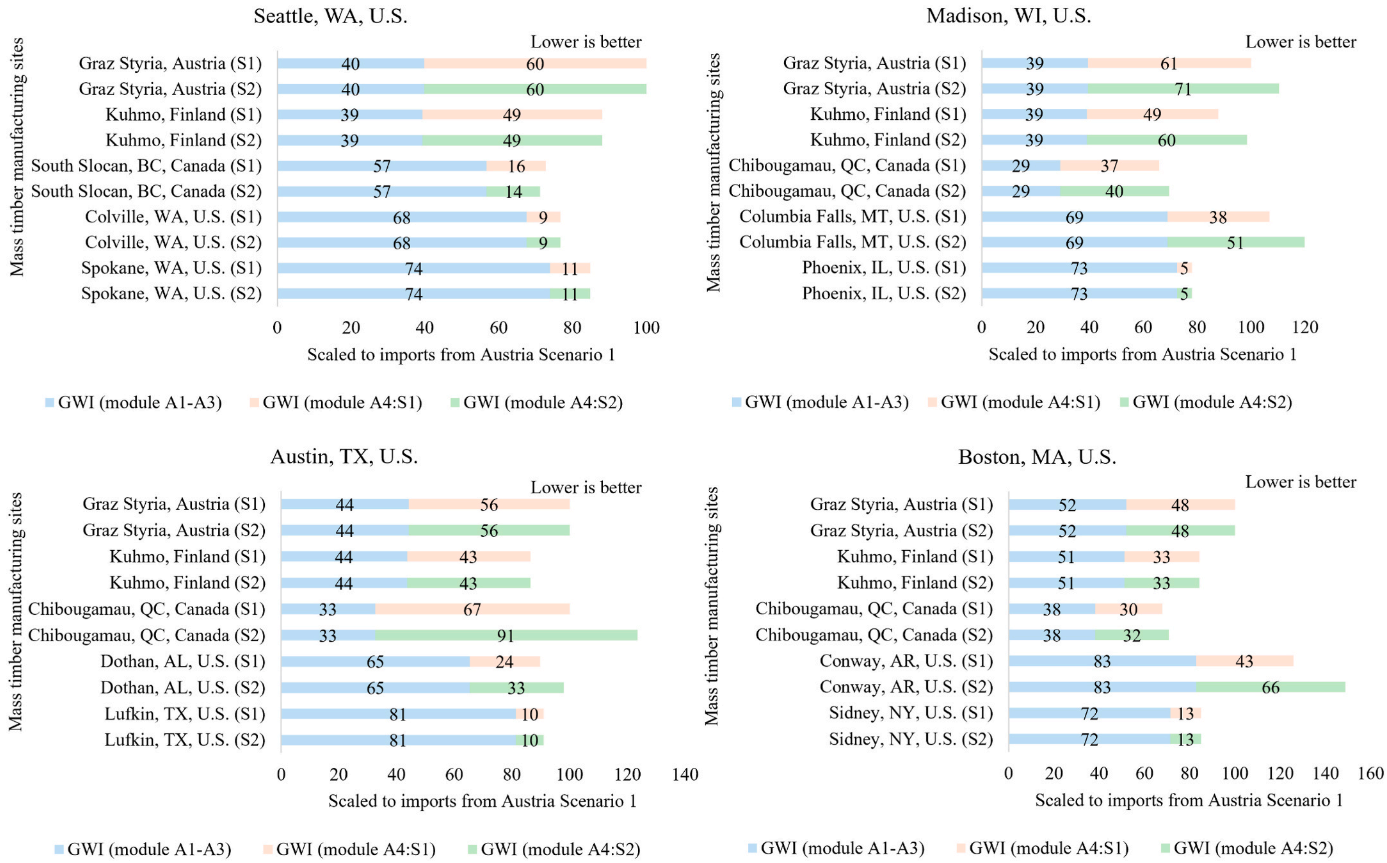

Fig. 3. Comparison of GWI for MT sourced from eight domestic (U.S.) and four international manufacturing sites in Canada, Austria, Finland to four MT construction destinations in U.S. (Seattle, WA; Madison, WI; Austin, TX; and Boston, MA). All values are normalized relative to imports from Austria Scenario 1 for consistent comparison across sourcing scenarios.

with efficient maritime transportation. In contrast, the other three locations: Seattle, Madison, and Austin exhibit lower GWI with most of the domestic sourcing options compared to imports from Canada, Finland, or Austria (Fig. 3, Table 1), reflecting the balance between regional manufacturing impacts and transportation efficiencies.

Analysis of sourcing MT using an all-road transportation scenario, as outlined in Scenario 2 of Tables 1–3, reveals a notable increase in transportation-related (module A4) GWIs, with emissions rising compared to intermodal routes (Table 1), due to higher per-kilometer emission factors. For example, when importing to Madison from Austria, transportation emissions account for 61% of the total within module A1–A4 under Scenario 1. This share increases to 71% in Scenario 2, as illustrated in Fig. 3 and summarized in Table 1.

3.1.4. GWI comparison with literature

In contrast to the narrower margins reported by Liang et al. (2021) (4.6%) and Puettmann et al. (2021) (4.7% to 11.7%), our estimated GWI ratio (A4/[A1+A2+A3+A4]) spans a significantly broader range of 7.0% to 73.7% due to the inclusion of diverse sourcing options from Finland, Austria, Canada, and various domestic U.S. sites.

Table 2
Estimated market price and transportation costs in U.S. dollars per tonne. Scenario 1 represents intermodal transport (road-maritime-rail-road), while Scenario 2 (road-maritime-road) represents road only transport for North American routes, reflecting variations in logistics from domestic and international sourcing.

MT sourcing sites	Market price index ($/tonne)	Building construction sites							
		Transportation cost ($/tonne)							
		Seattle, WA, U.S.		Madison, WI, U.S.		Boston, MA, U.S.		Austin, TX, U.S.	
		Scenario 1	Scenario 2	Scenario 1	Scenario 2	Scenario 1	Scenario 2	Scenario 1	Scenario 2
Graz Styria, Austria	3306	232	232	350	375	165	165	191	191
Kuhmo, Finland	3306	165	165	283	309	99	99	124	124
Chibougamau, QC, Canada	3306	-	-	267	253	158	155	462	497
South Slocan, BC, Canada	3306	125	91	-	-	-	-	-	-
Columbia, MT, U.S.	3060	-	-	309	317	-	-	-	-
Phoenix, IL, U.S.	3060	-	-	34	34	-	-	-	-
Dothan, AL, U.S.	3060	-	-					161	183
Colville, WA, U.S.	3060	58	58	-	-	-	-	-	-
Spokane, WA, U.S.	3060	68	68	-	-	-	-	-	-
Conway, AR, U.S.	3060	-	-	-	-	272	312	-	-
Lufkin, TX, U.S.	3060	-	-	-	-	-	-	54	54
Sidney, NY, U.S.	3060	-	-	-	-	63	63	-	-

Table 3
Estimated transportation times in days. Scenario 1 represents intermodal transport (road-maritime-rail-road), while Scenario 2 (road-maritime-road) represents road only transport for North American routes, reflecting variations in logistics from domestic and international sourcing.

MT sourcing sites	Building construction sites							
	Transportation time (days)							
	Seattle, WA, U.S.		Madison, WI, U.S.		Boston, MA, U.S.		Austin, TX, U.S.	
	Scenario 1	Scenario 2	Scenario 1	Scenario 2	Scenario 1	Scenario 2	Scenario 1	Scenario 2
Graz Styria, Austria	43.8	43.8	27.0	23.8	20.3	20.3	28.0	28.0
Kuhmo, Finland	46.3	46.3	29.4	26.2	22.7	22.7	30.4	30.4
Chibougamau, QC, Canada	-	-	8.8	5.4	6.7	4.1	13.7	8.8
South Slocan, BC, Canada	6.5	3.2	-	-	-	-	-	-
Columbia, MT, U.S.	-	-	10.9	6.3	-	-	-	-
Phoenix, IL, U.S.	-	-	2.4	2.4	-	-	-	-
Dothan, AL, U.S.	-	-					6.7	4.5
Colville, WA, U.S.	2.8	2.8	-	-	-	-	-	-
Spokane, WA, U.S.	2.9	2.9	-	-	-	-	-	-
Conway, AR, U.S.	-	-	-	-	10.4	6.2	-	-
Lufkin, TX, U.S.	-	-	-	-	-	-	2.7	2.7
Sidney, NY, U.S.	-	-	-	-	2.8	2.8	-	-

Additionally, our estimated GWI of 25 to 326 kg CO_2 eq/tonne aligns closely with the range of 24 to 285 kg CO_2 eq/tonne reported by Hemmati et al., (2022), validating the consistency of our intermodal transport modeling within the multi-criteria decision analysis framework. When expressed per square meter, our estimated module A4 GWI of 5.12 to 76.62 kg CO_2 eq^2 per square meter (m^2) of floor area is in range of lower to 2 times higher than estimates reported by (Kumar et al., 2024a) at 35.43 kg CO_2 eq/m^2. This variation is largely attributed to differences in various source regions considered in this study (domestic, and Canada, Austria, Finland) and the incorporation of intermodal transport systems (maritime, rail, road), which introduce diverse logistical factors. Notably, Kumar et al., 2024 included emissions from various building materials alongside MT, potentially diluting their MT-specific impact. Our estimated A4 GWI range of 5.12 to 76.62 kg CO_2 eq/m^2 is marginally wider to the values reported in the range of 3.4 to 47 kg CO_2 eq/m^2 reported by Liang et al., (2021), reflecting our emphasis on intermodal routes and longer distances.

3.2. Material and transport cost estimates

3.2.1. Estimated MT market prices

The estimated market prices for MT are presented in Supplementary Table S8, and Table 2 on a per-tonne basis and visually represented in Supplementary Fig. S4, and combined with transportation prices in Fig. 4, supporting the MCDA for sourcing MT to four construction destination cities from various domestic and international

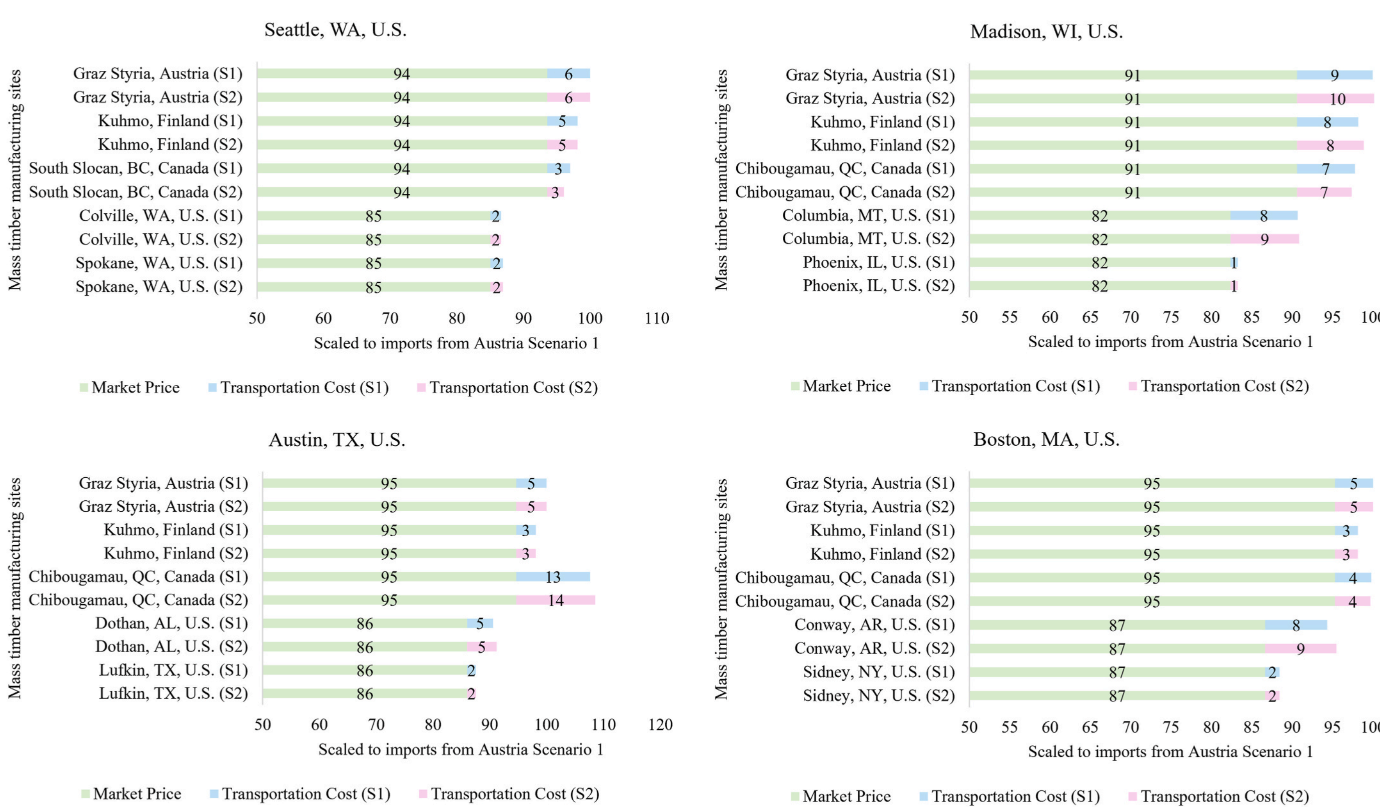

Fig. 4. Comparison of total costs (MT material price and transportation cost) for MT sourced from eight domestic (United States) and four international manufacturing sites in Canada, Austria, Finland to four MT construction destinations in U.S. (Seattle, WA; Madison, WI; Austin, TX; and Boston, MA). All values are normalized relative to imports from Austria Scenario 1 to ensure consistent comparison across sourcing scenarios.

manufacturing locations. These unit prices, derived from the 2025 Mass Timber Performance Index data [46], indicate that MT material costs in the United States are generally lower to those of European and Canadian counterparts (Supplementary Fig. S4). Domestic prices are lower because global manufacturers face an added 10% uniform tariff (Avalara, 2026).

3.2.2. Transportation cost estimates

Transportation cost results are detailed in Table 2 and shown along with market prices in Fig. 4. These costs, derived from intermodal transport modeling (maritime, rail, road) and adjusted for distances from domestic and international supply locations, indicate that most domestically sourced MT incurs lower costs than imports from Austria and Finland, as expected. For example, sourcing MT from Austria costs approximately $350 per tonne, while sourcing from Finland costs about $283 per tonne compared to only $34 per tonne when sourcing from Phoenix, IL for delivery to Madison, WI. Notably, sourcing from Canada is also more cost-effective than European options, primarily due to shorter transportation distances and more efficient logistics. For instance, sourcing from Chibougamau, QC costs around $267 per tonne, versus $350 from Austria and $283 from Finland for delivery to Madison, WI.

For scenarios with ground transportation entirely by road, transportation costs either increase or remain relatively stable, as shown for Scenario 2 in Table 2. These changes are primarily driven by higher fuel consumption and operational expenses. For example, when importing to Madison from Austria, the transportation cost rises from $350 per tonne to $375 per tonne; however, because this increase represents less than 1% of the total cost, it is not visible in Fig. 4. In contrast, when importing from Chibougamau, QC, Canada to Austin, TX, transportation costs increase from 13% in Scenario 1 to 14% in Scenario 2, as illustrated in Fig. 4 (Table 2).

3.2.3. Comparative results for total cost estimates

Total cost estimates, encompassing MT sales prices and costs associated with their transport, are presented in Fig. 4 and Table 2. The results reveal that domestically sourced MT generally exhibits lower total costs compared to imports from Austria and Finland, driven by reduced transportation expenses and competitive manufacturing prices. Similarly, sourcing from Canada emerges as more economical than European alternatives, benefiting from geographical proximity and optimized supply chains. These findings, evaluated for the four U.S. cities, reflect the cost advantages of regional and North American sourcing strategies.

3.3. Transportation time estimates

The estimated transportation times (Table 3, Fig. 5) highlight a clear advantage of using domestically produced MT over imports from international sources, unlike the trends observed for GWI and total cost. For instance, for Madison destination, Finland exhibits higher transportation times than Austria, primarily due to longer maritime distances (e.g., 8345 km from Oulu, Finland to Port of New York, U.S., versus 6704 km from Hamburg, Germany to Port of New York). Domestic sourcing benefits from shorter regional distances, reducing delivery times significantly. For instance, sourcing from Phoenix, IL to Madison reuires only 2.4 days, while sourcing from Austria to Madison requires 27 days in scenario 1.

In Scenario 2, transportation time is reduced, as shown in Table 3, by eliminating layovers except for port transfers during imports from Austria and Finland, thereby enhancing delivery efficiency. For example, when importing from Austria, transportation time decreases by 12%, dropping from 100% in Scenario 1 to 88% in Scenario 2, as shown in Fig. 5.

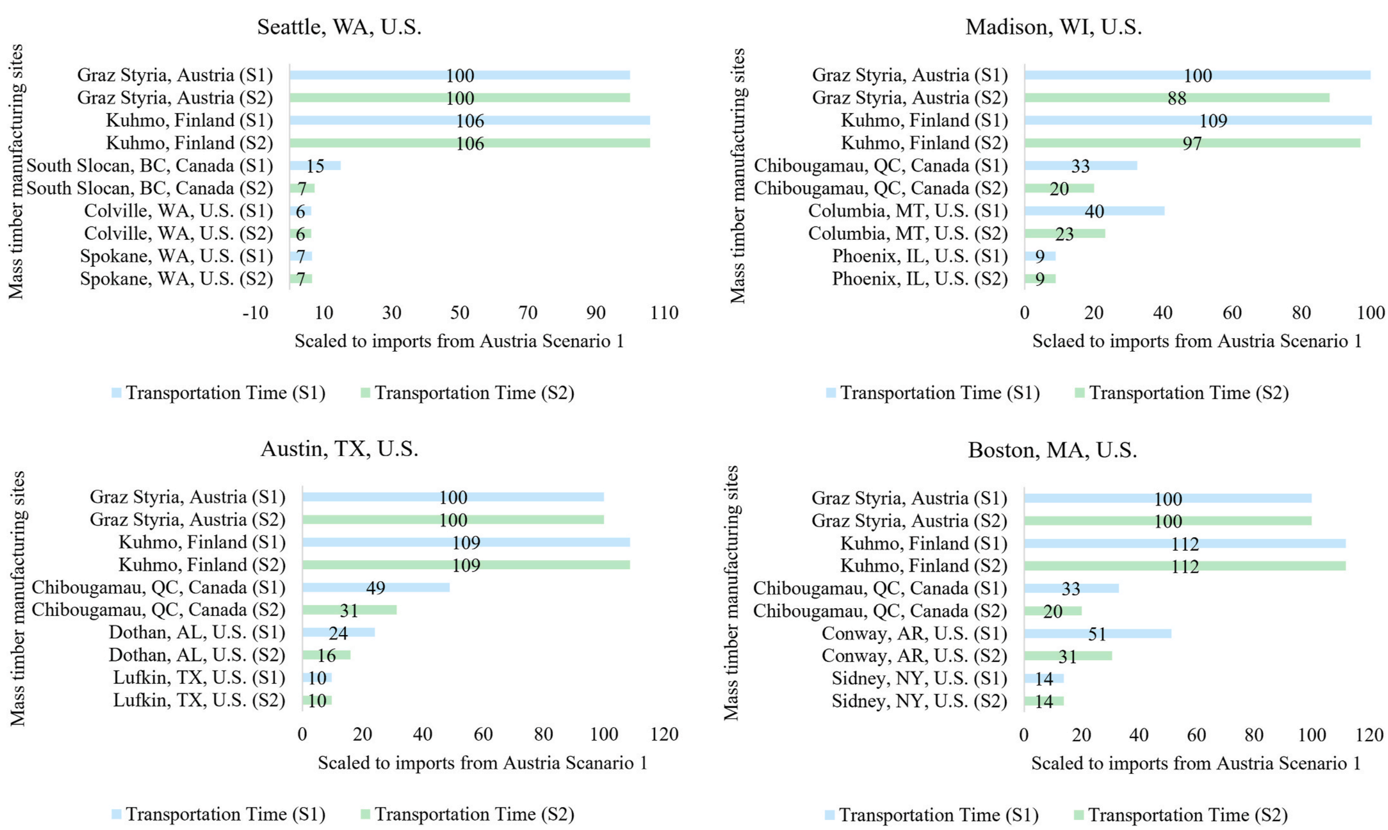

Fig. 5. Comparison of transportation time for MT sourced from eight domestic (U.S.) and four international manufacturing sites in Canada, Austria, Finland to four MT construction destinations in U.S. (Seattle, WA; Madison, WI; Austin, TX; and Boston, MA). All values are normalized relative to imports from Austria Scenario 1 to ensure consistent comparison across sourcing scenarios.

3.4. Multi criteria decision analysis

The weighted sum model for MCDA assigned a 50% weight to GWI, a 40% weight to total cost (includes selling price and transportation costs), and a 10% weight to transportation time, reflecting their relative importance in MT sourcing decisions. The relative MCDA results are presented in Fig. 6. Sourcing from the Canadian sites generally yields lower MCDA values (lower GWI, cost, and delivery time) for Boston due to the proximity to the Canadian border, whereas for Madison, Seattle and Austin, domestic options perform better because of their closer proximity to U.S.-based MT manufacturing facilities. Overall, domestically produced MT materials show lower MCDA scores compared to European counterparts (Austria and Finland), driven by reduced transportation times and costs, enhancing their sustainability and economic viability.

3.5. Results of the sensitivity analysis based on variations in GWI and cost

The probabilistic sensitivity analysis evaluated three extreme weighting cases to assess the impact of a ± 40% variation in A1-A3 GWI and ± 25% variation in total costs and times. Case 1 emphasized environmental impact (70% GWI, 20% cost, 10% time); Case 2 emphasized total cost (70% cost, 20% GWI, 10% time); and Case 3 emphasized transportation time (70% time, 15% cost, 15% GWI). All supply locations were evaluated holistically with transportation variability incorporated through the full set of feasible routes rather than isolating Scenario 1 or Scenario 2.

Under Case 1 (GWI emphasis), Canadian imports ranked highest, except for of shipments to Austin, TX (Fig. 7). Under Case 2 (cost emphasis), domestic manufacturers consistently performed best (Fig. 8). Under Case 3 (time emphasis), domestic suppliers showed the highest rank stability and emerged as the optimal sourcing option.

The Monte Carlo simulation shows that the probability of achieving the optimal (lowest) MCDA score is distributed across multiple candidate locations in Cases 1 and 2, reflecting underlying parametric uncertainty. For instance, when shipping to Seattle, WA under the GWI-prioritized weighting (Case 1), South Slocan, BC, Canada holds the highest probability of being optimal (43.9%), closely followed by Colville, WA (38.4%), with the remaining locations capturing diminishing probabilities (Fig. 7). Under the cost-prioritized weighting (Case 2) for Seattle, WA, Colville, WA shifts to the most favorable position with a 44.0% probability of achieving the optimal score, followed by Spokane, WA (33.9%) and South Slocan, BC (15.8%) (Fig. 8).

This pattern of distributed optimality probabilities across top-ranking sites remains consistent across all evaluated destinations for both the GWI and cost prioritizations.

In contrast, the time-prioritized weighting (Case 3) often exhibits a highly concentrated probability distribution among candidate sites. For example, for Seattle, WA, Colville, WA retains the most favorable position with a 52.9% probability of achieving the optimal score, followed by Spokane, WA (29.1%) and South Slocan, BC (18.0%) (Fig. 9). For Madison, WI, Phoenix, IL achieves a dominant 96.4% probability of optimality, followed by a mere 3.6% for Chibougamau, QC, Canada, while all other candidate locations register a zero probability (Fig. 9).

3.6. Limitations and future research

While the study mitigated the limitations of deterministic point estimates by integrating Monte Carlo-based stochastic approach into the MCDA framework to better capture variations in regional manufacturing processes, logistical variability, and cost difference, other important limitations remain. For instance, the system boundary of this study excluded biogenic carbon storage and end-of-life (EoL) treatment scenarios (e.g., potential emission credits or burdens from recycling, landfill decay, or energy recovery). However, because this analysis evaluates comparative sourcing strategies within the MT category, rather than benchmarking against alternative structural materials (e.g., reinforced concrete or structural steel), this exclusion of EoL scenarios does not alter the fundamental logistical rankings. The biogenic carbon sequestered within the wood and the eventual EoL scenario for the

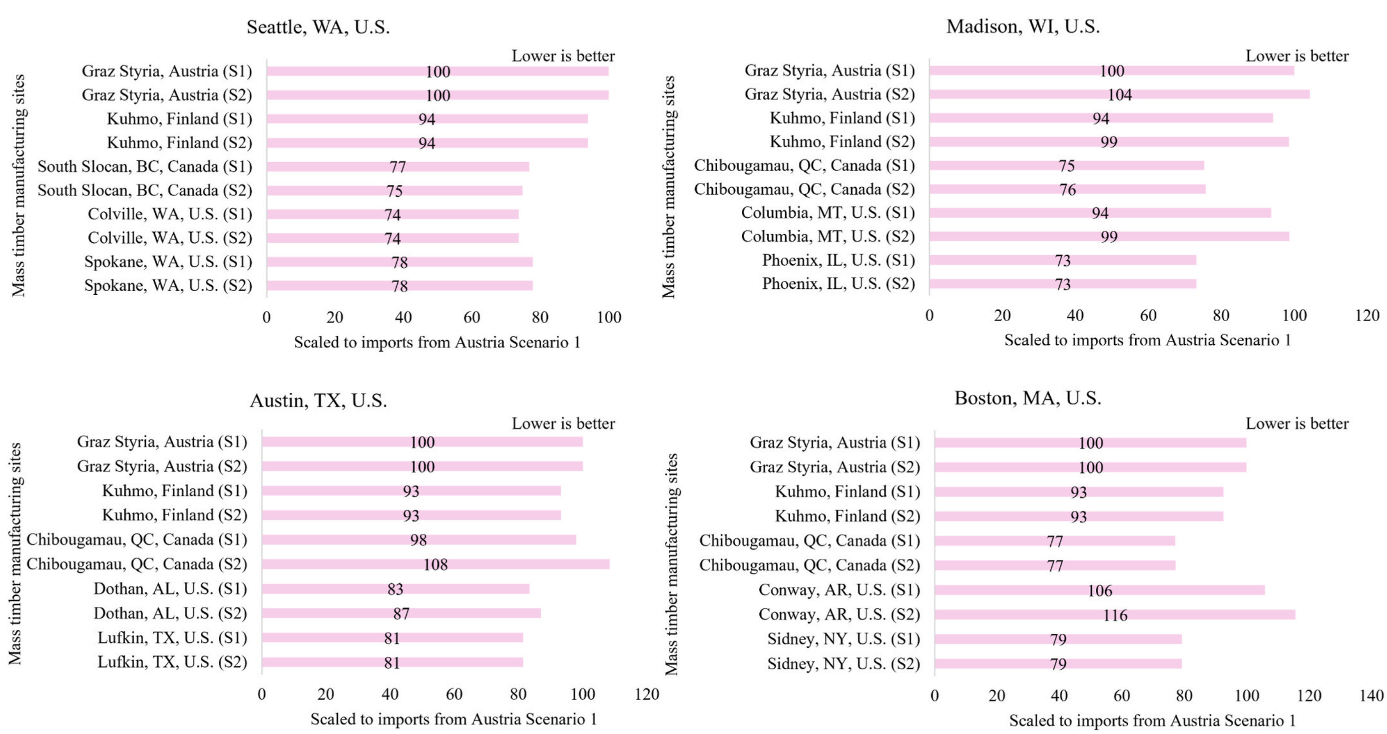

Fig. 6. Comparison of multi-criteria decision analysis scores. (weighted 50% GWI, 40% Total cost, 10% transportation time) for MT sourced from eight domestic (U.S.) and four international manufacturing sites in Canada, Austria, Finland to four MT construction destinations in U.S. (Seattle, WA; Madison, WI; Austin, TX; and Boston, MA). All values are normalized relative to imports from Austria Scenario 1 to ensure consistent comparison across sourcing scenarios.

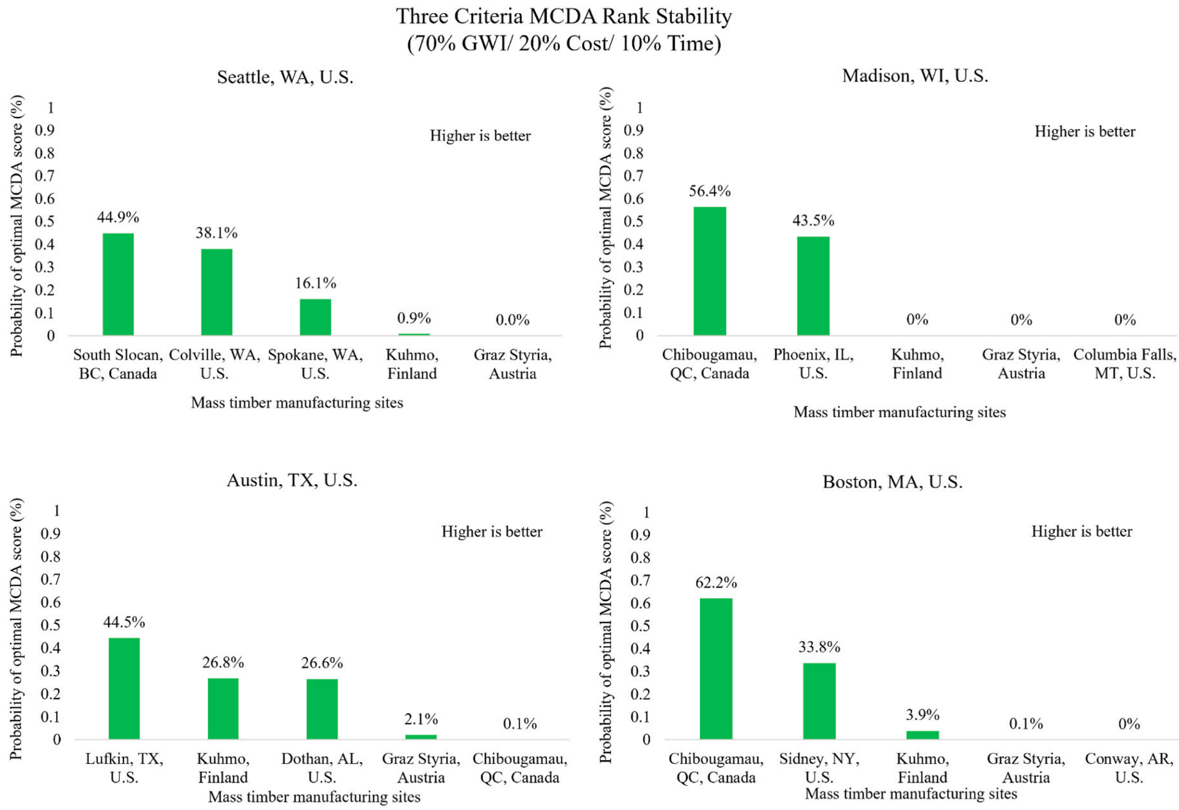

Fig. 7. Probability of achieving optimal MCDA scores for MT suppliers under a GWI-prioritized scenario (70% GWI, 20% Cost, 10% Time). Panels illustrate rank stability for four U.S. cities based on a 10,000-iteration Monte Carlo simulation under parametric uncertainty.

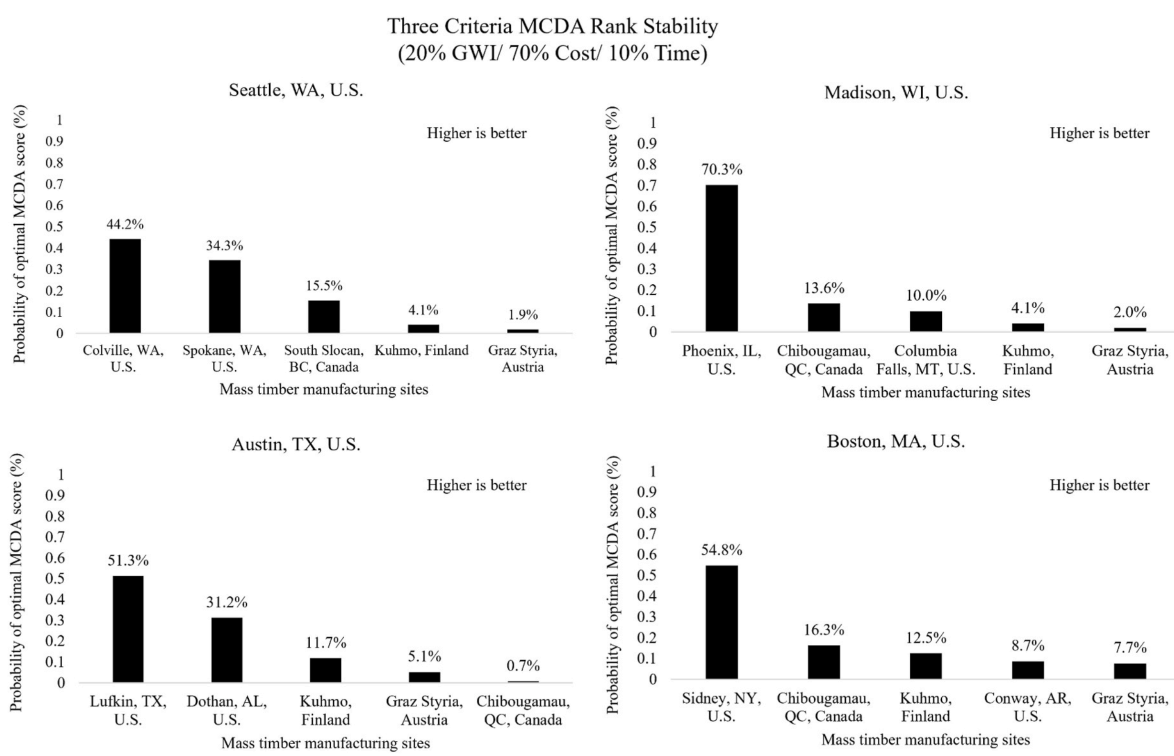

Fig. 8. Probability of achieving optimal MCDA scores for MT suppliers under a Cost-prioritized scenario (20% GWI, 70% Cost, 10% Time). Panels illustrate rank stability for four U.S. cities based on a 10,000-iteration Monte Carlo simulation under parametric uncertainty.

building would be similar across evaluated cases regardless of where the MT was originally manufactured, effectively canceling out in a comparative logistical model. However, in the context of comprehensive WBLCA, quantifying the net benefits of biogenic carbon storage and EoL

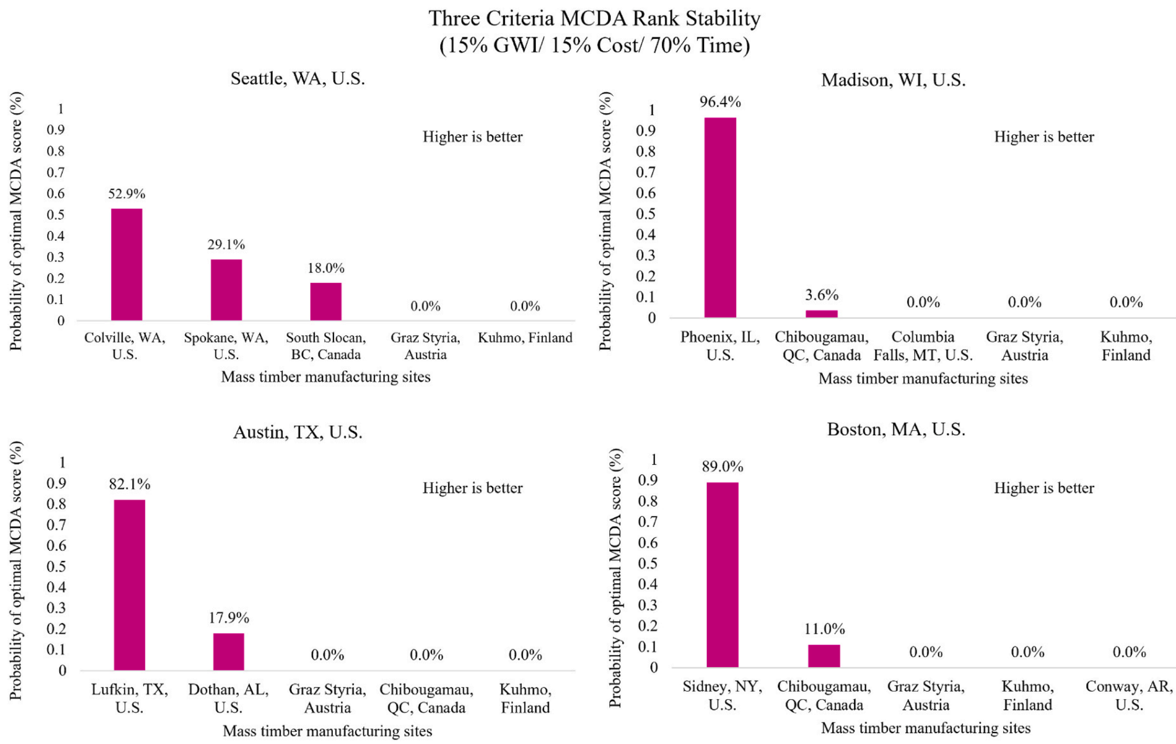

Fig. 9. Probability of achieving optimal MCDA scores for MT suppliers under a time-prioritized scenario (15% GWI, 15% Cost, 70% Time). Panels illustrate rank stability for four U.S. cities based on a 10,000-iteration Monte Carlo simulation under parametric uncertainty.

credits remain essential.

Additionally, current transportation time estimates rely on fixed modal speeds and a uniform 24-h intermodal layover. While this constant layover effectively buffers against minor scheduling variability, it may not adequately capture severe real-time disruptions such as port congestion, rail scheduling delays, or extreme weather events that fall outside the scope of the current logistical model. Furthermore, while the density-based pricing approach broadly accounts for volumetric variations across different MT products (e.g., cross-laminated timber versus glue-laminated timber), the use of generalized rather than facility-specific density metrics presents an area for further refinement.

Finally, while the selection of four U.S. cities (Seattle, Madison, Austin, and Boston) provides a diverse cross-section of regional logistics, these specific case study results represent a snapshot of current market conditions and cannot be universally generalized to all regions, particularly those lacking equivalent transportation infrastructure. However, the primary contribution of this study, the weighted sum MCDA framework with deterministic baseline with stochastic MC sensitivity analysis is inherently adaptable. Future researchers and industry practitioners can readily apply this customizable model to other regions by integrating localized supply chain data, thereby evaluating distinct market conditions and expanding the geographical scope of MT optimization.

4. Conclusions

This study offers an integrated assessment of upfront life-cycle environmental impacts, material and transport costs, and transportation times associated with MT delivery across four U.S. cities (Seattle, WA; Madison, WI; Austin, TX; and Boston, MA). The research evaluates multi-modal sourcing strategies from eight domestic and four international MT production sites by integrating LCA (Modules A1-A4) and cost analysis within a MCDA framework with deterministic baseline and probabilistic Monte Carlo sensitivity analysis.

The results reveal that optimal sourcing strategies are highly dependent on stakeholder value systems. When evaluating supply chains under a weighting scenario that prioritizes environmental impacts (70% GWI), Canadian imports frequently achieve the highest probability of rank optimality due to cleaner grid energy and manufacturing efficiencies (Modules A1-A3). Conversely, when prioritizing economic expenditures or delivery schedules, domestic U.S. manufacturing consistently emerges as the optimal choice, offsetting higher manufacturing emissions with significantly reduced transportation burdens (Module A4) and geographical proximity. Across all scenarios, the results demonstrate that geographic proximity alone does not universally guarantee the most sustainable outcome, highlighting the complex tension between manufacturing efficiency and logistical emissions.

While the optimal sourcing selections for these four specific cities represent a snapshot of localized, current market conditions, they suggest broader implications for the industry. Specifically, these findings indicate that establishing a more regionally distributed MT manufacturing network in the U.S., coupled with ongoing investments in cleaner grid infrastructure, is necessary for domestic suppliers to outcompete international alternatives on strict environmental metrics.

Ultimately, the primary contribution of this study is the adaptable MCDA framework that integrates deterministic baseline estimates with stochastic Monte Carlo sensitivity analysis to estimate the probability of rank stability. By moving beyond traditional static point estimates that are vulnerable to data ambiguity, this approach offers industry practitioners, architects, and policymakers with a highly robust decision-support tool. By addressing uncertainty, the probabilistic approach recognizes fluctuation in values and mitigation selection bias, by reporting several suitable sources.

Future research may apply this customizable model/framework to other global regions using localized, facility-specific data and expand the scope to model severe, real-time infrastructure disruptions. The methodology developed in this study provides an adaptable, data-driven framework essential for optimizing sustainable supply chains where logistics, economics, and embodied carbon are critical, competing drivers of sustainability.

CRediT authorship contribution statement

Vaibhav Kumar: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Resources, Software, Validation, Visualization, Writing – original draft. **Marco Lo Ricco:** Formal analysis, Investigation, Supervision, Validation, Visualization, Writing – review & editing. **Prakash Nepal:** Conceptualization, Formal analysis, Funding acquisition, Investigation, Project administration, Resources, Supervision, Validation, Visualization, Writing – review & editing. **Poonam Khatri:** Validation, Writing – review & editing. **Richard D. Bergman:** Investigation, Project administration, Resources, Supervision, Writing – review & editing. **Neelam C. Poudyal:** Funding acquisition, Project administration, Resources, Supervision, Writing – review & editing.

Declaration of generative AI in scientific writing

During the preparation of this manuscript, the authors used ChatGPT/Grok/Copilot/Gemini Pro to improve readability and language clarity. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

Declaration of competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Abbreviations

BC	British Columbia
CLT	Cross Laminated Timber
CO_2eq	Carbon Dioxide Equivalent
EoL	End-of-Life
EPD	Environmental Product Declaration
Glulam	Glue Laminated Timber
GWI	Global Warming Impacts
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
LVL	Laminated Veneer Lumber
MA	Massachusetts
MCDA	Multi Criteria Decision Analysis
MT	Mass Timber
QC	Quebec
TX	Texas
U.S.	United States
UNEP	United Nations Environment Programme
WA	Washington
WBLCA	Whole Building Lifecycle Assessment/Analysis
WI	Wisconsin
WSM	Weighted Sum Model/Method

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2026.149188.

Data availability

Data will be made available on request.

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