Comparison of Building Construction and Life-Cycle Cost for a High-Rise Mass Timber Building with its Concrete Alternative

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Abstract

Mass timber building materials such as cross-laminated timber (CLT) have captured attention in mid- to high-rise building designs because of their potential environmental benefits. The recently updated multistory building code also enables greater utilization of these wood building materials. The cost-effectiveness of mass timber buildings is also undergoing substantial analysis. Given the relatively new presence of CLT in United States, high front-end construction costs are expected. This study presents the life-cycle cost (LCC) for a 12-story, 8,360-m^2 mass timber building to be built in Portland, Oregon. The goal was to assess its total life-cycle cost (TLCC) relative to a functionally equivalent reinforced-concrete building design using our in-house-developed LCC tool. Based on commercial construction cost data from the RSMeans database, a mass timber building design is estimated to have 26 percent higher front-end costs than its concrete alternative. Front-end construction costs dominated the TLCC for both buildings. However, a decrease of 2.4 percent TLCC relative to concrete building was observed because of the estimated longer lifespan and higher end-of-life salvage value for the mass timber building. The end-of-life savings from demolition cost or salvage values in mass timber building could offset some initial construction costs. There are minimal historical construction cost data and lack of operational cost data for mass timber buildings; therefore, more studies and data are needed to make the generalization of these results. However, a solid methodology for mass timber building LCC was developed and applied to demonstrate several cost scenarios for mass timber building benefits or disadvantages.

The building sector is the largest consumer of primary energy (Intergovernmental Panel on Climate Change 2014). Globally, approximately 40 percent of carbon dioxide emissions have been traced to the building industry (Abergel et al. 2017), especially from energy-intensive concrete and steel use along with operational energy use in buildings. Substituting concrete and steel with low environmental impact building materials such as lumber and engineered wood products along with the more recently developed mass timber products has attracted interest as a climate change mitigation strategy (Sathre and O'Connor 2010, Wang et al. 2014, Anderson et al. 2019). Wood products offer not only carbon storage benefits but also low carbon footprints during their life-cycle stages (Bergman et al. 2014, Oliver et al. 2014, Sahoo et al. 2019). Mass timber, formed with massive wood material, has been approved as suitable for mid- to high-rise buildings (Hasburgh et al. 2018, Pei et al. 2018, Wang et al. 2018, Zelinka et al. 2019). The opportunity to mitigate climate change using mass timber materials in construction globally would advance sustainability in the built environment (Fargione et al. 2018, Churkina et al. 2020).

Mass timber, as a generic engineered wood product, includes glulam, laminated veneer lumber, and cross-laminated timber (CLT; American National Standards Institute/APA—The Engineered Wood Association [ANSI/APA] 2019). CLT is a large-scale, engineered solid wood

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panel, fabricated with kiln-dried boards stacked in several odd-numbered layers, usually 3, 5, 7, or 9. Each layer is aligned perpendicularly to its adjacent layer and bonded with structural adhesive. Such engineered products minimize wood's inherited expansion and differential shrinkage problem and increase stability and structural capacity. CLT can provide strength comparable with steel and concrete as structural building materials that can be used as prefabricated walls and floors in building systems (Karacabeyli and Douglas 2013, Anderson et al. 2019). The method to make CLT and similar wood products dates back to the early 20th century in the United States (Walch and Watts 1923). CLT manufacturing and construction has received more consideration in Europe during the past few decades, but more recently it is gaining attention in North America. Several mid- to high-rise mixed-use commercial, residential, and institutional mass timber buildings have been built globally (Forestry Innovation Investment [FII] 2016, WoodWorks 2019), and interest in using CLT in North America is expanding. The updated 2021 International Building Code includes mechanisms for using mass timber in new construction Type IV-A/B/C for up to 18 stories for residential and commercial buildings (Breneman and Richardson 2019).

Current CLT research has focused on structural, moisture, acoustic, thermal, market, and environmental performances to promote CLT use in mid- to high-rise residential building (Williamson and Ross 2016, Oregon BEST 2017, Zelinka et al. 2019, Scouse et al. 2020). One of the greatest advantages of a CLT structure is the safety and efficiency during the construction process brought about by easy material handling and off-site prefabrication of the CLT panels (ThinkWood 2018, APA 2019) along with decreased waste generation and noise level on the building site. In addition to the renewable nature of wood, mass timber structures also exhibit a significantly lower carbon footprint compared with similar structure made from concrete (Karacabeyli and Douglas 2013, Pierobon et al. 2019, Dong et al. 2020, Liang et al. 2020). The cost-effectiveness of mass timber buildings has received attention from academies and industries. The construction cost differential between mass timber and other traditional building structures is under hot debate (Oregon BEST 2017, Kremer and Ritchie 2018, Cary Kopczynski & Company 2018, Smith et al. 2018) because very little transparent data and cost analyses are available on the market. This makes the estimation of initial costs for mass timber buildings hard to generalize. Life-cycle cost (LCC) performance to examine the total economic effectiveness of mass timber buildings is even more limited.

LCC analysis is an economic technique to evaluate the total cost performance of an ownership over a designed study period (Dwaikat and Ali 2018). In the building industry, LCC analysis is applied to compare different design options of whole buildings, building systems, and building materials (ASTM International 2017, Tam et al. 2017). It is used to determine the cost-effectiveness of building designs or explore trade-offs between initial costs and long-term cost savings and to identify cost-effective systems for a given application. Limited LCC research has been conducted to compare mass timber buildings with traditional concrete and steel buildings. One recent publication (Liang et al. 2019) developed the methodology set-up and comparison scheme to provide information on cost-performance for mid- to high-rise mass timber buildings. The publication was intended to set up the LCC tool for mass timber buildings but with only a hypothetical case analysis.

As part of a larger project centered on a pioneering high-rise mass timber building named Framework, Kelley and Bergman (2017) focused on the LCC analysis (LCCA) task. The analysis included different scenarios to compare the cost-performance of a high-rise CLT mass timber building from the construction document (CD) with a concrete alternative building with schematic design (SD). The SD phase in construction design entails comprehensive and detailed drawings (e.g., sections, floor plans, elevations, schedule), whereas the CD is the final blueprint that contains details from structural to mechanical, electrical, and plumbing systems along with material quality and quantity specifications. With these practical design data from the Framework building, the LCC tool developed by Liang et al. (2019) will be applied in this study.

Despite the important role that LCCA plays in helping architects, property owners, and even policy makers make decisions on material choice, historically there have been challenges with the method (Evison et al. 2018, Anderson et al. 2019). These challenges come from incomplete data for maintenance and replacement costs associated with the new mass timber buildings, as well as uncertainty about the end-of-life schemes for CLT mass timber buildings (Anderson et al. 2019). LCCA methods need to address the uncertainties and incomplete data as well as risk factors inherent with system inputs in order to provide a conclusive analysis. Therefore, sensitivity analysis using the LCCA developed in this study is included at the end to show the potential cost benefits of the mass timber building with these uncertainties in the mass timber building sector.

Goal and Scope

The goal of this study was to compare the total life cycle cost of a mass timber building with its functionally equivalent concrete alternative using the LCCA methodology developed by Liang et al. (2019) following the general guidelines of ASTM E917-17 and ISO 15686-5 standards (ASTM International 2017, International Organization for Standardization 2017). The LCCA tool was applied to the construction design for the Framework 12-story mixed-use office and apartment complex mass timber building in Portland, Oregon. The scope of this building LCCA covered building construction cost, operational cost, maintenance and repair (M&R) cost, and residual value and/or demolition cost at the end of building life for a study period of 60 years. It should be noted as a point of uncertainty (Kuzman and Sandberg 2017, Markström et al. 2019) thatthe design for this mass timber building was assumed to last for 100 years as explicitly specified by the building architect (Heppner 2018). In addition, financial variables such as discount and escalation rates were used in the analysis, whereas the land acquisition, planning, and externalities such as management and insurance were excluded.

Building Design

As the first high-rise mass timber building in the United States, a 12-story, 8,360-m^2 floor area, mixed-use office–apartment complex was designed using CLT and glulam materials. The design for the mass timber building was a detailed CD with materials takeoff. The building was

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designed to be built in Portland, Oregon, but the project was on hold as a result of funding gaps (Framework 2020). Then a functionally equivalent building with concrete and the same fire-proofing performance, insulation, and energy consumption outcomes was also designed for a comparison analysis. Both building designs were completed by LEVER Architecture (Portland, Oregon) with additional structural design and analysis from their partner, KPFF Engineering (Seattle). Both buildings comply with Type 1B fire-resistive construction code with noncombustible capacities of 2-hour exterior walls, 2-hour structural frame, 2-hour ceiling–floor separation, and 1-hour ceiling–roof assembly. The bill of materials (BOM) for the two buildings was taken from the design blueprints and was grouped into the assemblies of ceilings–roof, floor, foundation, post–beam, and walls. Material quantity comparison of the two buildings is shown in Table 1. Total weight of the mass timber building was about 33 percent less than the concrete building because of the lighter weight of CLT compared with concrete when used in buildings for structural materials.

Life-Cycle Cost Analysis Methodology

LCCA is a method to evaluate the cost-effectiveness of building construction from its initial cost including permit and design cost, material and construction cost; its use stage cost including utility, maintenance, and replacement; and end-of-life building deconstruction demolition costs with residual and salvage value. The LCC also encompasses the time value of money by discount feature costs as they occur with time. Inflation was excluded with real-term price escalation rates applied to utilities. The future value of money is discounted to the present value (PV) in the LCC calculations to be able to sum and compare the results. These calculations are presented as follows.

Life-cycle cost computation

To analyze the cost-effectiveness of the mass timber building from a whole-life-cycle perspective, the building's total life-cycle cost (TLCC) was calculated as the PV of construction cost ($\mathrm{PV}_{\mathrm{Construction}}$), utility cost ($\mathrm{PV}_{\mathrm{Utility}}$), M&R cost ($\mathrm{PV}_{\mathrm{M\&R}}$), and residual–salvage value or cost at the end of building service life or study period ($\mathrm{PV}_{\mathrm{EoL}}$; Eq. 1).

$$\mathrm{TLCC} = \mathrm{PV}_{\mathrm{Construction}} + \mathrm{PV}_{\mathrm{Utility}} + \mathrm{PV}_{\mathrm{MR}} + \mathrm{PV}_{\mathrm{EoL}} \tag{1}$$

The costs occurring in any future year cannot be simply summed because of the effect of time on the value of money. They must be discounted to the PV of base-year dollars prior to summation, as shown in Equation 2. The PV is the current value of a future lump sum of money or stream of cash flows given a specified rate of return or discount rate.

$$\mathrm{PV} = \sum_{t=0}^{N} \frac{C_t}{(1+d)^t} \tag{2}$$

where C_t = the sum of all relevant costs ($) occurring in year t; d = discount rate; and N = the study period (number of years).

The construction cost $\mathrm{PV}_{\mathrm{Construction}}$ is the direct building construction cost in the year 0. It includes the cost of building materials, labor, and overhead during the construction process. The PV of utility cost ($\mathrm{PV}_{\mathrm{Utility}}$) includes PV of electricity ($\mathrm{PV}_{\mathrm{Electricity}}$), natural gas ($\mathrm{PV}_{\mathrm{Gas}}$), and water ($\mathrm{PV}_{\mathrm{Water}}$) costs (if applicable), as shown in Equation 3. The utility components use the same formula to calculate the PV. For example, the PV of electricity ($\mathrm{PV}_{\mathrm{Electricity}}$) is the summation of discounted electricity cost including projected utility price escalation, as shown in Equation 4.

$$\mathrm{PV}_{\mathrm{Utility}} = \mathrm{PV}_{\mathrm{Electricity}} + \mathrm{PV}_{\mathrm{Gas}} + \mathrm{PV}_{\mathrm{Water}} \tag{3}$$

$$\mathrm{PV}_{\mathrm{Electricity}} = \sum_{t=1}^{N} \frac{A_0 \times (1+e)^t}{(1+d)^t} \tag{4}$$

where A_0 = the estimated annual cost ($) in base year 0; e = the price escalation rate; d = the discount rate; and N = the study period (year).

The PV of total M&R cost ($\mathrm{PV}_{\mathrm{M\&R}}$) is the sum of PV of annual maintenance, nonannual repair, and major replacement, as shown in Equation 5. The calculation of PV for M&R costs shares the same approach with electricity PV calculation in Equation 4.

$$\mathrm{PV}_{\mathrm{MR}} = \mathrm{PV}_{\mathrm{Maintenance}} + \mathrm{PV}_{\mathrm{Repair}} + \mathrm{PV}_{\mathrm{Replacement}} \tag{5}$$

The PV of building residual value at the end of the study period is estimated through linear deterioration of building construction cost for the building life span. The demolition cost and salvage value, when the building reached its end of service life, were estimated using RSMeans data (RSMeans 2018). More details on this LCC calculation model can be found in Liang et al. (2019).

Cost data and financial variables

The building construction cost estimation relies on the BOMs from the architectural designs and material cost data from RSMeans. RSMeans is a database of current building construction cost estimates. It includes localized industry-averaged cost data for construction materials, labor, transportation, and storage. The operational energy use—such as daily electricity, natural gas, and water usage—usually can be estimated through energy simulation software and plumbing design systems. The operational cost can be calculated by multiplying energy and water use by the current utility rate. The building M&R cost could be collected from a commercial database for building construction, such as RSMeans, or based on professional inputs. The M&R cost for mass timber buildings is not available at this time and is difficult to obtain because most mass timber buildings in North American have been built within the past 10 years and no recorded historical data are available. Therefore, the M&R costs were estimated based on M&R frequencies from a case study using an Athena report (Gu

Table 1.—Material comparison of mass timber building and concrete alternative building.

	Mass timber building		Concrete building	
Building assemblies	Mass (kg)	Percentage	Mass (kg)	Percentage
Ceilings–roof	214,865	4.2	105,250	1.4
Floors	2,965,104	57.9	4,653,033	61.6
Foundation	335,531	6.5	412,998	5.5
Columns and beams	339,600	6.6	447,186	5.9
Walls	1,269,582	24.8	1,929,490	25.6
Total	5,124,683	100	7,547,958	100

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and Bergman 2018) and the unit material costs from the RSMeans database.

The discount rate varies to reflect the building owner's expected return and risk on investment. Other variables such as utility prices and escalation rate could be obtained from relevant authorities. In this study, the discount and escalation rates were used in their real terms. A discount rate of 3 percent was assumed, and escalation rates for electricity (1%), natural gas (2%), water (4.5%), and labor wages (0.6%) were based on US government statistics and the literature (US Department of Energy 2017, Lavappa and Kneifel 2018, US Department of Labor Bureau of Labor Statistics 2018).

The utilities and M&R recurring costs are expected to increase at their escalation rates, and the future costs need to be calculated in the base year dollars, as shown in Equation 6:

$$A_t = A_0 \times (1 + e)^t \tag{6}$$

where $A_t =$ the annual cost ($) in year t; $A_0 =$ the estimated annual cost ($) in base year 0; and $e =$ the price escalation rate.

Sensitivity analysis

This LCCA study includes various uncertainties from input variables and assumptions. Sensitivity analysis is a useful tool to determine how changing independent variables affects the results under a given set of assumptions. Such analysis will provide the effect of changes in inputs on the outputs and increase the understanding of relationships between input and output in a system.

In the following case study, the sensitivity analysis was applied to the study period (testing study periods ranging from 20 to 75 yr) and the discount rate (ranging between 0% and 10%) to evaluate their impacts on the building LCC analysis. More sensitivity analysis was also completed for the inputs with uncertainties, such as CLT material price, salvage or residual values at the end of building life or end of building study period, and M&R cost for mass timber buildings.

Comparison analysis was completed using different end-of-life scenarios to examine the TLCC advantage or disadvantage of the CLT mass timber buildings to assist architects, developers, and policy makers to make science-based decisions.

Results

Construction cost

There were no itemized cost estimates provided from the architects or building contractors for the two designed buildings. Therefore, the material unit, labor, and overhead costs for each material included in the BOMs were quoted from the RSMeans 2018 database. For the most common building materials, cost data can be found from RSMeans database. For CLT, the unit cost was estimated based on the glulam cost, including the labor and overhead cost data found in the RSMeans, as a proxy. These construction costs are all based on the material's regional industry average cost data in Portland, Oregon. The summarized construction costs for the two buildings grouped into building assemblies are presented in Table 2 and Figure 1.

In this case, the mass timber building is estimated to have 88 percent higher total front-end costs compared with the concrete building with the data calculated based on the BOM provided from the building designs and RSMeans database. This was due to the higher price for CLT and glulam as noncommodity products compared with concrete and steel as commodity products. Even though manufacturers of CLT are emerging because of the increasing demands in the building sector, the price is still high as a result of limited suppliers in North America. In the mass timber building, CLT is mainly used in the floor and wall assemblies and glulam is used for post and beam assembly, whereas less expensive concrete is mainly used in these assemblies for the concrete building. If full commercialization of mass timber products is achieved, the front-end cost of high-rise mass timber buildings can become more competitive, especially with the time and cost savings during the erection of high-rise mass timber buildings compared with traditional concrete buildings (FII 2016, Oregon BEST 2017, WoodWorks 2019).

Table 2.—Two different high-rise building construction costs by assembly types.

	Construction cost estimation (US$)			
Assembly type	Material	Labor	Overhead	Total
Ceiling and roof				
Mass timber building	164,819	240,260	149,794	554,873
Concrete building	98,592	126,928	80,347	305,867
Floor				
Mass timber building	2,138,568	408,303	428,117	2,974,988
Concrete building	574,012	236,041	181,824	991,877
Foundation				
Mass timber building	60,701	50,489	37,115	148,306
Concrete building	84,444	71,526	53,035	209,005
Post and beam				
Mass timber building	936,605	142,659	170,023	1,249,287
Concrete building	173,503	57,780	50,749	282,032
Wall				
Mass timber building	1,708,556	1,091,486	750,321	3,550,362
Concrete building	1,110,229	975,842	635,150	2,721,221
Total				
Mass timber building				8,477,816
Concrete building				4,510,002

Total life-cycle cost comparison

The above described methodology (Eqs. 1 to 5) was applied to calculate the TLCC of the two buildings, one with CLT and glulam and one with concrete and steel as the main building materials. Each LCC component (construction cost, operational energy and water cost, M&R cost, and end-of-life deconstruction cost-residual value-salvage value) was calculated separately for each year and then discounted to the base year (year 0) for TLCC.

Annual utility cost data including energy and water consumption are listed in Table 3, in which the electricity and natural gas consumptions were simulated by Integrated Environmental Solutions Virtual Environment software and the water usage was estimated based on the plumbing system design. The prices for electricity, natural gas, and water-sewer were obtained from governmental authorities (City of Portland 2018, Portland Oregon Electricity

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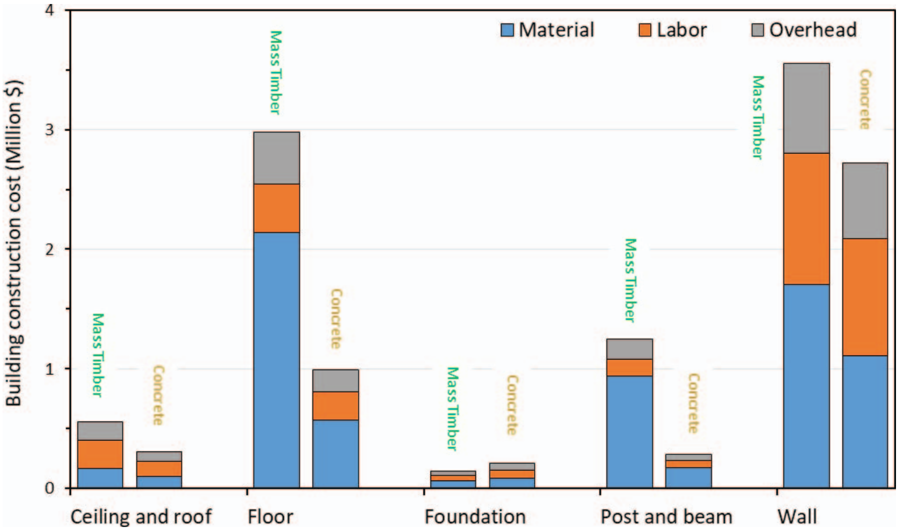

Figure 1.—Front-end construction costs by assembly type for high-rise mass timber and concrete buildings.

Statistics 2018, US Energy Information Administration 2018). The two buildings were designed to be functionally equivalent, so the annual operational energy and water use were the same for both buildings.

In this analysis, extra costs to include interior and exterior doors, exterior windows, fittings and services components, which were not provided in the BOM, were added. The total of the extra costs was estimated as $10,593,434, based on the square-foot cost estimator in RSMeans. Adding these costs to the construction cost of the buildings resulted in the final front-end costs of $19,071,250 and $15,103,437 for the mass timber building and the concrete building, respectively (Table 4).

In this study, we assumed the life span of the mass timber building was 100 years based on the architect's design and the life span of the concrete building was 75 years. This assumption was made based on the survey study of actual service lives of North American buildings by O'Connor (2004). It was discovered that wood buildings lasted longer than concrete buildings primarily as a result of the suitability of buildings. Scenario analyses were conducted that varied the building's service life and study period to evaluate the uncertainty of this key assumption (ASTM International 2017). There is not much difference in the use-stage costs of the two buildings because the assumption was made that the two buildings were functionally equivalent. Therefore, only the front-end construction costs and end-of-life cost or value play an important role in the TLCC comparisons.

The TLCCs of mass timber and concrete buildings with a 60-year study period were calculated and given in Table 4.

Table 3.—Annual utility cost estimation for the mass timber and concrete buildings.

Utility	Annual use	Unit	Unit price	Mass timber building (US$)	Concrete building (US$)
Electricity	738,128.00	kWh	$0.0845	62,372	62,372
Natural gas	332	MCF	$8.88	2,947	2,947
Water	2,250.30	CCF	$37.55	84,495	84,495

Under the base assumptions above, the TLCC for the mass timber building was $25.87 million, which was $0.64 million (2.4%) lower than the concrete building over 60 years. Specifically, front-end construction costs were 26 percent higher for the mass timber building, but the end-of-life value in year 60 was 153 percent higher than the concrete alternative. For the mass timber building 60-year TLCC, 57 percent of costs were from the construction costs, 31 percent from utility costs, and 12 percent from the M&R costs (excluding the building residual value). The percentage distribution is similar to an Australian study (Islam et al. 2015). Another recent green building study from Malaysia stated that 48 percent of building TLCC is from operational energy costs (Dwaikat and Ali 2018). However, comparing these results with other studies in the literature creates uncertainties because of the different model assumptions, building types, and geographical conditions.

TLCCs for study periods of 20 years, 40 years, and 75 years were also calculated for the two buildings with the methodology described above, and the results are presented in Table 5 and Figure 2. The building's residual value, if not being demolished at the end of the study period, was estimated with a linear deterioration from original construction cost to 0 percent beyond building longevity of 100 years or 75 years for mass timber and concrete buildings, respectively.

Table 4.—60-year study period life-cycle cost for the two high-rise buildings with base assumption. TLCC = total life-cycle cost; M&R = maintenance and repair; EoL = end-of-life.

	TLCC (US$)		
	Mass timber building	Concrete building	Difference (%)
Building	19,071,250	15,103,437	26.3
Energy	2,323,166	2,323,166	0
Water	8,183,069	8,183,069	0
M&R	3,917,780	3,921,900	0
EoL	−7,628,500	−3,020,687	152.5
Total	25,866,765	26,510,884	−2.4

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Table 5.—Total life-cycle costs (TLCC) of the high-rise mass timber and concrete buildings for different study years.

		Cost categories[a]						
Yr	Building type	Building	Energy	Water	M&R	EoL	TLCC	Difference (%)
20	Mass timber	19,071,250	1,079,683	1,977,936	1,912,585	−15,257,000	8,784,454	−2.4
	Concrete	15,103,437	1,079,683	1,977,936	1,910,843	−11,075,854	8,996,046	
40	Mass timber	19,071,250	1,817,620	4,629,217	3,146,949	−11,442,750	17,222,286	−2.4
	Concrete	15,103,437	1,817,620	4,629,217	3,145,261	−7,048,271	17,647,264	
60	Mass timber	19,071,250	2,323,166	8,183,069	3,917,780	−7,628,500	25,866,765	−2.4
	Concrete	15,103,437	2,323,166	8,183,069	3,921,900	−3,020,687	26,510,884	
75	Mass timber	19,071,250	2,595,404	11,621,971	4,282,553	−4,767,813	32,803,365	−4.6
	Concrete	15,103,437	2,595,404	11,621,971	4,287,932	787,952	34,396,697	

[a] M&R = maintenance and repair; EoL = end-of-life.

The TLCC increased as the study period increased as a result of incurring future costs for utilities and M&R as well as building deterioration. The TLCC for the mass timber building increased from $8.8 million for 20 years to $32.8 million for 75 years, in which the PV of building residual value decreased from $15.3 million to $4.8 million (Table 5).

When the residual value was included in the TLCC, the higher cost of the mass timber building was reversed at the end of each building study period (Table 5, Fig. 2). There was about a 2.4 to 4.6 percent decrease in TLCC for the mass timber building compared with the concrete building. At the end of 75-year study period, the concrete building was assumed to be demolished. Thus, there is demolition cost and salvage value left in the concrete building. The mass timber building has lower TLCC than the concrete alternative regardless of the study periods under this case assumption.

Discussion

Mid- to high-rise mass timber construction is just starting in North America and, more specifically, in the United States. Many unknowns exist in the cost estimates for construction and operations, which is causing many building developers and investors to hesitate to move forward. Therefore, sensitivity analyses and scenario analyses are helpful to reveal the life-cycle cost performance of mass timber buildings affected by these uncertainties.

Sensitivity analysis

The discount rate reflects the investor's expectation for return on time value of money. The effect of changing discount rate was evaluated by varying the base case rate of 3 percent down to 0 percent and up to 10 percent. The TLCC results from varying the discount rate for a 60-year study period are shown in Figure 3. The TLCC decreased as the discount rate increased, which was expected because future costs have a lower present value at higher discount rates. The lowest discount rate 0 to 1 percent was comparable with the long-term Treasury bill rate (US Department of the Treasury 2020). With the 1 percent discount rate, the TLCC for 60 years on the mass timber building was $39.2 million, which was $0.65 million (1.6%) lower than the concrete building. At the high discount rate of 10 percent, the TLCC for the mass timber building was $15.0 million, $0.64 million (4.1%) less than the concrete building. The change of discount rate significantly affected

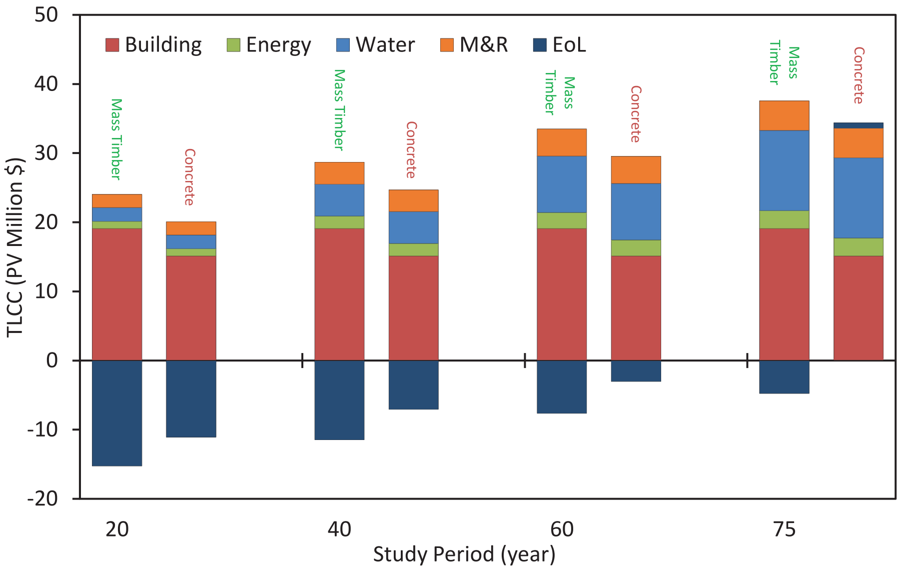

Figure 2.—Comparing the total life-cycle costs (TLCC) for the high-rise mass timber and concrete buildings under different study years.

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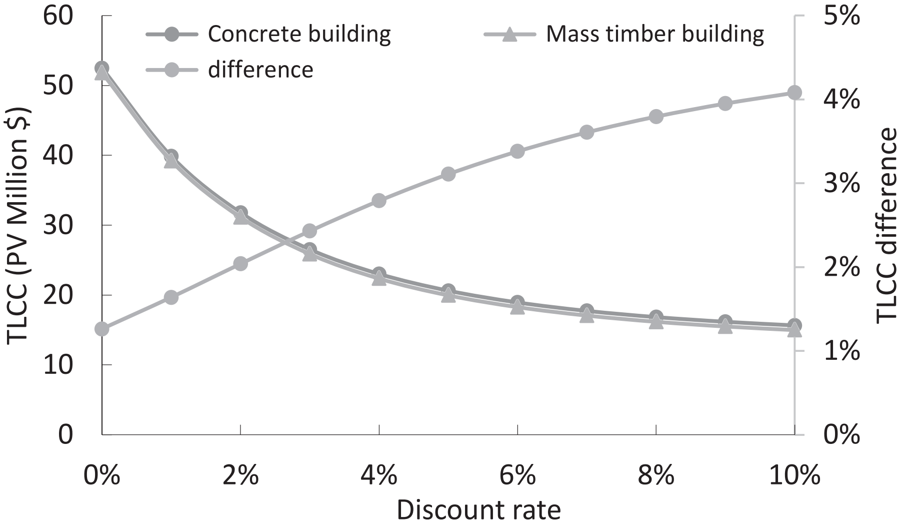

Figure 3.—Impacts on the total life-cycle costs (TLCC) and difference between the two buildings with the change of discount rate. PV = present value.

the PV of future costs of utilities, M&R, and building residual value at the end of study period. However, the PV of building construction costs was not affected substantially because the initial construction cost only happens at the early stages. The effects of discount rate variations on TLCC were significant. Therefore, care should be taken when making comparisons with other studies using different discount and inflation assumptions.

More sensitivity analysis was done on the input parameters—including the CLT price, gypsum board usage, M&R cost, residual value, and salvage value—beyond building life span. Figure 4 shows the changes of building TLCC affected by 30 percent variations of each of these costs and values. The TLCC is most sensitive to the building residual value, followed by M&R costs, and then CLT price. An increase or decrease of 30 percent in the CLT price could introduce a 4 percent increase or decrease in TLCC, which is nearly double the estimated TLCC savings.

Scenario analysis

Scenarios with different assumptions on the building life span for the two comparable buildings and direct front-cost assumptions were made to examine the TLCC performance for the two buildings. Below are the assumptions for each scenario constructed.

Scenario S0 was the base scenario in this study. S0 assumed the life span for the mass timber building was 100 years according to the architect's design, but the concrete building only lasted 75 years with a study period of 60 years. Therefore, at the end of study period, both buildings would have some residual value, and it was estimated by the LCC method with results shown above. Four more scenarios were made with different life span assumptions and recycling values and costs at the end of building life span for the two buildings.

- Scenario S1 assumed both buildings would last 75 years before demolition, with a study period of 60 years. Thus,

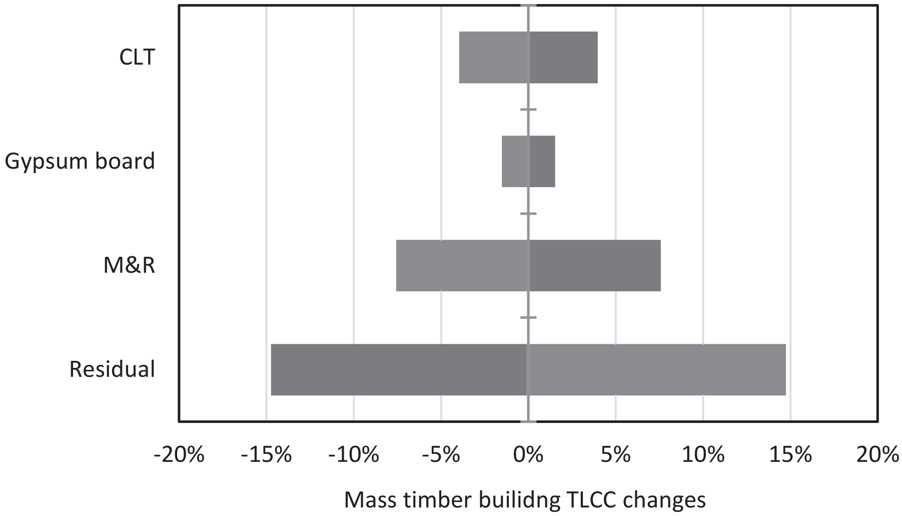

Figure 4.—Changes in the mass timber building total life-cycle cost (TLCC) at 60-year end of study period from the input values. CLT = cross-laminated timber; M&R = maintenance and repair.

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both buildings have an estimated residual value at the end of the study period.

- Scenario S2 assumed both buildings will last 60 years, with a study period of 60 years. The concrete building would be demolished, whereas the mass timber building would be deconstructed, and 70 percent of CLT and glulam would be further recycled, during which 75 percent of these could be further reused as virgin materials to estimate the salvage values.
- Scenario S3 assumed both buildings would be demolished after 75 years, with a study period now extended to 75 years. In this scenario, the deconstruction cost and salvage values of the two buildings were calculated the same as in Scenario S2.
- Scenario S4 was based on the default study assumptions (S0) but added $5 million to the initial construction cost of both buildings to increase the front-end cost. This addition to the front-end cost represented extra cost for building permit applications, design costs, and more.

The resulting TLCCs of the two buildings under these scenarios are shown in Table 6 and Figure 5. From the results of these scenarios, it was found that the TLCC for the mass timber building would have a cost advantage with its

Table 6.—Total life-cycle cost (TLCC) analysis for high-rise mass timber and concrete buildings under various scenarios.

Scenario[a]	Building	Energy	Water	M&R[b]	EoL[c]	TLCC	Difference (%)
S0							
Mass timber	19,071,250	2,323,166	8,183,069	3,917,780	−7,628,500	25,866,765	−2.4
Concrete	15,103,437	2,323,166	8,183,069	3,921,900	−3,020,687	26,510,884	
S1							
Mass timber	19,071,250	2,323,166	8,183,069	3,917,780	−3,814,250	29,681,015	12
Concrete	15,103,437	2,323,166	8,183,069	3,921,900	−3,020,687	26,510,884	
S2							
Mass timber	19,071,250	2,323,166	8,183,069	3,917,780	−1,137,894	32,357,371	6.7
Concrete	15,103,437	2,323,166	8,183,069	3,921,900	787,952	30,319,524	
S3							
Mass timber	19,071,250	2,595,404	11,621,971	4,282,553	−1,137,894	36,433,283	5.9
Concrete	15,103,437	2,595,404	11,621,971	4,287,932	787,952	34,396,697	
S4							
Mass timber	24,071,250	2,323,166	8,183,069	3,917,780	−10,400,000	28,095,265	−7.0
Concrete	20,103,437	2,323,166	8,183,069	3,917,593	−4,315,816	30,215,755	

[a] S0 =Base scenario assuming life span of the mass timber building is 100 yr, concrete building is 75 yr, and the study period is 60 yr; S1 = scenario assuming life span for both buildings is 75 yr, and the study period is 60 yr; S2 = scenario assuming life span for both buildings is 60 yr and at the end of 60-yr study period, both buildings will be demolished; S3 = scenario assuming life spans for both buildings are 75 yr and the study period is 75 yr; S4 = scenario increasing the front-end construction cost to include preconstruction costs, such as permit and design costs, and the other assumptions are the same as S0.

[b] M&R = maintenance and repair.

[c] EoL = end-of-life.

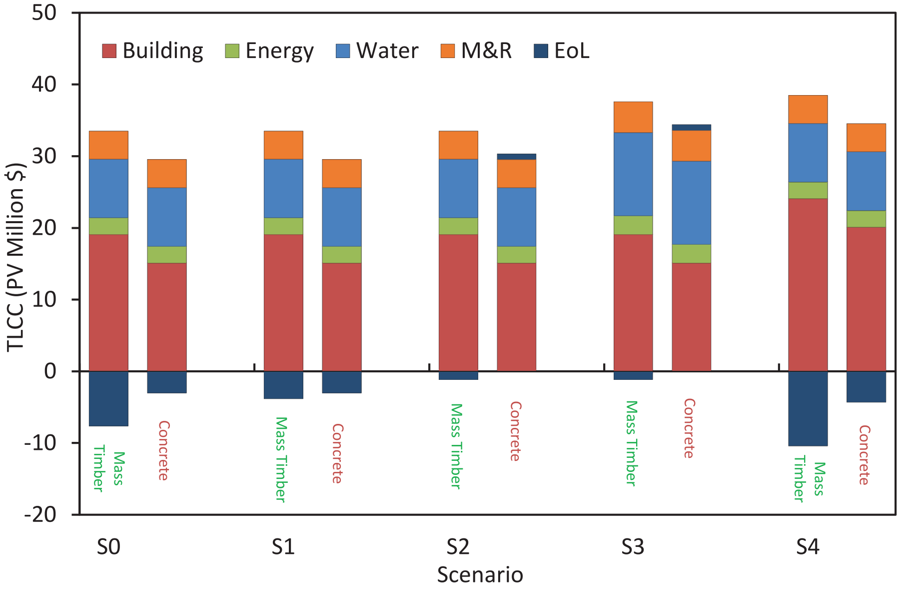

Figure 5.—Total life-cycle cost (TLCC) analysis for high-rise mass timber and concrete buildings under various scenarios. PV = present value; M&R = maintenance and repair.

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longer life span (100 yr) than the concrete alternative (75 yr) when other factors are the same (see Scenario S0 and S4), and the higher front-end cost (value) showed an even greater advantage of 7.0 percent difference (Scenario S4). When the life spans of the two buildings were the same, the end-of-life cost or value of the mass timber building was not able to be offset by the higher front-end costs (see Scenario S1 [12%], S2 [6.7%], and S3 [5.9%]). In this case study, the two buildings were designed to be functionally equivalent. Thus, we assumed the same operational utility and maintenance during the building-use stage. No impact from these parts were considered in the TLCC calculations on the cost-performance for the comparison of the two buildings. But if there are energy savings discovered in the new mass timber buildings, the LCC analysis would reveal more cost benefits (Liang et al. 2019).

Limitations

The construction costs for the two buildings were completely based on the BOM from architectural designs and a commercial construction cost database (RSMeans). Thus, the results from this study might not reflect the current actual construction costs for high-rise mass timber buildings. At the moment there is no commercial market price for the CLT product because of the limited number of manufacturers in United States. Preliminary estimations showed a selling price range from \$518 to \$601 per m^3 (Bédard et al. 2010, Brandt et al. 2019). In addition, the M&R costs in the mass timber building were assumed to be same as the common concrete and steel buildings because there is a lack of any historical data on the M&R for high-rise mass timber buildings. With the mass timber industry and building sector's increasing knowledge of these shortcomings, a more clear and complete picture of the economic benefits of mass timber buildings will be established with the help of the LCC tool.

Conclusion

Cost benefits from a whole-building life-cycle perspective were examined in this study by applying the previously developed LCC tool (Liang et al. 2019) to a 12-story mass timber building with detailed design parameters. Results were then compared with a functionally equivalent concrete building. The front-end costs were 26 percent higher for the mass timber building than its concrete alternative. However, because of its estimated much higher end-of-life salvage value compared with the concrete building, the TLCC calculated for a 60-year study period reversed the cost and showed about a 2.4 percent cost advantage for the mass timer building. Additionally, this LCC analysis approach was heavily sensitive to the variation of study period and discount rate. With the extended sensitivity analysis, the TLCC for mass timber buildings would have a cost advantage if the mass timber building had a longer life span (100 yr) than the concrete alternative (75 yr) when other factors are the same, and the higher the front-end cost (value) of the mass timber buildings, the more benefits would be declared in the TLCC results. When the life spans of the two buildings are the same, the end-of-life cost or value of the mass timber building would not be able to offset the higher front-end cost. In this case study, our two buildings were designed based on functional equivalency and thus were assumed to have the same operational cost. Therefore, there is no impact from these costs on the economic performance for the two buildings. However, if the mass timber building was designed with premium energy and water savings, then more cost benefits would be projected for the TLCC at the building's end-of-life study period. High recycling rates and values of the CLT and glulam materials used in high-rise mass timber buildings would improve the cost benefits of mass timber buildings as anticipated and observed in this study.

Environmental benefits or carbon savings from the new emerging mass timber products used in buildings have been observed. Cost to invest in such low-to-zero carbon-emission buildings is trending up. Sustainability return on investment will be examined in our next analysis in which the life-cycle assessment with LCC will be combined for the same mass timber building. With more mid- to high-rise mass timber buildings being erected in North America, currently unavailable data on M&R and service life will be collected, studied, and incorporated into LCC analyses and the associated tool. This life-cycle cost analysis will be more powerful and will help investors and stakeholders to choose building strategies.

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