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Regional and net economic impacts of high-rise mass timber construction in Oregon

Adam Scouse[a,*], Stephen S. Kelley[a], Shaobo Liang[b], Richard Bergman[b]

[a] Department of Forest Biomaterials, North Carolina State University, 2820 Faucette Drive, Raleigh, NC, United States
[b] U.S. Forest Service, United States Department of Agriculture, 1 Gifford Pinchot Drive, Madison, WI, United States

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ABSTRACT

Pacific Northwest policy makers are excited about the emergence of mass timber into U.S. construction markets as the product potentially creates local manufacturing jobs while utilizing Douglas fir growing sustainably in the region. This study assessed regional economic impacts generated by mass timber high-rise construction in Oregon. Economic impact estimates were derived using a regionally specific input-output model combined with analysis-by-parts methodology. Financial data from Portland's 12-story Framework building, estimated using RSMeans software, provided purchasing information. The study's economic model made use of regionally specific socioeconomic data from the American Community Survey to determine how economic impacts translated into increased earnings for study area residents. Because building with mass timber represented product substitution over traditional construction practices, this study assessed regional impacts of mass timber construction alongside the opportunity costs associated with a concrete frame alternative. Net impact assessment results indicated that construction of the 12-story building using a mass timber design generated larger economic impacts than traditional concrete frame construction and generated additional earnings for households of all income levels. Panels must be produced locally to realize the full economic benefits of mass timber construction as importing panels from outside the state creates economic leakage that reduces economic benefits.

1. Introduction

Mass timber products like cross laminated timber (CLT) have recently emerged onto the U.S. construction market as novel building products that contribute to the sustainability of cities by turning urban structures into carbon sinks (Mallo & Espinoza, 2015). Mass timber building designs heavily utilize wood products for building frames. These wood products generate fewer carbon dioxide emissions and require less fossil fuel consumption during manufacturing, transport, and construction than alternative steel or concrete building components (Oliver et al., 2014). As a result, replacing non-wood construction materials with lower embodied energy wood products reduces atmospheric carbon dioxide emissions by 1.9 metric tons per cubic meter of installed wood product (Sathre & O'Connor, 2010). Alongside product substitution, the prefabricated nature of mass timber construction allows for improved urban sustainability through efficient resource utilization while "design for disassembly" principles can be incorporated to maximize panel reuse following building deconstruction (Lehmann, 2013). Due to mass timber's sustainable and economic advantages, countries like Australia, Canada, and Japan have adopted wood encouragement policies that promote and facilitate timber use in new construction projects, which align with green building initiatives by using low carbon materials (Milestone & Kremer, 2019).

In the U.S., wood-based construction typically takes the form of light-frame or heavy-timber designs which are limited by local building codes to under six stories (ICC, INC, 2014). However, emerging mass timber products and their associated construction techniques are challenging these limitations. Hybrid building designs that incorporate mass timber alongside steel and concrete allow wood to serve as a significant building component in structures up to 14 stories tall, creating a new market niche for timber in multi-story applications. The recently approved 2021 International Building Code (IBC) will include provisions of new construction Type IV-A/B/C for up to 18 stories for business and residential occupancies mass timber buildings (Breneman & Richardson, 2019). Newly erected structures throughout Europe and Canada demonstrate mass timber capabilities in high rise applications (Hasan, 2017). And while the U.S. has been slow to adopt mass timber construction, the concept is gaining traction with designers, architects, and city planners due to its environmental advantages and aesthetic value (Espinoza & Buehlmann, 2018; Mallo & Espinoza, 2016;

* Corresponding author.
E-mail addresses: aascouse@ncsu.edu (A. Scouse), sskelley@ncsu.edu (S.S. Kelley), sshliang@gmail.com (S. Liang), richard.d.bergman@usda.gov (R. Bergman).

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Williamson & Ross, 2016). Mass timber not only brings new opportunities for sustainable architectural design, but could support rural economic development through domestic manufacturing of mass timber elements like CLT.

CLT is a prefabricated, solid, engineered wood panel consisting of at least three orthogonally bonded layers of visually or machine graded solid-sawn lumber or structural composite lumber (ANSI/APA, 2019). Similar to glue laminated timber (glulam), CLT panels are manufactured to meet one of seven stress classifications for use in floor, wall, or roof applications. The panels are customizable, meaning they can be manufactured to specific thicknesses, widths, lengths, and strengths based on the intended application, and efficiently utilize wood in situations that typically call for concrete, masonry, or steel.

The CLT manufacturing process, outlined in Karacabeyli and Douglas 's CLT Handbook (2013), looks similar to that of already established mass timber products like glulam. Panels are constructed from visually or stress-graded lumber at an approximate moisture content of 12 % and utilize No. 2 grade boards for parallel laminations and No. 3 for perpendicular laminations. Manufacturing standards provide raw material flexibility so that multiple softwood species can be utilized within the panels, provided individual pieces of lumber maintain a minimum specific gravity of 0.35. To manufacture CLT, graded lumber is grouped, planed, and cut to length. Dimensioned boards are then glued, layed up, and pressed together using a room temperature curing adhesive that conforms to glue line durability standards according to the intended service condition. Following pressing, panels are stacked, cut to dimension, and wrapped or treated with a temporary water resistant coating for weather protection (Karacabeyli & Douglas, 2013).

As emphasis on climate change mitigation strengthens, CLT's popularity has risen steadily in Europe over the last 20 years and is just now catching hold in the U.S., despite being patented by Walch and Watts (1923). Because the U.S. construction industry tends to be fragmented and risk adverse, introducing a novel construction material with new design and manufacturing processes takes time. The structure of sector supply chain relationships, established building practices, and limited technical capabilities make the construction industry less likely to adopt innovative solutions (Arora et al., 2014). Currently, the emergence of CLT in the U.S. is following a similar trajectory as that of Sweden in the mid 1990's (Falk, 2013). Concerns over fire and structural performance alongside minimal contractor, engineer, and architect experience means that product adoption is slow. Despite having cultural histories deeply rooted in forest management, wood product manufacturing, and wood construction, governmental policies encouraging mass timber designs have done little to help CLT gain market share (Falk, 2013).

CLT passed a major milestone in North America in 2012 with the publishing of ANSI/APA PRG 320, a recently updated standard that defined product manufacturing and design specifications for producers and users (ANSI/APA, 2019). According to J. Elling of the APA - The Engineered Wood Association, Tacoma, WA. (personal communication, August 2019), there are currently six CLT manufacturers scattered around the U.S.; D.R. Johnson, Freres Lumber Co., Inc., International Beams, Katerra, SmartLam, Sterling Solutions, and Vaagen Timbers. While the current level of CLT manufacturing capacity is unknown, recent publications indicate that capacity is at least 33,000 cubic meters, which represents approximately 7 % of Europe's 2012 production volume (Beyreuther et al., 2016; Brandner et al., 2016).

In addition to the environmental advantages of tall wooden buildings, policy makers are excited about mass timber's potential to create jobs while redefining high-rise construction in the U.S. They envision an emerging CLT industry as an opportunity to support rural job growth in regions currently facing forest products manufacturing decline. For example, the U.S. state of Oregon has witnessed a steady drop in primary wood products employment from 1980 to 2010, culminating in the closure of 193 mills and the loss of 30,000 jobs. Employment loss in these areas increased rural poverty rates by 3 % over neighboring metropolitan counties and resulted in poverty rates as high as 19.5 % in some locations (Olsen & Horne, 2017). However, manufacturing is still highly relevant to the U.S. economy. Although manufacturing sectors contribute less to GDP then they have historically, jobs in manufacturing have always offered wage premiums for private sector employees. In 2014, manufacturing jobs payed a 16.2 % premium over the national average. And although a number of low-skilled manufacturing jobs have disappeared or been relocated, those that remain are higher skilled and higher paying (Sjoquist, 2016). As of 2016, Oregon's forest based industries generated $18 billion dollars in output, or 3.7 % of the state's GDP, and supported 77,100 jobs, or approximately 3% of the state's employment (Latta et al., 2019).

In tandem with shifts in employment, relocation trends indicate that people are moving from rural to city environments, which increases demand for multi-family construction projects (Oregon Forest Resources Institute, 2017). Since 1996, Pacific Northwest multi-family development has maintained an annual 6.5 % growth rate as buildings have gotten taller. The percentage of multi-family square footage in buildings over five stories has grown from 38 % to 52 %. This rural to urban migration may be indicative of an even larger global trend, as many Asian-Pacific cities are also grappling with population growth and urbanization (Lehmann, 2012). Making the situation more complicated, the rural to urban migration has created a housing affordability issue that disproportionately affects minority communities (Diller & Sullivan, 2018). As U.S. housing continues trending towards multi-family high-rise construction, mass timber has the opportunity to grab market share away from concrete and steel and create disruption in both residential and non-residential markets as a building style that promotes environmental sustainability.

To date, much of the financial and market research associated with CLT has focused on the economic advantages of mass timber design. One of the largest reported benefits is reduced construction time associated with on-site assembly of prefabricated mass timber elements, which generates savings in construction loan interest while providing greater rate of return for project investors (Cazemier, 2017; Evison, Kremer, & Guiver, 2018; Mallo & Espinoza, 2014). Case studies are helpful for highlighting potential savings. Assembly and material costs were compared for alternative CLT and concrete designs for a 10 story residential building in Seattle. By building with CLT, analysts found a conservative four percent savings in the overall cost of construction (Mahlum, 2014). In a separate study, Mallo and Espinoza (2016) compared alternative construction types for a 40,000 square-foot performing arts center in Napa, California. When cast-in-place concrete, steel, and light steel frame construction elements were replaced with CLT, glulam, and engineered wood products, construction time was reduced by 61 % and overall building costs were reduced by 22 %. It may be that mass timber designs may be cost competitive for multi-story applications up to a certain height, after which building higher provides diminishing marginal returns. While the research literature doesn't specify at which height optimal savings are achieved, the university residence hall Brock Commons, located in British Columbia, Vancouver, illustrates that mass timber can remain cost competitive to functionally equivalent concrete designs up to 18-stories (Fast et al., 2016). These examples of cost savings are integral to successful CLT commercialization because process innovations that deliver results on-time and under-budget are the main drivers of competitive advantage in the construction sector (Arora et al., 2014).

While mass timber designs may offer beneficial cost savings during building construction, due to the infancy of the product and design style in the United States, little is known about the life cycle cost of mass timber designs or how CLT and concrete maintenance costs compare alongside one another. Structured interviews with Australian builders, tradesmen, and other construction professionals reveal that timber maintenance costs depend heavily upon the material's exposure conditions, but for radiata pine in structural applications, the cost of a maintenance event during the building's life cycle represented 0 %, 12

%, and 50 % of the building's initial capital cost for low, harsh, and extreme exposure conditions, respectively (Tam et al., 2017). In addition to maintenance costs, other factors like expected service life, energy consumption, and building demolition will also influence overall life cycle cost of mass timber and concrete multi-story structures.

While mass timber construction may be financially advantageous for high-rise construction projects, consumer preference for cross laminated timber amongst developers, architects, and building residents will ultimately influence its success as a building product. Survey results from Oregon and Washington residents suggest that only 19 % of survey respondents were familiar with the concept of tall buildings utilizing mass timber construction, but when shown photographs, the majority of respondents believed that these buildings offered a more aesthetic, positive, and healthy indoor environment (Larasatie et al., 2018). And while public perception of mass timber might be slowly on the rise, surveyed architects on the West Coast are familiar with CLT as a product and site its aesthetic value, ease of use, and cost as material advantages, while at the same time citing durability, fire resistance, and performance and strength as potential weaknesses (Conroy, Riggio, & Knowles, 2018). This stated preference has not necessarily translated into increased adoption of mass timber building designs. Successful product adoption is dependent upon education that describes building material advantages to appropriate target audiences (Mallo & Espinoza, 2015).

While most studies highlight the financial advantages that drive mass timber adoption, research investigating how construction markets or regional employment are impacted by mass timber product substitution are limited. Publications have examined how technology and macroeconomic market conditions have affected wood product sectors over time (Dahal, Henderson, & Munn, 2015; Gosselin et al., 2017; Prestemon, Wear, & Foster, 2015). These publications describe forest industry contribution to regional employment and economic output using a variety of survey methods, input-output techniques, and economic data. To date, one study has investigated the extent to which mass timber would create regional employment opportunities and economic growth (OregonBEST, 2017). According to the analysis, if mass timber design gained 5 % of Oregon's residential and non-residential construction market share, increased product demand would generate 2048 direct manufacturing jobs for the region. If mass timber gained as much as 15 % of construction market share, that number would increase to 6144 direct jobs. After considering further economic impacts generated through indirect and induced employment, which includes additional job creation as a result of industry supply chain growth and increased household spending, as many as 17,000 Oregon based jobs could be created. This level of employment would generate $1 billion in labor income for Oregon residents and $33.8 million in state personal income taxes (OregonBEST, 2017).

While these regional impact assessments are helpful for quantifying the economic potential of an emerging mass timber industry, there has been little research effort to investigate how mass timber designs will impact competing sectors, change the economic impacts of construction, or influence the amount of wages and earnings construction employment creates for households. This study addresses this knowledge gap. If CLT does represent a more sustainable alternative to traditional construction practices while facilitating manufacturing employment, careful consideration must be given to how mass timber designs will influence construction processes as well as create unintended consequences. Due to its prefabricated nature, manufacturing CLT may very well increase manufacturing employment in rural areas at the expense of construction employment at the job site. These shifts in employment and supply chain relationships will go on to impact regional economies.

Using a rarely seen opportunity cost comparison, this research quantified the change in regional economic impacts that result from shifting building construction from concrete to functionally equivalent mass timber structures by using the Framework building, a 12-story mixed use structure proposed for downtown Portland, Oregon, as a case study. Economic impact estimates were compared based on two scenarios; construction of the Framework building using a mass timber frame versus a concrete frame. Along with scenario economic impact estimates, net impacts estimates were generated by modeling a functionally equivalent loss in concrete frame construction alongside subsequent construction of the mass timber structure, which represents the opportunity costs that arise from product substitution. Alongside regional economic impacts, this study also reported net wage and earnings impacts for households at different income levels. Research that investigates the cost effectiveness of high-rise mass timber alongside competing materials, as this study did, ranked 13 in priority out of 117 research topics listed at the 2nd Mass Timber Research Needs Assessment Workshop (Zelinka et al., 2019). This study contributes unique economic impact assessment findings and mass timber cost information to architects, policy makers, economists, and city planners interested in green building and climate change mitigation.

2. Materials & methods

2.1. Model construction

This study used the social accounting matrix (SAM) modeling technique to assess net regional impacts derived from mass timber construction. A SAM model was constructed within IMpact analysis for PLANning (IMPLAN) version 3.0 using Oregon's 2015 data set (IMPLAN Group L.L.C., 2018). IMPLAN is a software package that combines regionally specific data with input-output and social-accounting techniques to estimate the economic impacts resulting from a change in final demand. Developed by the US Forest Service in the 1970s to assess the impact of alternative forest management options on local communities, the software has since evolved by integrating data from the Bureau of Labor Statistics, the Bureau of Economic Analysis, the US Department of Agriculture, and other sources to create a comprehensive economic modeling tool that represents 536 industrial sectors and households of varying income level (Day, 2012). The software and analytical technique can be an integral tool for sustainable development initiatives as it can be useful in identifying primary industries that make up a region's economic base along with describing the interconnectedness of regional sectors (Carroll & Stanfield, 2001).

The study model is represented in matrix form by Eq. (1) (Holland & Wyeth, 1993). Submatrix A represents inter-industry transactions. Submatrix C describes household consumption of locally produced goods and services. Submatrix V details industry value-added payments for employee compensation, proprietor income, and taxes on production and imports. Submatrix Y represents value-added contributions to households. Lastly, submatrix H describes how employee compensation payments were distributed to households based on income level.

$$SAM = \begin{bmatrix} A & 0 & C \\ V & 0 & 0 \\ 0 & Y & H \end{bmatrix} \tag{1}$$

$$reduced\ SAM = \begin{bmatrix} A & C \\ L & H \end{bmatrix} \tag{2}$$

Because submatrix Y describes industry earnings to households using a regional average for households, it oversimplifies structural wages differences inherent between industry sectors. To overcome this limitation and add resolution to our model, we followed the approach developed by Holland and Wyeth (1993) to create the reduced SAM represented in Eq. (2). Within the reduced SAM form, value added components of submatrices V and Y were redistributed to submatrix L so that households received earnings directly from industry sectors.

Using a method to augment IMPLAN's SAM with secondary industry-to-household earnings data, originally developed by Hughes and Shields (2007) and Hughes and Isengildina-Massa (2015), submatrix L was created from industry earnings distributions derived from information provided by the Oregon 2015 American Community Survey (ACS) Public Use Microdata Sample (PUMS). The data set contained demographic, social, and economic information for 39,992 respondents dwelling in 18,996 households. We maintained IMPLAN's household income classification scheme, but grouped these classes into low (less than \$50,000), medium (between \$50,000 and \$150,000), and high (greater than \$150,000) income households. Since Scouse et al.'s (2017) publication, the Bureau of Labor Statistics (BLS) found that the number of households in the lowest income categories had decreased, indicating that household incomes have been gradually increasing over time (Bureau of Labor Statistics, 2017). Therefore, it was necessary to move the low income threshold previously defined by Arita et al. (2013) from \$40,000 to \$50,000.

During construction of our reduced SAM, taxes associated with employee compensation and proprietary income were reallocated to exogenous institutional accounts on the basis of an industry output weighting scheme. Non-earnings components of value added included in the model were also treated as exogenous accounts. By excluding proprietor income (OPI) and taxes on production and import components of value-added (TOPI), it is likely that higher income households are underrepresented in our study (Olson, 2007). In addition, the reallocation of value-added components made it necessary to rebalance our SAM using the biproportional scaling technique described by Miller and Blair (2009). Matrix column sums served as control totals while consistency was forced between row and column sums over the course of sixteen iterations.

Following the SAM matrix rebalance, we applied the Leonteif Inverse (Miller & Blair, 2009) to generate the economic multipliers necessary for our assessment. To begin, a matrix of normalized expenditure shares (*S*) was generated by normalizing SAM matrix elements by their respective column totals. This step is described in Eq. (3). The *S* matrix was then subtracted from the reduced SAM's identity matrix to form the (*I-S*) matrix. Lastly, we inverted the (I–S) matrix to generate our SAM inverse matrix described in Eq. (4). This matrix could then be used to estimate the impacts of economic scenarios taking place in Oregon in the year 2015.

$$S = \frac{z_{ij}}{X_{.j}} \tag{3}$$

$$SAM\ Inverse\ Matrix = (I - S)^{-1} \tag{4}$$

2.2. Defining economic scenarios

After constructing our SAM model, it was shocked with economic "events" that represented the construction of the 12-story mixed-use Framework building frame in downtown Portland. Only architectural and structural element purchases were considered. Two scenarios were evaluated: Frameworks construction using a mass timber frame and Frameworks construction using a concrete frame. After obtaining impact estimates for each individual scenario, we modeled mass timber frame construction alongside the subsequent loss of the concrete frame building. Modeling the opportunity cost in this way illustrates important economic trade-offs; constructing a building using CLT and glue laminated timber results in reduced purchases of concrete, steel, and other components traditionally used in high-rise construction. By modeling mass timber products in markets traditionally served by concrete and steel, study results highlight how product substitution influences supply chains and regional economic impacts.

We defined our scenarios using the analysis-by-parts methodology. Day (2012) provides detailed information regarding the application of this technique. Construction costs data for Framework's 12-story mass timber and concrete frames were estimated using RSMeans' online database which contains adjustments for Portland, Oregon construction costs (RSMeans, 2018). The total cost of each building component consisted of material, labor, equipment rental costs, and overhead and profit. Because CLT costs are not available via RSMeans, glulam material and installation costs were considered representative of CLT. The total cost of installed CLT was defined as \$1919 per cubic meter. CLT material costs were \$1440 per cubic meter, or 75 % of the total installed cost. Labor costs were \$159 per cubic meter, or 8% of the total installed cost. Equipment rental costs were \$60 per cubic meter, or 3% of the total installed cost. While overhead costs were \$260 per cubic meter, or 14 % of the total installed cost. To quantify the impact of product price on scenario economic impacts, we varied CLT's selling price across the scenarios from \$600 to \$1500 per cubic meter based on Brandt et al.'s (2019) techno-economic analysis, which accounted for price variability based on manufacturing variables like yearly production volume and facility size. Labor, equipment rental, and overhead costs associated with CLT were also adjusted based on their original fixed percentage contribution.

Once construction cost estimates were defined for CLT and concrete building alternatives, these costs were deflated by 13.1 % to year 2015 dollars using the producer price index for industrial building construction products in order to provide harmonization with our 2015 SAM matrix (Bureau of Labor Statistics, 2018). Material, labor, equipment rental, and overhead purchases were assigned to their appropriate industry sector based on IMPLAN's sectoring scheme. Labor costs were allocated as payments to households based on ACS industry-to-household distributions. Equipment rental costs were allocated to the commercial and industrial machinery and equipment rental and leasing sector. Lastly, overhead costs were allocated to the construction of new multifamily residential structures sector.

After purchases were assigned to their appropriate sector, they were multiplied by that sector's corresponding regional purchase coefficient (RPC). RPCs, which range from 0 to 1, describe the proportion of regional demand that is supplied by local producers. We explored the impact of local CLT panel production by varying the model RPC for the "engineered wood product manufacturing" sector. When the engineered wood product sector RPC was set to 0.00, we described a scenario where CLT panels were purchased from outside the study area and imported to the construction site, representing a form of economic leakage. When the sector's RPC was assigned as 0.51, this scenario represented the current state of local engineered wood product purchasing in Oregon. When this RPC was set to 1.00, the scenario assumed that all CLT panels were sourced from in-state manufacturers. Table 1 describes relevant scenario purchases, presented in year 2019 dollars.

3. Results & discussion

3.1. Mass timber frame

The cost of the 12-story Framework building frame when constructed using mass timber was \$8.83 million dollars (year 2019 dollars, Table 1). This estimate included the price of materials, labor, equipment rental, overhead, and profit related to the building's architectural and structural elements. The cost estimate for the mass timber frame was considerably higher than the functionally equivalent concrete frame. This is due to high material, labor, and overhead costs associated with CLT, which were designated as similar to glulam for this analysis, as they were already known and estimated by RSMeans software. Mass timber and other engineered wood product elements were the most significant cost contributors to the building frame, representing 38 % of the structure's overall cost at \$3.39 million dollars. Project overhead and profit, were allocated to the "construction of new multifamily residential structures" sector, was the second largest cost contributor at \$1.54 million dollars, or 18 % of structure costs. Earnings paid for construction labor was the third largest cost contributor at \$1.39 million dollars, or 16 % of structure costs. Equipment rental, necessary for structural element installation, represented 3% of overall structure costs at \$262,616 dollars. Other relevant purchases included

Table 1
Framework construction sector purchases and sector regional purchase coefficients (RPC) by functionally equivalent frame designs.

IMPLAN sector code	Sector Name	RPC	Mass Timber Frame	Concrete Frame
60	Construction of new multifamily residential structures	1.00	$1,541,736	$1,003,215
137	Engineered wood member and truss manufacturing	0.51	$3,387,277	$20,582
177	Paint and coating manufacturing	0.22	$135,927	$132,172
192	Polystyrene foam product manufacturing	0.02	$151,971	$151,984
206	Ready-mix concrete manufacturing	0.75	$188,499	$464,104
211	Gypsum product manufacturing	0.59	$305,923	$227,651
217	Iron and steel mills and ferroalloy manufacturing	0.28	$104,875	$334,808
237	Prefabricated metal buildings and components manufacturing	0.35	$369,250	$369,522
238	Fabricated structural metal manufacturing	0.27	$353,587	$308,567
240	Metal window and door manufacturing	0.15	$504,462	$504,829
445	Commercial and industrial machinery and equipment rental and leasing	0.68	$262,616	$146,439
N/A	All other sectors	N/A	$134,238	$132,729
10001 – 10009	Labor	1.00	$1,390,389	$1,074,006
Total Cost			**$8,830,751**	**$4,870,608**
Regional Spending			**$5,558,613**	**$3,119,225**

window components, aluminum siding, and cold formed structural steel. Based on the regional SAM model built for this analysis, 63 % of the money spent on the mass timber frame ($5.56 million dollars) went to purchase goods or services from local, Oregon based businesses.

Because CLT is a lighter building material than steel or concrete, mass timber designs requires less foundation concrete to support the building's frame, which reduces the environmental impact of a building via resource efficiency while conforming to green building strategies. To illustrate this point, when Waugh Thistleton Architects & Techniker Engineers designed the Stadthaus in London, England, the mass timber design resulted in a 70 % reduction in foundation concrete (Byle, 2012). In addition to environmental advantages, less concrete can also indirectly shorten construction timelines, which in turn decreases the overall interest paid out for construction loans (Cazemier, 2017). Although Framework's mass timber design was more expensive than the comparative concrete design, our study found that the mass timber frame reduced ready-mix concrete purchases by 60 %. This observed reduction in concrete supports the assertion that mass timber designs support sustainable development by mitigating greenhouse gas emissions (Liang et al., 2020; Wang, Toppinen, & Juslin, 2014).

Model results indicate that constructing the Framework building using a mass timber frame generated a total economic impact of $9.71 million dollars, of which $3.92 million are earnings generated by direct employment in the construction supply chain and from induced purchases of goods and services throughout the Oregon economy (Table 2). Utilization of PUMS datasets into our reduced SAM model also allowed us to differentiate generated earnings by household income class. High-income households received 40 % of generated earnings, middle-income households received 52 %, and 8% went to low-income households. The $9.71 million dollar economic impact estimate can be described using an economic impact multiplier of 1.75, meaning that for every dollar spent on the Frameworks mass timber frame, an additional $0.75 of economic activity was generated by indirect and induced economic effects. This scenario multiplier agrees well with IMPLAN's regional multipliers for construction based industries, which range anywhere from 1.70 to 1.97 (IMPLAN Group L.L.C., 2018).

It is worthwhile to highlight the important role regional industries play in creating economic impacts by meeting product and service demand. Because CLT and other engineered wood products constitute a large portion of the building's cost (approximately 38 % of the frame cost), the economic impact estimate depends heavily on the degree to which engineered wood products are supplied by local manufacturers. IMPLAN data for the state of Oregon in 2015 asserts that 51 % of regional engineered wood product demand is met by local suppliers. Engineered wood products industries rely upon purchases from upstream suppliers which have even larger RPCs, indicating that regional forest product sectors have strongly linked supply chains which support local businesses and regional employment. For example, "sawmill" and "cut stock, resawing lumber, and planning" industries, which would supply lumber to CLT facilities, have RPCs of 0.61 and 0.92.

When CLT panels and all other necessary engineered wood construction materials were imported from outside the state, the economic impact of the Framework building dropped to $5.99 million dollars while household earnings dropped 24 % to $2.99 million (Table 3). In the opposite case, when engineered wood product demand was met completely by Oregon manufacturers, the economic impact of the scenario rose to $13.27 million dollars while household earnings rose 23 % to $4.81 million dollars. These estimates indicate that CLT construction has the potential to increase regional earnings over time as the product and its manufacturing establishes a regional foothold and gains market share. With this in mind, policy makers focused on sustainable development must encourage lumber manufacturers and forestry operations to grow alongside of mass timber construction to take full advantage of the potential environmental and economic benefits associated with local sourcing.

3.2. Concrete frame

The estimated cost of the Framework building when constructed with a concrete frame was $4.87 million dollars (year 2019 dollars). Labor was the most significant cost contributor for the concrete structure, coming in at 22 % or $1.07 million dollars. Overhead and profit was the second largest cost contributor, making up 21 % of the structure cost or $1.00 million dollars. Scenario ready-mix concrete use was

Table 2
Economic impact comparison of Framework building construction by functionally equivalent frame designs.

	Mass timber frame*	Relative Percentage	Concrete frame	Relative Percentage
Industry output	$5,785,719	–	$2,572,437	–
Low-income household earnings (< $50,000)	$317,705	8 %	$184,282	8 %
Mid-income household earnings ($50,000–$150,000)	$2,037,611	52 %	$1,165,097	50 %
High-income household earnings (> $150,000)	$1,563,998	40 %	$983,093	42 %
Total impact	$9,705,033		$4,904,909	

* Assumes an engineered wood product (EWP) sector regional purchase coefficient (RPC) of 0.51.

Table 3
Economic impact of mass timber frame construction by varying levels of regional engineered wood product sourcing (regional purchase coefficients of 0.00, 0.51, and 1.00).

	RPC = 0.00	RPC = 0.51	RPC = 1.00
Industry output	$3,002,168	$5,785,719	$8,460,111
Low-income household earnings (< $50,000)	$236,625	$317,705	$395,604
Mid-income household earnings ($50,000–$150,000)	$1,483,663	$2,037,611	$2,569,836
High-income household earnings (> $150,000)	$1,269,865	$1,563,998	$1,846,595
Total impact	$5,992,321	$9,705,033	$13,272,147

2.5 times greater than the mass timber frame and concrete purchases from this sector represented 10 % of the structure's overall cost. Commercial and industrial equipment rental expenses were similar to the mass timber scenario at 3% or $146,439 dollars. Other relevant purchases for the concrete frame included window components, aluminum siding, cold formed structural steel, window components, and steel reinforcing rod. Of the $4.87 million dollar estimate, 64 % or $3.12 million was spent within the state of Oregon.

With a concrete frame design, the estimated construction of the Frameworks building generated a total economic impact of $4.90 million dollars for the region, of which $2.33 million were earnings and wages to households. Approximately 42 % of those earnings were distributed to high income households, 50 % of earnings were distributed to middle income households, and 8% were distributed to low income households. The remaining $2.57 million dollars represented industry growth throughout relevant supply chains. The economic impact of the concrete frame construction scenario can be described using an economic multiplier of 1.57, somewhat smaller than the mass timber frame alternative (1.75), indicating that mass timber construction creates larger economic impacts and earnings for regional households while offering a more sustainable building design.

This smaller multiplier associated with the concrete frame was due to multiple effects acting in conjunction. One explanation is that the concrete frame required roughly three times the amount of rebar than the mass timber alternative. Rebar is manufactured from iron and steel industries that are not heavily present within the region (RPC of 0.28). This means that 72 % of the money spent on rebar transfers outside the state and no longer circulates through the Oregon economy, creating economic leakage. In comparison, Oregon based forest industries like engineered wood product manufacturing, sawmilling, and commercial logging have regional PRCs of 0.51, 0.61, and 0.96, respectively. Demand for products from these industries are more likely to be supplied by local businesses, which increases the regional direct, indirect, and induced economic impacts created by product use and manufacturing.

In addition to industry regional presence, it is important to consider the degree to which individual sectors create wages and earnings. Ready-mix concrete and iron and steel manufacturing sector earnings multipliers are 0.41 and 0.26, respectively. This means that for every dollar of product sold, $0.41 and $0.26 of earnings are generated through direct, indirect, and induced employment. Theses earnings multipliers can be contrasted with the somewhat larger 0.54, 0.62, and 0.91 earnings multipliers for respective engineered wood product, sawmill, and forestry sectors. Indicating that specifying locally sourced wood products in green building projects creates additional earnings and wages through economic ripple effects than do purchases of ready-mix concrete or iron and steel. Therefore, sustainable economic development policy should encourage the utilization of mass timber designs in relevant applications as they utilize sustainable and local timber resources while creating greater regional earnings through forest sector employment.

3.3. Net economic impacts

While an economic event's gross impacts can be helpful in illuminating regional gains that result from industry growth, Hughes et al. (2008) points out that it is necessary to consider net impacts by quantifying scenario opportunity costs. Therefore, impact analysis studies that focus on mass timber designs should recognize that constructing multi-story buildings with CLT and glulam is a departure from traditional steel and concrete construction methods and presents opportunities for product substitution that significantly affect the building design process and construction supply chain. To estimate how green building substitution can influence economic impacts, we modeled construction of the 12-story mass timber Frameworks building alongside an equivalent reduction in construction via the concrete frame.

When both mass timber frame construction and a functional equivalent loss of concrete frame construction were modeled alongside one another at the default level of local engineered wood product manufacturing (RPC = 0.51), the event produced a net positive economic benefit of $4.80 million dollars (Table 4, Fig. 1). The bulk of the additional economic growth, approximately 70 %, represented additional industry output. The remaining 30 % of the net impact, or $1.59 million dollars, came from increased employee earnings. Once again, net impacts depend upon the degree to which CLT panels and other wood products were sourced within the region. If all necessary wood products were imported from outside the study area (RPC = 0.00), the net positive economic impact of mass timber frame construction dropped to $1.09 million dollars while generated earnings dropped to $0.66 million dollars. Under this scenario, it is appropriate to conclude that the economic impacts of mass timber are only slightly advantageous to concrete construction when mass timber elements are imported into the region from non-local producers. However, when mass timber elements are sourced exclusively from local manufacturers (RPC = 1.0), the economic impact can be driven as high as $8.37 million dollars, with $2.48 million of those dollars representing employee earnings that end up in local households. These results support Oregon BEST's (2017) assertion that regional CLT production has the potential

Table 4
Net economic impact of mass timber frame construction by varying level of regional engineered wood product sourcing (regional purchase coefficients of 0, 0.51, and 1).

	RPC = 0.00	RPC = 0.51	RPC = 1.00
Industry output	$429,731	$3,213,282	$5,887,674
Low-income household earnings (< $50,000)	$52,343	$133,423	$211,323
Mid-income household earnings ($50,000–$150,000)	$318,565	$872,514	$1,404,739
High-income household earnings (> $150,000)	$286,773	$580,905	$863,503
Total impact	$1,087,412	$4,800,123	$8,367,238

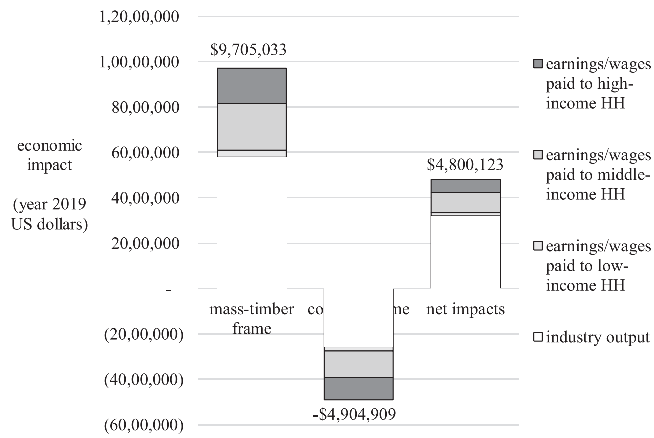

Fig. 1. Gross and net impacts associated with the construction of the Frameworks building using a mass timber frame after accounting for product substitution effects.
*HH = households.

to support rural and urban economies by generating employment opportunities that provide livable wages while at the same time facilitating climate change mitigation through green building.

Another implication of modeling the opportunity costs of mass timber construction alongside concrete is the ability to identify scenario specific winners and losers. When mass timber replaced concrete in the Frameworks building, the ready-mix concrete, iron and steel mill, and sand and gravel mining sectors loss $185,122, $62,838, and $22,387 dollars' worth of economic activity, respectively. Ready-mix concrete and sand and gravel purchases do tend to be highly local (RPCs of 0.75 and 0.89, respectively) in the state of Oregon, likely due to the bulky nature of these products which prevents long transportation distances. However, these economic losses were offset by positive economic gains for upstream CLT suppliers like logging, sawmilling, and lumber resawing and planing industries equivalent to $332,531 dollars. This finding suggests that mass timber construction will generate negative economic trade-offs for some regional industries, but these losses are offset by economic gains in forest-based sectors.

3.4. Sensitivity analysis

The nature of CLT as a specialized product, coupled alongside its early adoption status in the U.S., means that the unit price of CLT is relatively uncertain. Academic literature suggests that CLT's minimum selling price from the manufacturer likely ranges from $600 to $750 per cubic meter. This cost per unit is influenced by a number of variables like facility size, the facility's ability to run at full capacity, raw material prices, and the cost of delivery. Under certain contexts, the minimum selling price of CLT can climb as high as $1500 (Brandt et al., 2019). This study modeled and reported regional economic impacts of mass timber construction based on a CLT price of $1440 per cubic meter. However, to better understand how CLT price influences regional impacts, we varied the price of CLT from $600 to $1500 per cubic meter across scenarios and report net impacts based on these upper and lower bound price estimates.

At the state of Oregon's default level of local engineered wood product sourcing (RPC = 0.51), the net economic impacts generated by constructing the 12-story building using a mass timber frame ranged from $2.39 million dollars at a CLT price of $600 per cubic meter to $4.97 million dollars at a CLT price of $1500 per cubic meter (Fig. 2). This estimate includes the economic losses resulting from decreased concrete frame construction. This economic impact translated to an additional $0.79 to $1.64 million dollars paid to Oregon households in the form of earnings and wages. However, when CLT panels are sourced exclusively from outside the study area (RPC = 0.00), economic impacts drop heavily. Framework construction using imported wood products generated an economic impact that ranged from $0.32 million dollars at a CLT price of $600 per cubic meter to $1.14 million dollars at a CLT price of $1500 per cubic meter. This finding suggests that mass timber construction will not generate additional economic impacts over traditional concrete construction when mass timber elements are imported. Local production of mass timber frame elements, along with CLT selling price, are the substantial drivers of economic impacts. When Framework's mass timber elements are sourced exclusively from Oregon wood product manufacturers (RPC = 1.00), the net economic impact of building construction rises to $4.38 million dollars at a CLT price of $600 per cubic meter to $8.65 million dollars at a CLT price of $1500 per cubic meter. Under this scenario, mass timber construction generated an additional $1.29 to $2.56 million dollars of earnings and wages, the majority of which were paid out to middle and high income households. This finding suggests that economic impacts of mass timber construction are greatest during the early stages of product adoption, when local CLT manufacturers are producing on a relatively small scale and product prices are set high to account for the increased risk of early market entry.

3.5. Housing affordability

The 12-story Framework building was slated for construction in downtown Portland, OR, an area with notorious housing affordability challenges. Population growth and in-migration as a result of economic expansion have drastically shaped Portland's housing situation and by 2015, approximately half of Oregon renters were "housing cost burdened," spending over one-third of their income on housing costs. Homeowners, alongside renters, have also felt the financial pressure of housing. Since 1970, the average value of a Portland home increased from 1.6 to 2.9 times the average household income while high housing costs have disproportionately impacted low income households, minority communities, residents on fixed incomes, and individuals with disabilities (Diller & Sullivan, 2018). In addition to improving the environmental performance of buildings, sustainable urban development must also address housing affordability as a critical societal and economic issue.

Simply constructing multi-unit dwellings using mass timber designs will not address housing affordability through the lowering of construction costs. As shown in this study, CLT designs can be more expensive than functionally equivalent alternatives utilizing traditional construction practices. One alternative approach has advocated for government intervention to ensure new multi-family construction projects offer dwelling units at a range of prices to ensure that tenant occupancy is balanced amongst income level (Been, Ellen, & O'Regan, 2019). Since 2017, permits for Portland based multi-family construction projects with over 20 units require that 20 % of dwelling units be allocated to families' earnings less than $58,650 a year (Diller & Sullivan, 2018). By offering all 60 apartment dwellings as affordable housing units, the Framework building highlights how mass timber high-rise construction can simultaneously support an economically productive and environmentally sustainable forest products sector, address housing affordability, and reduce the environmental burden of high-rise construction and operation (Framework, 2019).

4. Conclusions

This work presents unique economic impact results that compare mass timber green building techniques alongside traditional concrete construction while providing estimates that consider relevant opportunity costs, a technique rarely seen in economic impact assessment studies. The 12-story Frameworks building with a mass timber frame generated larger economic impacts for the state of Oregon than a functionally equivalent concrete frame alternative. Constructing Framework with mass timber created an additional $2.39–$4.97

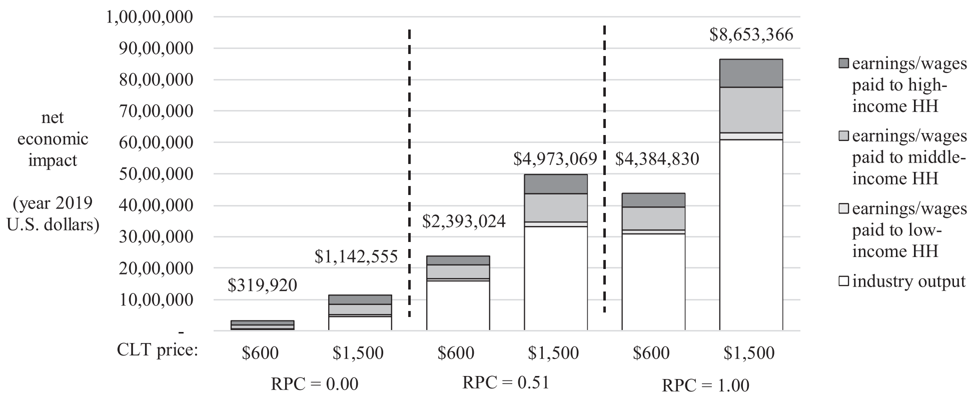

Fig. 2. Net economic impact generated by construction of the Frameworks building using a mass timber frame according to CLT price and level of regional engineered wood product sourcing.
*HH = households, RPC = regional purchase coefficient.

million dollars of economic activity, assuming that approximately half of CLT elements were sourced from Oregon manufacturers. This estimate includes opportunity costs as a result of product substitution. Intuitively, increasing the amount of locally sourced mass timber elements during construction drastically increased the overall local economic impacts by providing earnings to local residents, particularly for middle and high-income housholds. When mass timber construction required importing wood product elements from manufacturers outside the study area, net economic impacts of mass timber and concrete frame scenarios become relatively similar.

This analysis concentrated on construction purchases associated with architectural and structural elements, which represented approximately 30 %–45 % of overall building costs. Purchases of other building components, like exterior and interior doors and windows, fittings, and services were similar for both mass timber and concrete frames and would not create differences in economic impacts for the two building frames. In addition, the study did not take into account relevant savings that might be realized from other aspects of mass timber construction like reduced construction time or subsequent savings on construction loan payments. It is in the construction phase where mass timbers can accomplish substantial savings through quicker assembly, over 50 % faster than other alternative materials (APA, 2019).

Green building techniques that frame high-rise buildings with mass timber is a form of product substitution and created net losses in three relevant traditional sectors, ready-mix concrete manufacturing, iron and steel mills and ferroalloy manufacturing, and sand and gravel mining. Negative economic impacts resulting from product substitution were more likely to result from losses in the ready-mix concrete sector, as ready-mix concrete tends to be a locally produced product (RPC = 0.75). Reduced spending in the iron and steel mills and ferroalloy manufacturing sectors did not affect regional impacts as drastically, as this industry did not have much local presence in the region (RPC = 0.28) and purchases from this industry created substantial economic leakage.

As mass timber construction moves purchases move away from ready-mix concrete and steel and into engineered wood products, economic impacts which benefit the local economy increased due to regional supply chain characteristics. The extent of those impacts were maximized when mass timber and other engineered wood products were sourced locally within the state at high prices. Oregon's forest based industries tend to be strongly backward linked, with relatively large RPCs and earnings multipliers. Therefore, mass timber construction can offer a unique and innovative green building construction style to meet high-rise construction demand while utilizing regionally grown and sustainable wood resources and creating additional economic impacts for the state of Oregon.

5. Study limitations

This study focused its analysis on the construction of one mass timber building as a short-term one-time impact that supports local employment and wages, without necessarily translating to additional job creation. By doing so we better conform to traditional SAM input-output modeling limitations. Other limitations pertinent to this study, described in better detail by Bess and Ambargis (2011), included assumed industry homogeneity, fixed production patterns, fixed prices, and zero supply chain constraints. By adhering to the supply constraint assumptions, our economic scenario suggested that regional construction demand can be met with the current supply of materials and labor. This study made no attempts to address mass timber's ability to influence lumber or labor prices as the construction technique grows. It also asserts that the current timber inventory in the Pacific Northwest was capable of meeting potential CLT demand. For a more comprehensive analysis of how these assertions influence regional economic impacts and the wood products supply chain, see Oregon BEST (2017).

Study results should also be interpreted with the following limitations in mind. The scenarios analyzed in this study did not include design costs, purchases of property, or purchases of building components that were not part of the architectural or structural integrity of the building. Including these purchases would better represent the actual cost of the mass timber and concrete designs while boosting impact estimates. Therefore the estimates presented here were likely conservative in nature. In addition, labor costs associated with CLT installation were modeled as similar to glulam, which may not adequately reflect labor savings typically recognized for mass timber frames (Burback & Pei, 2017; Mallo and Espinoza, 2016). However, the major limitation of this study is the assumption that construction of the Frameworks building using a CLT design would take place despite the presence of cheaper, functionally equivalent design and material alternatives. This assumption depends upon consumer willingness to pay for the aesthetic value of heavy timber construction, the perceived sustainability of the building material, and potential benefits associated with faster construction timelines.

Declaration of Competing Interest

This original manuscript has yet to be published and is not under consideration for publication at any other journals. In addition, manuscript authors do not have any conflict of interests to disclose. Thank you for the consideration.

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