

Identifying Optimal Locations for Hardwood CLT Plants in Tennessee: Application of a Spatially Explicit Framework

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Abstract

The prospect of using mass timber products, such as cross-laminated timber (CLT), for building material has increased in recent years because of the advantage of these products over their substitutes in terms of structural rigidity, cost efficiency, and climate benefits. However, the American National Standard developed for CLT currently applies to softwood only. With the expected increase in the market for CLT, the supply chain needs to address the projected rise in demand for hardwood as well. Promoting the production of hardwood mass timber like CLT requires studying the feasibility of quality hardwood lumber supply and identifying the optimal locations for investing capital in CLT manufacturing plants. By presenting a case from Tennessee, this study provides a spatially explicit framework to use a variety of factors such as transportation networks, proximity to sawmills, sawmill capacity, and roundwood supply to identify optimal CLT plant locations. Specifically, fuzzy multicriteria analysis was used to identify potential locations, which provided inputs for a location-allocation model to identify optimal locations for CLT plants. Among the several potential locations, three optimal locations suitable for CLT plants were identified with 12,504 thousand cubic feet (MCF) annual production potential of CLT panels in Tennessee. Although increasing transportation distance for lumber procurement would increase CLT production capacity, it would also result in increased lumber supply costs. Potential investors and regional planners interested in using hardwood forest products can benefit from these findings to locate suitable sites for new investment.

Mass timber products are a class of engineered wood products manufactured by combining wood's inherent strength with modern engineering (Atkins et al. 2022). Manufacturing of mass timber products involves gluing or fastening small pieces of wood together. As a result, the product is significantly stronger than a solid wood product of the same dimensions. Cross-laminated timber (CLT) is the most common type of mass timber product. CLT manufacturing and design specifications for producers and users are outlined in "Standard for Performance-Rated Cross-Laminated Timber (ANSI/APA PRG 320)" prepared by APA—The Engineered Wood Association (ANSI/APA 2020). ANSI/APA (2020) defines CLT as "a prefabricated engineered wood product made of at least three orthogonal layers of graded sawn lumber or structural composite lumber that are laminated by gluing with structural adhesives." However, the current standard considers only

softwood species for CLT manufacturing, not hardwood species.

Compared with other mass timber products, the number of projects using CLT panels increased continuously in the United States between 2012 and 2021 (Atkins et al. 2022).

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As of September 2022, WoodWorks (2022) recorded 1,571 mass timber projects in United States that were either constructed or at the design phase, with more than half of them using CLT panels. In 2021 alone, mass timber projects totaled 5.7 million square feet of construction and CLT accounted for 71 percent of total constructed square footage (Atkins et al. 2022). One of the drivers of growing CLT use is the building code known as “Tall Wood Provisions” included in the 2021 International Building Code—Construction Type IV, which contains provisions for the use of mass timber as a primary structural material in buildings of up to 18 stories (Gale et al. 2019, Atkins et al. 2022).

One of the factors driving growing mass timber demand in the United States and Canada has been a perceived climate mitigation benefit of using relatively lower-carbon footprint mass timber products in buildings, instead of higher-carbon footprint nonwood materials (Puettmann et al. 2017, Chen et al. 2019, Anderson et al. 2020, Lan et al. 2020). Using mass timber products as building materials not only stores carbon for a longer period in harvested wood products, but also avoids emissions by substituting higher-carbon-emitting nonwood materials. Other benefits of mass timber products include the requirement of a small workforce during construction, aesthetic appeal, and prefabricated characteristics of timber panels (Ahmed and Arocho 2021). Besides these cobenefits, mass timber products also reduce building construction and development costs and generate larger economic impacts than traditional concrete and steel frame construction (Scouse et al. 2020).

Currently, there are 15 mass timber manufacturing facilities operating in North America, including 9 facilities in the United States. These 15 facilities are reported to have practical production capacity of 36.73 million cubic feet (1.04 million m³) per year (Atkins et al. 2022). However, an average of roughly 10.59 million cubic feet (0.30 million m³) of mass timber products were used in building construction each year during 2019 through 2021 in North America (Atkins et al. 2022). As reported by the Softwood Lumber Board (2020), lumber demand associated with mass timber in the United States could reach about 1 billion board feet (2.36 million m³) per year by 2025 and could grow to nearly 5 billion board feet (11.80 million m³) per year by 2035. Similarly, Nepal et al. (2021) provided an estimate of the projected demand for mass timber in 12 selected countries in Asia, Europe, North America, and South America under three contrasting demand scenarios. They projected that the United States would consume more than 9 million m³ of combined CLT and glulam demand by 2060 (equivalent to 11.25 million m³ of softwood lumber) under their extreme demand scenarios. Because of growing demand for mass timber products, softwood timber harvest rate could increase from a current 66 percent to 82 percent of accessible forest growth by 2035 (Comnick et al. 2022). Increased harvesting needed to meet rising mass timber demand has raised concerns about sustainability of softwood timber supply in the United States, as there is growing demand on forests to supply various goods and services such as wildlife habitat, recreation, flood control, and freshwater.

In the eastern United States, hardwoods comprise up to 68 percent of total timberland growing stocks (Oswalt et al. 2019). Use of hardwood fiber for manufacturing of mass timber products has a potential to improve hardwood forests' health, which are under increasing threats from disturbances such as invasive insects, diseases, and

wildfires. For example, in 2019, emerald ash borer was detected in 1.3 million acres of forest lands across the conterminous United States, threatening millions of ash trees (Potter and Conkling 2021). Similarly, studies conducted in Louisiana and Texas indicated that emerald ash borer infestations could remove a substantial quantity of ash tree growing stock and affect regional economy (McConnell et al. 2019, Vanderschaaf et al. 2021). Reducing the loss of timber in these diseased forests from those threats requires large-scale tree removal as preventive measures or salvage operations. In this context, finding value-added uses is critically important not only for disturbance-affected but also other underused or low-value hardwoods (Espinoza and Buehlmann 2018). Thus, mass timber products can provide value-added uses for the nation's vast hardwood resources and contribute to forest health.

Furthermore, hardwood mass timber production could serve as an engine of economic development in distressed regions, especially if required raw materials are sourced from regionally grown forests (Scouse et al. 2020). Recent changes in market demand for traditional forest products including pulp and paper, particularly due to shifting consumer demand from paper-based communication (e.g., mailing, print newspaper) to electronic systems (e.g., online billing, banking), has led to the closure of several pulp and paper mills throughout the nation (Brandeis and Guo 2016). This has resulted in loss of jobs for mill workers and others along the supply chain (e.g., truckers, loggers). In addition, the forest landowners that supplied wood fiber to those mills have reduced markets for their woods. For example, International Paper permanently closed its Courtland Mill in northern Alabama, which used substantial amounts of hardwood fiber from Tennessee (Poudyal et al. 2017). There is a need for investment in new wood product markets to use hardwood fiber and perhaps create job opportunities for a trained local workforce. Assessing the feasibility and establishing hardwood CLT plants may be one of the many options to revitalize the rural economy affected by a declining market for traditional forest products.

The objective of this study is to identify optimal locations for hardwood CLT plants in Tennessee and evaluate CLT production potential on the basis of the existing capacity of sawmills. In addition to identifying optimal locations for establishing hardwood CLT manufacturing facilities in Tennessee, this study examines how changes in transportation distance for lumber procurement affect the delivery cost of hardwood lumber (i.e., lumber supply cost). Whereas existing studies are mostly related to the technical feasibility of hardwood for CLT panels, few studies have analyzed hardwood CLT production potentials and associated lumber supply costs (Ehrhart and Brandner 2018, Espinoza and Buehlmann 2018, Crovella et al. 2019).

Previous studies of facility location problems

Location is considered a most important factor in helping the long-term success of a business. Past studies on location analysis of forest business used objective function approaches that maximize revenues, profits, and coverage or minimize costs to address such facility location problems and identified single or multiple locations (Zhang et al. 2011, Kühle et al. 2019, Jayarathna et al. 2020). On the basis of the source of raw materials, forest industries can be classified into two broad categories, primary forest product

manufacturers and secondary forest product manufacturers. Primary forest product manufacturers produce lumber, veneer, pulp, biofuel, and biomass energy by directly using sawlogs, pulpwood, and forest wastes (Aguilar and Vlosky 2006, Hagadone and Grala 2012). Secondary forest products manufacturers produce final products such as paper, paperboard, wood-based panels, engineered composites, and furniture by using forest products obtained from primary manufacturers (Aguilar and Vlosky 2006; Hagadone and Grala 2012). Thus, the category of forest industries (primary or secondary) may have implications for a business selecting facility locations.

Zhang et al. (2011) adopted a geographic information system (GIS)-based two-stage approach to identify the optimal location for a biofuel production facility in the Upper Peninsula of Michigan. In the first stage, they identified the potential facility locations for biofuel production from forest biomass by considering different relevant factors including road and rail networks, workforce availability, and pulpwood production. In the second stage, they computed the total transportation cost for each facility by considering the Euclidian distance between the biofuel facility and pulpwood production points. Nearest pulpwood production points were assigned to a biofuel facility until a fixed amount (700,000 tons) of pulpwood was available for that potential facility. The biofuel production facility that had the lowest total transportation cost among candidate locations was selected as the optimal location. Total transportation cost was associated with several factors such as transportation distance, fuel price, and pulpwood availability. Jayarathna et al. (2020) also used a similar GIS-based framework to identify the optimal location and size of biomass energy plants from sugarcane and forest waste materials in Australia. Without considering capacitated (fixed-capacity) biomass energy plants, the authors chose the optimal locations from a set of candidate locations on the basis of transportation distance and spatial biomass availability. Those studies reaffirm the assumption that the optimal locations of primary forest product manufacturers such as biofuel production facilities and bioenergy plants are affected by transportation distance and availability of raw materials in each supply point.

By minimizing the total supply cost of the entire supply network in a mixed-integer linear programming model, Kühle et al. (2019) identified optimal locations for laminated beech production facilities in Austria. Laminated beech is a secondary forest product manufactured by using sawmill-supplied lamellas. The supply costs included transportation costs (forests to sawmills, sawmills to facilities, facilities to customers), investment costs, production costs, and storage costs. The key assumptions of this model were fixed capacities (capacitated facility) of laminated beech production facilities, multiperiod production, and deterministic or fixed demand for laminated beech products. Candidate locations were selected from each Austrian state where land price was lowest. Thus, candidate selection criteria for laminated beech production were more generic and sensitive to land values.

In the southern United States, forest industries are widely distributed because of a large proportion of timberlands¹ available for timber harvests and the existence of highly populated areas. For instance, in Louisiana, primary forest product manufacturers were located near raw materials, whereas secondary forest product manufacturers were

concentrated near major populated areas (Aguilar and Vlosky 2006). Another location analysis of existing sawmills in the southern United States found that counties with cost advantages, labor availability, and road access were the main factors affecting lumber industry location (Aguilar 2009). Similarly, in Mississippi, harvested volume of sawlogs at the county level had a positive effect on the location of primary forest product manufacturers (Hagadone and Grala 2012), whereas the number of primary forest product manufacturers in a county, proximity to railways, and available labor force had a positive effect on locations of secondary forest product manufacturers (Hagadone and Grala 2012). Thus, raw materials, market, labor availability, and transportation facilities were important factors for both types of forest industries (primary and secondary forest product manufacturers) while selecting their business locations.

Aguilar (2009) adopted the utility maximization approach to predict location of sawmills at a county level, rather than specifying point locations. In addition, he did not consider sawmill size and type for the regression analysis. Thus, Aguilar's work was basically limited to identifying suitable factors that affect the locations of the lumber industry from the perspective of businesspeople. Likewise, Hagadone and Grala (2012) followed a Poisson regression approach to predict the locations for primary and secondary forest manufacturers at the county level. Like Aguilar (2009), they also identified several important factors to address facility location problems, but neither of these studies considered sawmill size and type nor determined optimal locations for forest product manufacturers.

The review of past studies described above demonstrated that an integrated approach that considers both mathematical modeling and GIS-based operation can be a suitable approach to identify the optimal location for secondary forest product manufacturers like CLT manufacturing facilities. Likewise, the above reviews also indicated that several factors, such as transportation distance for lumber procurement, availability of raw materials, accessibility of markets, and labor force, would need to be considered while solving the CLT facility location problem. Our approach to identifying suitable locations for hardwood lumber CLT manufacturing plants is thus based on the strong mathematical and GIS-based foundation provided by the related past studies that identified optimal mill locations for biofuel production facilities, bioenergy plants, and laminated beech production facilities.

Study area

This study was conducted in the State of Tennessee. According to Tennessee Division of Forestry estimates (2020), Tennessee has almost 14 million acres of forestland, of which hardwood forests represent 89 percent. Likewise, Tennessee's timberland covers approximately 13 million acres. Tennessee and nearby states have abundant standing timber inventory on timberland that is available for harvest given market demand for wood products. In Tennessee, hardwood timberland amounts to over 14.9 billion cubic feet of total growing stock, of which only 187.3 million cubic feet (1.3%) are harvested annually. Thus, available growing stocks are large enough to meet future demand for CLT manufactured from hardwood lumber. For our analysis of the optimal locations for CLT plants, we considered only yellow poplar (*Liriodendron tulipifera* L.), red maple (*Acer*

rubrum L.), white ash (*Fraxinus americana* L.), and American beech (*Fagus grandifolia* Ehrh.) on the basis of past research works, which indicated that these four hardwood species had suitable wood properties required for CLT panels (Ehrhart and Brandner 2018, Espinoza and Buehlmann 2018, Crovella et al. 2019). According to Forest Inventory and Analysis (FIA) data (USDA Forest Service 2022a), these preferred species comprise nearly 3.7 billion cubic feet of Tennessee's total growing stock, with current annual removals of 45 million cubic feet (1.2%).

In this study, only the sawmills that procured hardwood sawlogs from Tennessee and produce lumber or other sawn products that are useful for mass timber production are considered (USDA Forest Service 2022b). In total, the study included 268 hardwood sawmills, with 235 of them located in Tennessee and 33 in nearby states (Fig. 1). Among these sawmills, 66 produce both hardwood and softwood, whereas 202 produced only hardwood sawn products. In terms of mill capacity, 180 sawmills (67%) have sawlog consumption capacity of less than 500 thousand cubic feet (MCF), 37 sawmills (14%) had consumed between 500 to 999.99 MCF, and 51 sawmills (19%) had a consumption of 1,000 MCF or more (Fig. 1). In total, these sawmills used 160.84 million cubic feet of hardwood sawlogs in 2017.

Method

The spatial modeling to determine the optimal locations of CLT plants was conducted in a GIS-based environment and the data required for the modeling were collected from various sources (Table 1). All potential sites for CLT plants were identified by performing exclusion and preference

analyses, whereas optimal sites were identified using location-allocation analysis (Fig. 2). The following sections describe data sources and methods used for the specific spatial analysis in detail.

Exclusion analysis

We used three criteria for exclusion analysis: land cover type, slope, and urban areas, and generated a separate normalized raster layer for each criterion, assigning values of 1 (suitable) and 0 (unsuitable). For the land-cover criterion, potential CLT facilities were excluded from forests, wetlands, or built-up areas (assigned value = 0). From the land-cover perspective, the suitable sites (value = 1) were on land covered by pasture/hay or cultivated crops and other sites. Similarly, for the slope criterion, potential CLT sites were excluded from land that has more than a 10 percent slope, as gentle grades help minimize the costs of facility construction (Mildner et al. 2020). Finally, potential CLT sites were planned to be located within 5 miles of an urbanized area or urban cluster because of better availability of utilities and other infrastructural resources such as electricity, water, communication, banking, and health centers (Chen et al. 2019). Combining the three criteria layers by multiplying them generated the final raster layer indicating site suitability for a CLT plant.

Land-cover data were collected from the National Land Cover Database 2019 created by Multi-Resolution Land Characteristics Consortium (Dewitz and US Geological Survey 2021). Land slope criterion was computed by using the digital elevation model data (US Geological Survey 2022a) on ArcGIS Pro's spatial analyst tool (ESRI 2022).

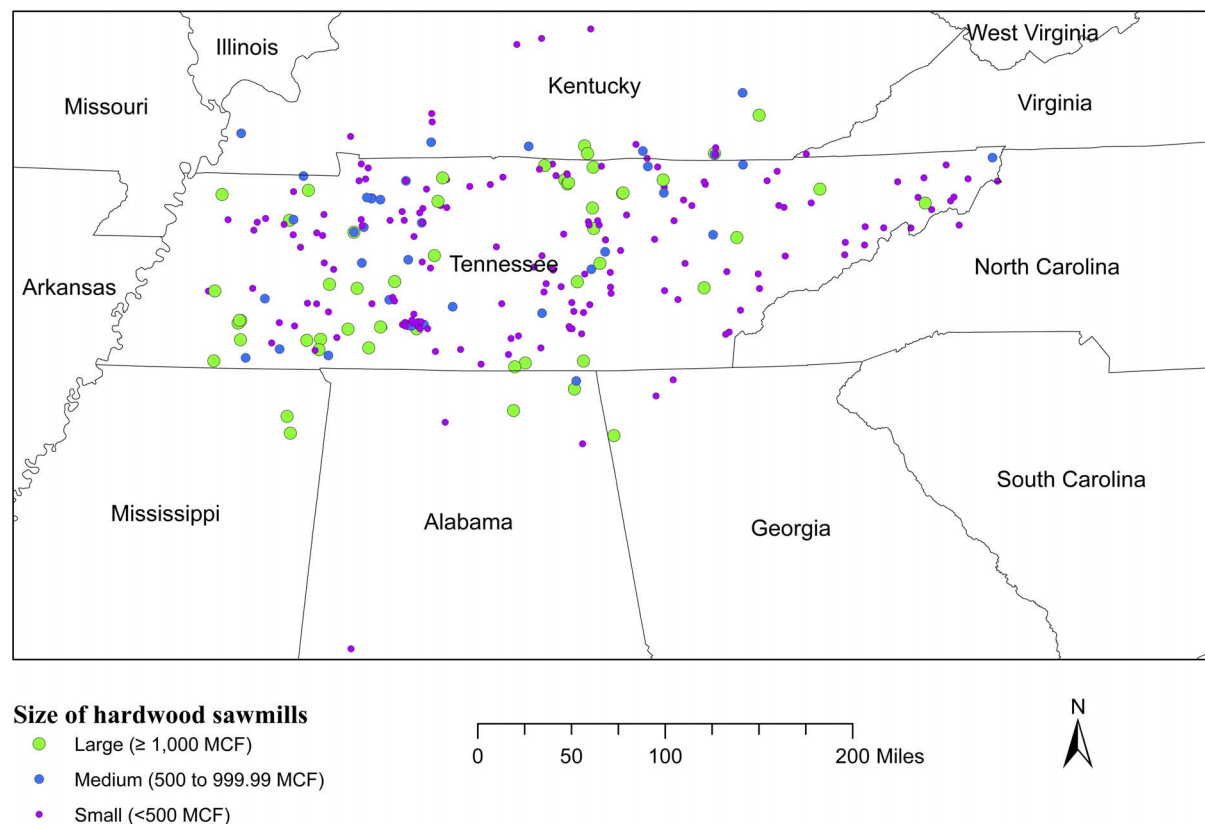


Figure 1.—Location of hardwood sawmills in Tennessee and nearby states (n = 268).

Table 1.—Description of data sets used in determining optimal sites for hardwood cross-laminated timber (CLT) plant in Tennessee.

Data set	Data source	Data type	Data purpose
Land cover	National Land Cover Database 2019 (Dewitz and US Geological Survey 2021)	Raster layer	Exclude forests, water bodies, and built-up areas from potential CLT sites
Digital elevation model	US Geological Survey (U.S. Geological Survey 2022a)	Raster layer	Determine slope of potential locations
Urbanized areas and urban clusters	US Census Bureau (U.S. Census Bureau 2022b)	Polygon layer	Identify area with better availability of electricity and water
Metropolitan areas	US Census Bureau (US Census Bureau 2022b)	Polygon layer	Identify future CLT markets
Major roads	US Geological Survey (U.S. Geological Survey 2022b)	Line layer	Create accessibility information and network data set for location-allocation model
Primary roads	US Census Bureau (US Census Bureau 2022b)	Line layer	Create accessibility information
Rail network	US Census Bureau (US Census Bureau 2022b)	Line layer	Create accessibility information
Labor force	US Census Bureau (US Census Bureau 2022a)	Table	Identify labor force (population 16 yr and over) in each county
Sawlog volume	Forest inventory and analysis (FIA), inventory (USDA Forest Service 2022a)	Table	Identify net standing sawlog volume of selected hardwood species in each county
Sawmill locations	FIA—timber products output (USDA Forest Service 2022b)	Point layer	This data worked as the demand point layer

Similarly, feature polygons related to urbanized areas and urban clusters were obtained from the US Census Bureau (US Census Bureau 2022b).

Preference analysis

Exclusion analysis was followed by preference analysis, which identified potential CLT sites by considering five different criteria including potential market, labor force, sawlog availability, and proximity to primary roads and rail networks. There are large metropolitan areas (>1 million population) in and around the State of Tennessee and these large population centers can be a potential market in future. Thus, proximity to metropolitan areas was an important criterion for locating a CLT plant as it helps reduce transportation costs of mass timber products to the market. The metropolitan areas considered in this study were Nashville, Memphis, Birmingham, Atlanta, Charlotte, and

Louisville (Fig. 3). Similarly, proximity to major roads and rail networks was also important for the transportation of raw materials and finished products when determining potential locations of CLT plants. Although CLT plants receive raw materials (i.e., dimensional lumber) from sawmills, availability of sawlogs in nearby areas can indirectly help the cost-effective production of mass timber because of potential establishment of new sawmills due to increased lumber demands. Finally, labor availability at the county level was also considered when selecting a potential site, on the basis of the labor force data for each county (US Census Bureau 2022a).

Data related to location of metropolitan areas, primary roads, rail network, and county populations of the labor force were obtained from the US Census Bureau (U.S. Census Bureau 2022a, 2022b). Location of major roads was downloaded from the US Geological Survey (USGS; US Geological Survey 2022b) and total available sawlog volume of selected tree species at the county level was collected from FIA (USDA Forest Service 2022a). Since the potential CLT plants were targeted for hardwood lumber, only sawlog volume of four hardwood species such as yellow poplar, red maple, American beech, and white ash was considered for the analysis, on the basis of the species suitability for CLT manufacturing.

A fuzzy multicriteria analysis was used to identify the suitable sites for CLT plants considering all the criteria described above (Greene et al. 2011). Fuzzy logic helped standardize each criterion, and then those normalized layers were combined using a weighted overlay tool in ArcGIS Pro's spatial analyst tool (ESRI 2022). An analytical hierarchy process was used to determine the weight for each decision criterion where a pairwise comparison matrix was developed and used to estimate weights for the criteria. These relative weights were 14 percent for metropolitan areas, 29 percent for primary roads, 14 percent for rail networks, 29 percent for labor force, and 14 percent for sawlog availability. The weighted overlay process produced a suitability map in a continuous scale for locating CLT plants.

A final raster layer of suitable sites for CLT plants was produced using the raster analysis. In this raster analysis, we removed the unsuitable sites as identified by the exclusion analysis from the suitability map. The raster layer of suitable sites was reclassified into three categories using

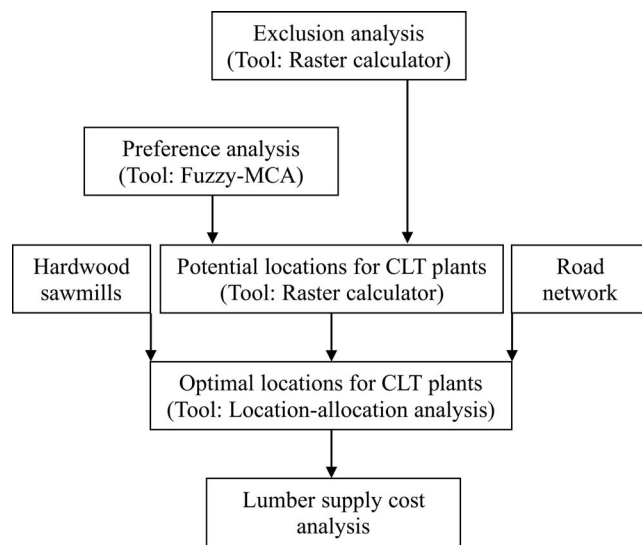


Figure 2.—A methodological framework displaying interconnection between exclusion analysis, preference analysis, and location-allocation analysis and tools used to perform these analyses. Fuzzy-MCA = fuzzy multicriteria analysis; CLT = cross-laminated timber.

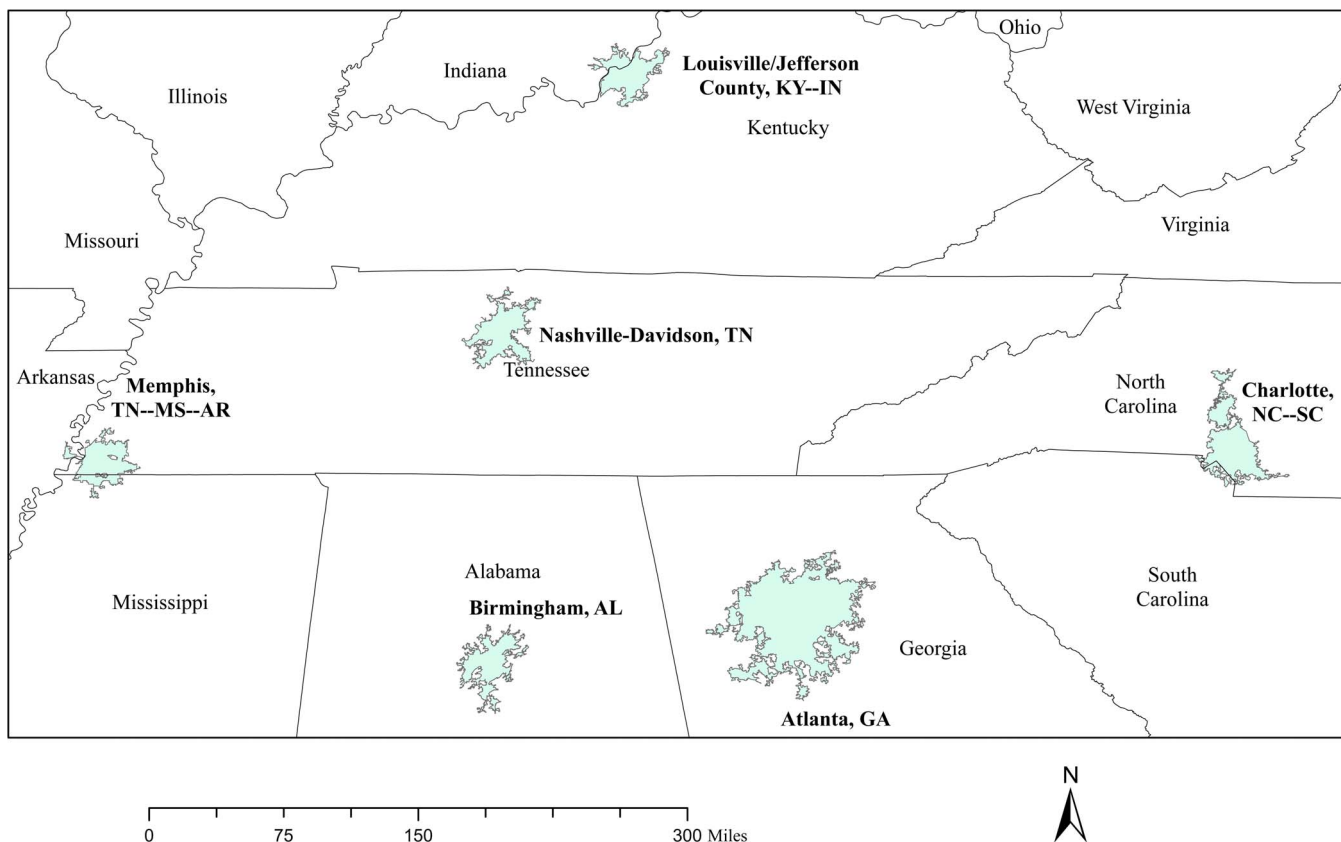


Figure 3.—Major metropolitan areas in and around Tennessee.

equal interval classification method. These categories were labeled as least suitable (1–2), moderately suitable (3–4), and most suitable (5–6) sites for CLT plants depending on field values. Besides these categories, the raster layer also included unsuitable sites (0) as identified by the exclusion analysis described above.

Location-allocation analysis

Location-allocation analysis solves two problems simultaneously. First, it locates p facilities among the m candidate facilities and then allocates n demand points most efficiently to the chosen facilities. This is a typical p -median problem where either coverage is maximized, or distance is minimized while solving the problems. In this study, p facilities are optimally located, and n geographically distributed demand points are assigned in each chosen facility such that the sum of the weighted distance between all demand points and corresponding facilities is minimized. A mixed-integer programming with the following objective function was used to solve a p -median problem here following Jayarathna et al. (2020):

$$\text{Minimize } \sum_{ij} w_i x_{ij} d_{ij} \quad (1)$$

subject to the following constraints

$$\sum_j x_{ij} = 1; \forall i \in V \quad (2)$$

$$x_{ij} \leq y_j; \forall i \in V, j \in U \quad (3)$$

$$\sum_j y_j = p \quad (4)$$

$$x_{ij} \in (0, 1); \forall i \in V, j \in U \quad (5)$$

$$y_j \in (0, 1), \forall j \in U \quad (6)$$

In the above equations, a set of demand points is represented by $V(1, \dots, i, \dots, n)$ and a set of candidate facilities is represented by $U(1, \dots, j, \dots, m)$. Similarly, w_i represents the weight associated with the i th demand point, and d_{ij} represents the distance between the i th demand point and the j th facility. Decision variable x_{ij} is 1 if demand point i is assigned to facility j , and 0 otherwise, and y_j is 1 if the facility is located at j and 0 otherwise. The objective function (Eq. 1) minimizes the demand-weighted total distance. Constraint 1 (Eq. 2) indicates that each demand point will be assigned to only one facility. Constraint 2 (Eq. 3) requires that demand points be assigned to only open facilities. Constraint 3 (Eq. 4) requires exactly p facilities to be located. Constraints 4 and 5 (Eqs. 5 and 6) denote that the decision variables must be binary and integers.

In this study, the potential CLT facilities identified by our preference and exclusion analyses serve as candidate facilities, whereas demand points are represented by sawmills. Hardwood sawlog consumption capacity was treated as the weight of each sawmill for the location-allocation analysis. The major roads data set, obtained from USGS, was used to create the network data set. The location-allocation problem was solved using the minimize weighted impedance criteria (p -median) because assigning

nearby sawmills to a CLT facility helps minimize transportation costs of raw materials. The network analyst tool in ArcGIS Pro was used to solve the location-allocation problem and the estimated model assumes that a chosen facility has an infinite service capacity. We did not choose a capacity constraint assumption because existing CLT plants have a wide range of panel production capacities. However, the availability of sawmills or dimensional lumber will constrain the production capacity of CLT plants, which we have considered in the analysis by including sawlog consumption capacities of sawmills. For the study we chose to locate a maximum of three CLT plants to provide multiple options.

Sawmill data including location of sawmills and sawlog consumption capacity was obtained from the FIA timber products output (TPO) data set maintained by the US Forest Service Southern Research Station (USDA Forest Service 2022b). These data covered all hardwood sawmills of Tennessee and a few sawmills from neighboring states including Kentucky, Mississippi, Alabama, Georgia, North Carolina, and Virginia. Some of the selected sawmills also consume both hardwood and softwood logs to produce lumber and other sawn products.

Optimal plant size and lumber supply cost by transportation distance

Location-allocation analysis was used to identify how changes in transportation distance affect optimal plant size. Likewise, lumber supply costs were determined by using simple arithmetic operations. Maximum CLT panel production capacity of each chosen facility was computed on the basis of the number of sawmills allocated to them, their annual sawlog consumption volumes, and the conversion factors as described in Anderson et al. (2020). Assuming that the number of facilities remains unchanged, a CLT facility size depends on how far each of those facilities can go for hauling hardwood lumber from sawmills. Likewise, the change in lumber hauling distance has implications on lumber supply cost from sawmills to CLT facilities. Average cost for acquiring dimensional lumber can increase with the transportation distance. In this study, lumber supply costs include lumber purchase and transportation costs only. Cost factors, as presented in Table 2, were used to compute the average lumber supply cost of each optimally chosen CLT facility. The cost calculation assumed that further lumber seasoning that is required for CLT manufacturing was borne by CLT facilities. Similarly, sawmills were assumed to cover the loading costs, whereas the unloading costs were assumed to be borne by the CLT facilities. The unloading process mostly involves mechanical work (forklift use), which takes less than an hour for a truck.

In calculating the plant size and lumber supply cost, we considered the transportation distance ranging from 50 miles to 160 miles. Given the existing spatial distribution of sawmills in Tennessee, we assumed that an average-size

CLT plant has a minimum 50-mile range for procurement of dimensional lumber from sawmills. Similarly, when we consider 160 miles transportation distance for lumber procurement, it covered almost all the available sawmills included in this study. We have only displayed the optimal location result when maximum transportation distance was 150 miles; however, we considered all transportation distance ranges (50 to 160 miles) when calculating plant size and lumber supply costs. Regarding the effect of transportation distance on lumber supply cost, we considered unit lumber supply cost rather than total supply costs, as the former helps compare the cost efficiency among the optimal sites.

Results

Preliminary selection of potential sites

Raster analysis that integrated the exclusion and the preference criteria showed that 87 percent of the total Tennessee surface area was unsuitable for establishing a CLT plant. These areas were mostly covered by forests, wetlands, or built-up areas. In addition, these areas had steeper than 10 percent slope and were beyond 5 miles from urban areas. Among the suitable areas, very suitable sites covered only 4 percent of total suitable areas, which were distributed in 12 different clusters across the state (Fig. 4). Likewise, least-suitable and moderately suitable sites covered 78 percent and 18 percent geographic areas respectively.

Table 3 presents the list of 12 candidate sites for CLT plants. These sites are in 12 different counties and spread across Tennessee. Active labor force in these counties ranged from 5,925 to 21,574. Considering the existence of local roads and city limits, a specific point in each cluster was manually chosen as candidate sites from these 12 clusters.

Optimal locations for CLT plants

Location-allocation analysis identified 3 optimal sites for CLT plants of 12 candidate sites. These optimal sites were Location 2 (Harrogate/Middlesboro), Location 5 (Woodbury/McMinnville), and Location 9 (Adamsville/Savannah). Those sites were chosen as optimal sites when we assumed maximum transportation distance of 150 miles (Fig. 5).

One of the three optimal CLT plant locations identified lies in Claiborne County (Location 2, Harrogate/Middlesboro). A total of 49 sawmills was allocated to this optimal CLT plant location by assuming that this plant will haul lumber from a maximum 150 miles away. However, the average road distance between the plant and sawmills was 81.64 miles. The assigned sawmills were annually consuming a total of 24,022 MCF hardwood sawlogs. If one-fifth of these sawlogs was from preferred species (yellow poplar, red maple, white ash, and American beech), this location would support establishing a CLT plant with 1,873 MCF (53,039 m³) annual capacity. It is worth noting here that the

Table 2.—Description of supply cost items for dimensional lumber.

Item	Costs	Source	Remark
Trucking cost per mile	\$1.646/mi	Leslie and Murray (2021)	
Truckload capacity	37 m ³	Pokharel and Latta (2020)	
Lumber price	\$332/m ³	Luppold and Bumgardner (2021)	Yellow poplar species

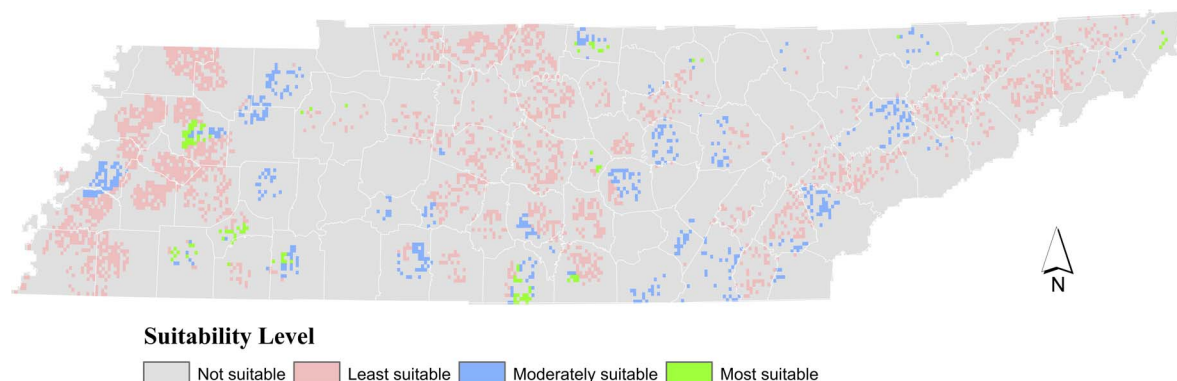


Figure 4.—Statewide depiction of suitability score from fuzzy multicriteria analysis for optimal location of hardwood cross-laminated timber plants in Tennessee.

statewide share of wood volumes from these preferred species is about 25 percent (USDA Forest Service 2022a).

Likewise, the second optimal location identified for a CLT plant is in Cannon County (Location 5, Woodbury/McMinnville). This CLT plant location has a total of 108 sawmills with a maximum of 66,334 MCF annual sawlog consumption possibilities. The average distance between the plant and sawmills was 67.14 miles, ranging from less than a mile to 149 miles. This location can have a CLT manufacturing facility of 5,172 MCF (146,461 m³) CLT panels if one-fifth of the total sawlog volumes comes from the preferred species.

Located in Hardin County, the third optimal CLT plant location (Location 9, Adamsville/Savannah) was associated with a total of 108 sawmills. These sawmills consume a maximum of 70,003 MCF hardwood sawlogs and can produce 5,458 MCF (154,562 m³) CLT panels if one fifth of those volumes comes from preferred hardwood species. Like the previous two locations, this location also assumes maximum hauling road distance of 150 miles. However, the average distance between the plant site and sawmills was 65.62 miles.

Effect of maximum transportation distance on CLT plant size and lumber supply costs

Location-allocation analysis was used to assess the sensitivity of transportation distance change on CLT plant

size. Assuming a constant number of CLT manufacturing facilities (three in our case), an increase in transportation distance for lumber hauling is expected to increase the production capacity of the CLT plant. However, when maximum transportation distance was changed from 50 miles to 60 miles or more, the three chosen locations were not necessarily the same as in the initial step (Fig. 6). For example, three CLT plants with 2,486 MCF, 1,154 MCF, and 2,343 MCF production capacity can be established if the maximum lumber hauling distance is limited by 50 miles. However, such a plant size would change to 1,571 MCF, 4,933 MCF, and 4,577 MCF if each potential plant considers hauling lumber from a maximum transportation distance of 100 miles. Similarly, collecting lumber from a maximum of 150 miles can help establish CLT plants with 1,873 MCF, 5,172 MCF, and 5,458 MCF capacity.

A simple arithmetic operation was used to calculate average cost for acquiring lumber from the sawmill. With the increase of maximum transportation distance, the average cost for acquiring lumber increased from 50 miles to 120 miles distance. However, the transportation distance had variable effects on lumber supply costs beyond 120 miles (Fig. 7). Specifically, average lumber supply cost for CLT plant 3 was found to be decreasing beyond 120 miles of transportation distance as the optimization model allocated fewer distant sawmills to this plant than other CLT plants. When those three optimally selected CLT plants hauled lumber from 50, 100, and 150 miles, their

Table 3.—List of candidate sites for cross-laminated timber (CLT) plant establishment in Tennessee determined using fuzzy multicriteria analysis (Fuzzy-MCA).

Location	City	Latitude	Longitude	County	Labor force in the county
1	Mountain City	36°26'31.2"N	81°47'56.4"W	Johnson	5,925
2	Harrogate/Middlesboro ^a	36°31'22.8"N	83°45'39.5994"W	Claiborne	13,668
3	Livingston	36°24'57.2994"N	85°16'55.1994"W	Overton	9,988
4	Lafayette	36°31'26.4"N	86°2'38.3994"W	Macon	11,285
5	Woodbury/McMinnville ^a	35°47'2.3994"N	85°59'42"W	Cannon	6,525
6	Winchester	35°9'10.7994"N	86°8'34.8"W	Franklin	19,101
7	Fayetteville	35°2'42"N	86°34'19.2"W	Lincoln	16,176
8	Camden	36°7'33.5994"N	88°9'7.2"W	Benton	6,094
9	Adamsville/Savannah ^a	35°14'2.4"N	88°21'18"W	Hardin	10,464
10	Bolivar	35°16'51.5994"N	89°2'20.4"W	Hardeman	9,588
11	Henderson	35°24'50.4"N	88°39'46.7994"W	Chester	7,169
12	Trenton/Humboldt	35°56'42"N	88°57'32.4"W	Gibson	21,574

^a Chosen location after implementation of location-allocation model.

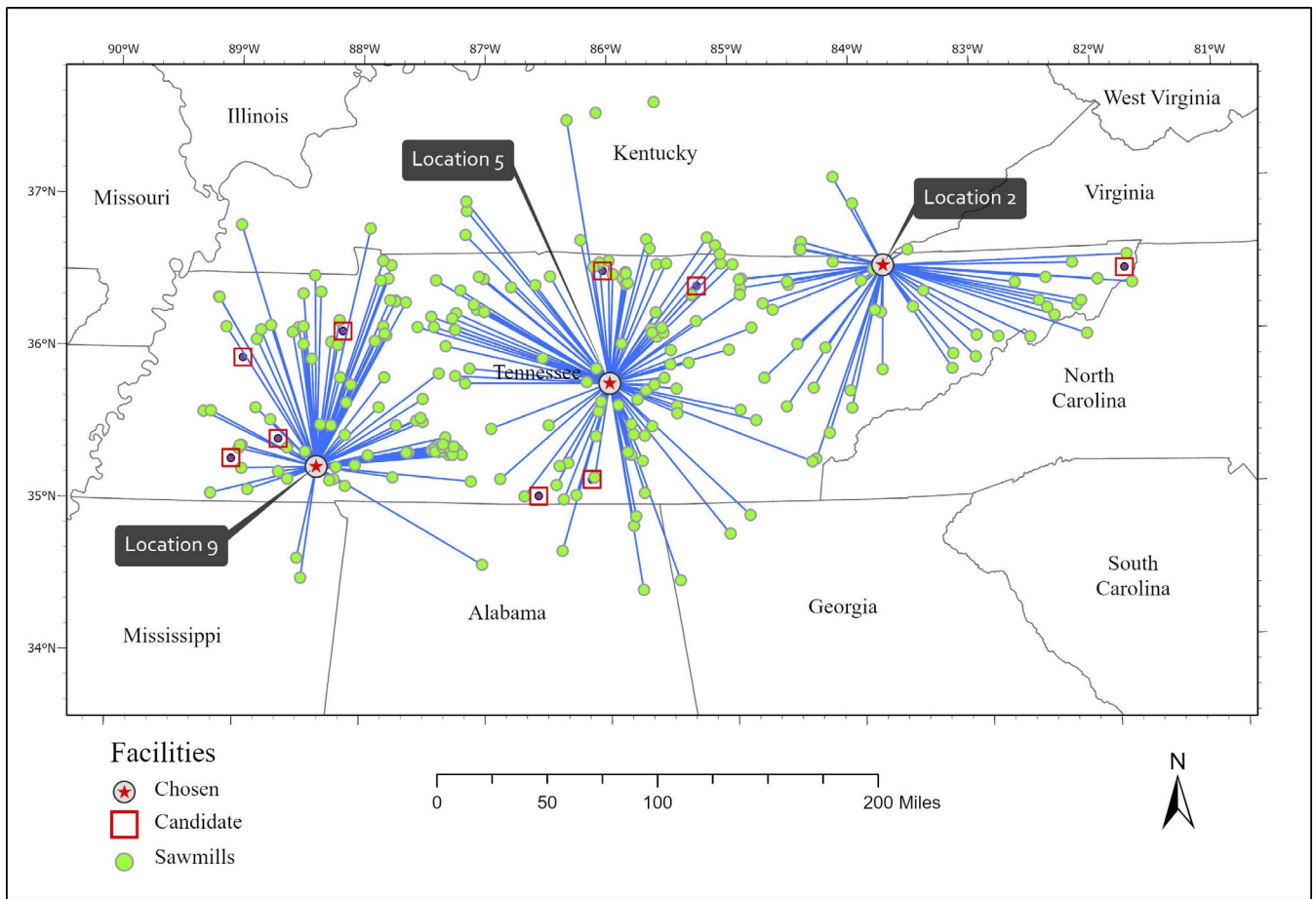


Figure 5.—Identification of optimal cross-laminated timber plant sites using geographic information system-based location-allocation tool (maximum hauling road distance: 150 miles).

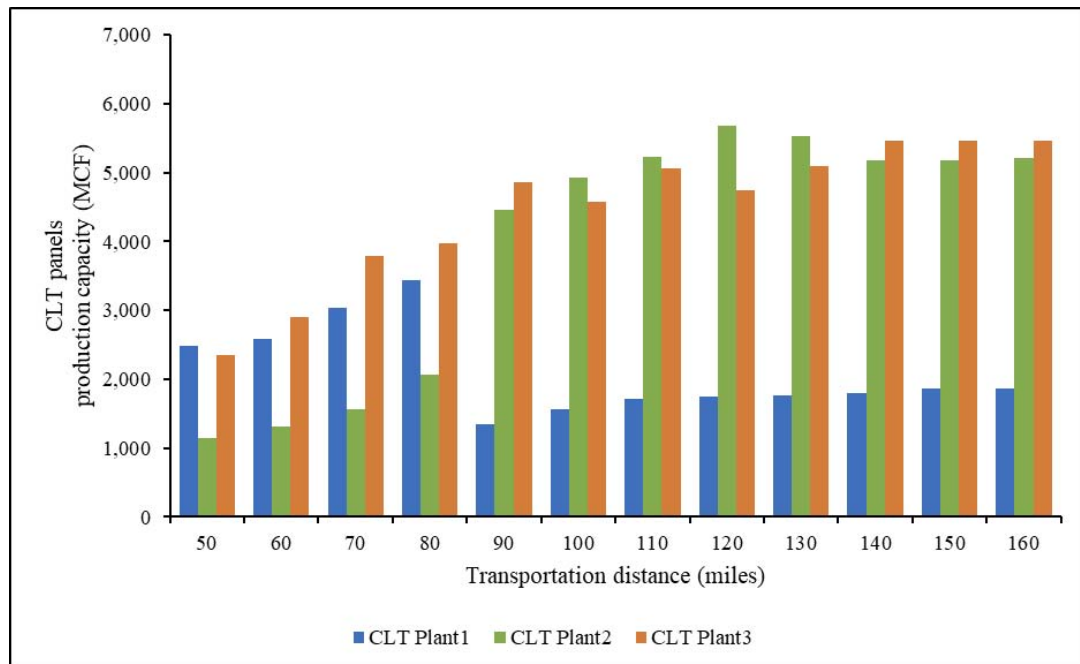


Figure 6.—Variation in cross-laminated timber (CLT) plant size with varying maximum transportation distances.

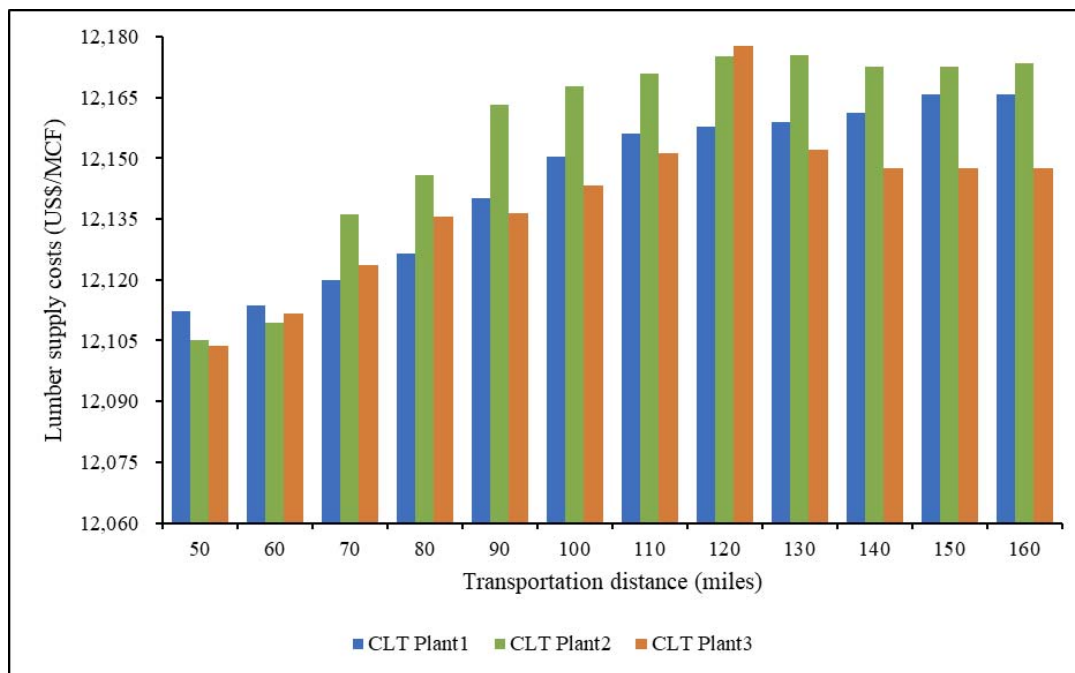


Figure 7.—Variation of unit lumber supply cost with different maximum transportation distances. CLT = cross-laminated timber.

average lumber supply costs ranged from \$12,104/MCF to \$12,112/MCF; \$12,143/MCF to \$12,168/MCF; and \$12,148/MCF to \$12,173/MCF respectively.

Discussion

This study used a spatially explicit optimization model to identify optimal locations for CLT plants in Tennessee emphasizing transportation distance to sawmills and their sawlog consumption capacity as key criteria. Because no hardwood CLT plants exist in Tennessee, we identified three optimal CLT locations that can provide flexibility to account for additional factors when selecting a final location. The uniqueness of this study, in contrast to a previous study (Kühle et al. 2019), lies in the application of a comprehensive set of criteria for the selection of candidate sites as selection of optimal sites depends solely on those candidate sites. In doing so, this study presents a framework that uses both spatial and aspatial data (for example, sawmill capacity) in finding an optimal site, which could also be adopted in investment decisions of products other than hardwood CLT. Another important feature of this approach is the prevision in location of sites (actual geographic coordinates as opposed to broader geographic regions such as a grid, hot spot, county, etc.), which allowed use of precise measure of distance and cost estimation (Jayarathna et al. 2020).

This study indicated that 87 percent of the total surface area in Tennessee was unsuitable for a CLT facility location. Of the total suitable sites, only 4 percent may be deemed most suitable according to the criteria considered. We note our estimated unavailable surface area for potential CLT sites with those reported in the 2017 National Resources Inventory, which reported that almost 64 percent of the total surface area of Tennessee was covered by federal land, water areas, developed land, and forest lands (US Department of Agriculture 2020). Our results showing limited areas being suitable for potential CLT location is

partly attributable to very stringent exclusion criteria we adopted during the analysis. As we have also used multiple criteria to select the candidate sites, site suitability for CLT plants was measured on a continuous scale so that we could choose as many potential sites as desired, from the most suitable to less suitable categories. Our analysis suggests that the most suitable sites for CLT plants are found in areas near most populated areas and that have a significant hardwood fiber shed (i.e., availability of large amount of hardwood growing stock nearby), which makes intuitive sense.

Sawmills considered for this study consumed almost 160.84 million cubic feet of hardwood sawlogs in 2017. Consistent with the current statewide proportion of preferred species to all hardwood species indicated by FIA data (USDA Forest Service 2022a), our study assumed that one-fifth of the total hardwood harvests would be physically available for CLT production in the study area. This assumption may have overpredicted the hardwood sawlog availability as all sawmills may not be interested in supplying specific sizes of lumber to the CLT plants because of low grade, technical constraints, and existing obligations. In contrast, the establishment of hardwood CLT plants can boost the demand for hardwood lumber and these sawmills can increase their production as well as technical capacity. In addition, other forest-related industries such as logging and lumber resawing and planning can also optimize their operations. Since 68 percent of total timberland growing stock in eastern forests is comprised of hardwood species including the four preferred hardwood species (Oswalt et al. 2019), a sustainable supply of raw materials for hardwood CLT facilities may not be an issue at least in the short run. Further, such CLT facilities can be an alternative for a large volume of unused hardwood sawlogs resulting from the closure of several pulp and paper mills in the southern region (Brandeis and Guo 2016, Poudyal et al. 2017).

This study considered only those sawmills that purchased hardwoods from the State of Tennessee but no other hardwood sawmills that exist in neighboring states. With the growing demand for hardwood lumber in the future from established CLT plants, nearby states could also supply hardwood lumbers, contributing to larger CLT plant sizes. Similarly, this study did not take into account small-sized sawmills, which do not currently focus on grade lumber production but rather engage in the production of other sawn products. However, these sawmills may switch to lumber production, given future increased demand for hardwood lumber from established CLT manufacturing facilities. Over the years, the distribution of sawmills in Tennessee has become more clustered, with fewer but larger-capacity mills (Brandeis and Hodges 2018). Thus, the number of currently existing sawmills might not constrain the adequate supply of lumber for three CLT plants, but sawmills might need to upgrade to produce lumber of appropriate dimensions and reduce lumber moisture to meet the required standard.

Our study also indicated varying cost effectiveness of the identified optimal CLT plants. For instance, the third CLT plant (Location 9) located in Hardin County was found to be the most cost-effective one, with a higher potential of producing CLT panels than the other two CLT plants. The cost effectiveness might have resulted from shorter average transportation distance (65.62 miles) than the other CLT plants. When locating multiple CLT plants, we did not limit their production capacity. A capacity constraint or predetermined CLT facility capacity was not assumed for the analysis because, on the basis of the softwood CLT industry, existing facilities have a wide capacity range, from 800 m³ to 125,000 m³ (Larasatie et al. 2021). Our analysis indicated that the location of facilities was sensitive to the number of facilities that were simultaneously chosen and the distance that such facilities cover for lumber procurement from sawmills. In addition, the size of CLT plants was also associated with the number of CLT plants considered and transportation distance for lumber procurement.

Given the similar hardwood and softwood lumber prices currently in the market, the estimates of lumber supply costs are also reasonable in our study. The softwood CLT costs \$20 to \$25 per cubic foot and lumber supply cost comprises more than half (47% to 68%) of its total operating costs (Atkins et al. 2022, Zhang and Lan 2022). Although this study assumed a constant rate of lumber price and transportation costs all over the study area, these costs can, in fact, be volatile and vary widely in different locations (Brandt et al. 2019). Government subsidies and taxes also affect the production costs of CLT panels. As CLT optimal locations are near economically at-risk or distressed counties in Tennessee, their establishment would benefit those economies.

Even though this study was based in Tennessee, the results and the methods used in this study have broader applications. First, for any state or nation interested in planning for the CLT market, our analysis demonstrates how to identify optimal locations for CLT manufacturing facilities on the basis of the spatially explicit framework using both spatial and aspatial data. This method could be easily adopted, with proper modification of variables and metrics, in determining optimal locations for other forest products as well as energy production facilities (e.g., biofuel, biopower, laminated beech products). Several states in the region (e.g., North Carolina, Alabama) have recently

seen closure of pulp and paper mills due to decline in demand for traditional forest products and revitalizing the economy of those regions will require identifying sites for facilities that can create a new market for forest products. In addition, this model could be expanded to the national level by combining data on housing demand, population density, and supply of lumber and investigate how growth of mass timber production facilities at various regions could affect the economy (e.g., jobs, output, value added) and environment (e.g., carbon offset benefit).

Conclusions

Recent emergence of mass timber products including CLT has shown tremendous potential for replacing concrete and steel in construction, storing carbon in wood products, and most important, creating a new market for forest products. Despite this market potential, the investors and regional economic development planners currently have little information regarding where to invest capital to establish CLT manufacturing facilities. With the help of the publicly available data and FIA-TPO data, this study assessed optimal locations for hardwood CLT manufacturing facilities in Tennessee. The study identified optimal locations for CLT plants in Tennessee mainly considering the capacity of existing hardwood sawmills and distance from these mills. The key findings of our analysis include (1) identification of three optimal hardwood CLT plants in Tennessee that can produce 12,504 MCF hardwood CLT panels annually, (2) an estimate of the average lumber hauling distance of identified CLT plants that ranged from 65.62 miles to 81.60 miles, and (3) general observation that the CLT production potential and lumber supply costs would increase with the lumber procurement distance.

Using hardwood lumber for CLT manufacturing not only benefits forest industries (e.g., sawmills) that consume hardwood sawlogs but also the forest industry overall. New policy provisions such as subsidy for embodied carbon in CLT panels and American national standard for hardwood and hybrid CLT panels can spur investors' interest and develop the hardwood CLT manufacturing industry in Tennessee and hardwood-supplying regions.

Our study assumed a constant rate of lumber prices and transportation costs, although higher lumber demand originating from a CLT plant will likely affect those prices. Future work examining the effect of higher lumber demand on prices and consequently higher costs to a CLT plant is needed. Another caveat in our data analysis includes an assumption of equal distribution of timber growing across a county. Future study can address this limitation by excluding nonforest areas as well as assuming the growing stock distribution on the basis of site quality of forest areas.

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