

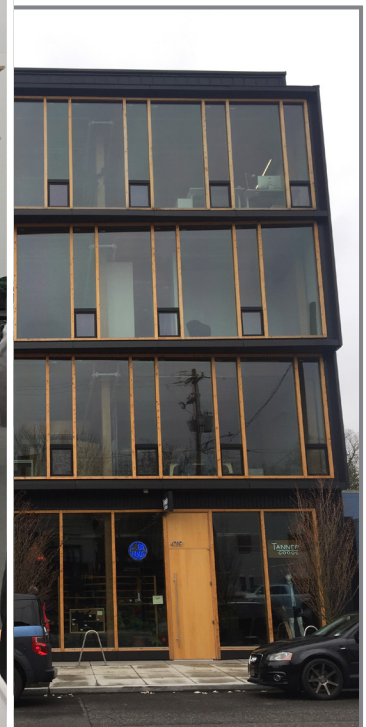


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Life-Cycle Cost Analysis of a Mass Timber Building

Methodology and Hypothetical Case Study

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Abstract

The use of cross-laminated timber (CLT) as a building material is gaining popularity in the North American building sector, especially in mid- to high-rise building designs. This study presents the methodology of life-cycle cost analysis (LCCA) and an example of a hypothetical case study in Portland, Oregon, USA, of a CLT mass timber building compared with a baseline code-compliant concrete alternative. It was found, not unexpectedly, that the mass timber building with premium energy and water saving designs exhibited a lower total life-cycle cost (TLCC) than a concrete building for a 60-year study period under provided research assumptions and limitations. The construction cost dominated the TLCCs for both buildings. Little to no historical construction and operational data exist for mass timber buildings in North America, which made this analysis limited for generalizing the results. However, a solid methodology was established for future LCCA on mass timber buildings, and cost-specific data will be implemented when the information becomes available.

Keywords: Cross-laminated timber, life-cycle cost analysis, mass timber building, sensitivity analysis

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Life-Cycle Cost Analysis of a Mass Timber Building

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Introduction

Sustainability in the building sector has become increasingly vital. The USDA Forest Service, Forest Products Laboratory (FPL) has long been providing critical research to support the wood industry's sustainability profile in the market (Ritter and others 2011). Wood in general is recognized for its sustainability, overall low environmental impact, natural beauty, and speed of construction (Jakes and others 2016, Ramage and others 2017, Gu and Bergman 2018). For instance, cross-laminated timber (CLT)—a new option for constructing mass timber buildings in the United States—offers advantages including renewable material, lighter carbon footprint (CFP), long-term carbon storage within completed structures, and lighter foundations and footings compared with steel and concrete buildings (Pei and others 2016, FPIInnovations 2013, Espinoza and others 2016, Asdrubali and others 2017).

CLT is a large-scale, engineered wood panel product, fabricated with kiln-dried boards stacked to 3, 5, 7, or 9 layers. Each layer is aligned perpendicularly to its adjacent layer and bonded with structural adhesive. This engineered designed product minimizes wood's inherent expansion and differential shrinkage problem and increases the stability and structural capacity of wood. CLT can provide comparable strength with steel and concrete as a structural building material and can be used as prefabricated walls and floors in building systems (Karacabeyli and Douglas 2013). The production of CLT and similar perpendicular engineered wood products dates back to the early 20th century in the United States (Walch and Watts 1923). CLT manufacturing and construction has received attention in Europe in the last few decades, and many mid- to high-rise mixed-use commercial, residential, and institutional mass timber buildings have been built globally (FII 2016). Interest in manufacturing and construction using CLT or similar engineered mass timber products in North America is expanding. Current CLT research in the United States is focusing on structural, moisture, acoustic, thermal,

market, and environmental performances to promote CLT use in mid- to high-rise residential buildings (Oregon BEST 2017, Williamson and Ross 2016). The greatest advantage of a CLT structure is the safety and efficiency during the construction process brought about by easier handling and higher-level prefabrication compared with alternative materials (Kremer and Symmons 2015, Smith and others 2018, Connolly and others 2018). There is also less waste generation and noise pollution during construction. In addition to the renewable aspect of wood in a CLT structure, it also exhibits a significantly lower CFP compared with similar structures made from concrete (Karacabeyli and Douglas 2013, Gu and Bergman 2018). The cost effectiveness of mass timber buildings has received attention from academia and industry. The construction cost differential between mass timber and other traditional building structures is under intense debate (Bowyer and others 2013, Cary Kopczynski & Company 2018, Oregon BEST 2017). Very limited economic data and research are available on the market for accurate estimations of initial costs of mass timber buildings. The studies on life-cycle cost analysis (LCCA) for mass timber buildings are even more limited.

LCCA is an economic technique to evaluate the total life-cycle cost performance of a building during a designed study period (ASTM 2017, Dwaikat and Ali 2018). In the building industry, LCCA is applied to compare different design options of whole buildings, building systems, and building materials (ASTM 2017, Tam and others 2017). It is used to determine the cost effectiveness of building designs, to explore trade-offs between initial costs and long-term cost savings, and to identify cost-effective systems for a given application. This study focused on the methodology of LCCA of mass timber building and compared the life-cycle cost performance of a conceptual CLT mass timber building with a typical concrete building designed to meet basic code requirements. This analysis is part of a more comprehensive project investigating the CLT supply chain along with the potential economic contributions and environmental

implications of increased mass timber building construction (Kelley and Bergman 2017). The methodology set-up and comparison analysis in this research provided hypothetical information on life-cycle cost performance of mid- to high-rise mass timber buildings, which is a new, emerging idea in construction.

Goal and Scope

The goal of this study was to set up LCCA methodology for mass timber buildings based on the general guidelines of ASTM E917-17 and ISO 15686-5 standards (ASTM 2017, ISO 2017). A hypothetical case study of a conceptual design of a 12-story mixed-use office and apartment mass timber building was applied to evaluate life-cycle cost performance. The design was compared with a concrete code design with the same building dimensions for the city of Portland, Oregon, USA. The scope of this building LCCA covered building construction cost, operational cost, maintenance and repair (M&R), and residual value at the end of study period of 60 years. In addition, financial variables such as inflation, discounts, interest, and escalation rates, as well as taxation were included in this analysis, whereas the land acquisition, planning, and externalities such as management and insurance were excluded.

Methods

LCCA is a method of assessing the life-time costs arising from the development, construction, operation, decommissioning, and disposal of a building or constructed asset, including both capital and operating costs (ASTM 2017, Bionova/One Click LCA 2018, Bowyer and others 2013, ISO 2017). This study was based on compiling all these phases as described in the following details from ASTM E917-17.

Cost Data and Financial Variables

In performing an LCCA, the building construction cost should be obtained from contractors' estimates or building construction databases, such as RSMeans, with updated cross-industry averages for the bill of materials provided by the architects or building designers. The operational cost such as annual electricity, natural gas, and water usage usually can be estimated through energy simulation software and plumbing design systems. The building M&R cost can be estimated by building professionals based on historical records or a commercial database for building constructions. The M&R costs for mass timber buildings are not available at this time, and it is difficult to obtain from historical data because most mass timber buildings in North America have been built within the past 5 to 10 years. Therefore, the M&R costs for mass timber buildings were assumed to be the same as concrete buildings in this analysis. The uncertainty introduced in this assumption can be examined for effect with sensitivity analysis described in the following.

The discount rate varies to reflect the building owner's expected return and risk on investment. Other variables such as utility prices, interest rate, escalation rate, and tax rate can be obtained from relevant authorities. The financial parameters can be denoted at either real or nominal terms. In this study, the discount and escalation rates were used in their real terms and then converted into nominal terms to include the effect of general inflation.

The time-related costs (annual utilities and recurring M&R) are expected to increase at their escalation rates, and the future costs need to be calculated in the base-year dollars:

$$A_t = A_0 \times (1 + e)^t \quad (1)$$

where A_t is the annual cost (\$) in year t , A_0 is the estimated annual cost (\$) in base year 0, and e is the nominal price escalation rate.

The cost happening at any future year cannot be simply summed because of the time value of money and must be discounted to the base-year dollars prior to summation. The present value (PV) is the current year value of a future lump sum of money or stream of cash flow given a specified rate of return:

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

where C_t is the sum of all relevant cost (\$) occurring in year t , d is nominal discount rate, and N is the study period (in years).

Life-Cycle Cost Computation

To analyze the cost effectiveness of a mass timber building from the whole life-cycle perspective, the building's total life-cycle cost (TLCC) is calculated by the sum of PV of construction cost ($PV_{\text{Construction}}$), utility cost (PV_{Utility}), M&R cost ($PV_{\text{M\&R}}$), and residual value at the end of study period (PV_{Residual}):

$$TLCC = PV_{\text{Construction}} + PV_{\text{Utility}} + PV_{\text{M\&R}} - PV_{\text{Residual}} \quad (3)$$

The PV of construction cost ($PV_{\text{Construction}}$) is the sum of estimated front-end building construction down payment cost with the discounted annual loan cost and with the summation of discounted building asset depreciation subtracted:

$$PV_{\text{Construction}} = P_0 + \sum_{t=1}^m \frac{P_t - S_t \times T}{(1 + d)^t} - \sum_{t=1}^n \frac{K / n \times T}{(1 + d)^t} \quad (4)$$

where P_0 is the down payment of estimated construction cost (\$), P_t is the annual loan payment (\$) in year t , S_t is the annual interest proportion (\$) in year t , m is the loan term (years), K is the estimated total building and construction cost (\$), n is the building asset depreciation period (years), d is the nominal discount rate, and T is the tax rate.

The PV of utility cost ($PV_{Utility}$) is the sum of PVs of all utilities including electricity ($PV_{Electricity}$), natural gas (PV_{Gas}), and water (PV_{Water}) costs (if applied):

$$PV_{Utility} = PV_{Electricity} + PV_{Gas} + PV_{Water} \quad (5)$$

The utility cost PV is calculated using the same discounted approach. For example, the PV of electricity ($PV_{Electricity}$) is the summation of discounted electricity cost, with the escalation and tax deduction included:

$$PV_{Electricity} = \sum_{t=1}^N \frac{A_0 \times (1+e)^t \times (1-T)}{(1+d)^t} \quad (6)$$

where A_0 is the estimated annual cost (\$) in base year 0, e is the nominal price escalation rate, d is the nominal discount rate, t is the time of utility costs incurred (years), T is the tax rate, and N is the study period (years).

The PV of total M&R cost ($PV_{M\&R}$) is the sum of PVs of annual maintenance ($PV_{Maintenance}$), nonannual repair (PV_{Repair}), and major replacement ($PV_{Replacement}$):

$$PV_{M\&R} = PV_{Maintenance} + PV_{Repair} + PV_{Replacement} \quad (7)$$

The calculation of PVs for annual maintenance and nonannual repair shares the same approach with electricity PV calculation in Equation (6). In addition, the calculation of PV of major replacement cost ($PV_{Replacement}$) needs to include the depreciation, which happens from the next year after installation:

$$PV_{Replacement} = \sum_{t=1}^N \frac{R_0 \times (1+e)^t}{(1+d)^t} - \sum_{t=1}^{t+k} \left(R_0 \times \frac{(1+e)^t}{k} \times T \right) / (1+d)^t \quad (8)$$

where R_0 is the estimated replacement cost (\$) in base year 0, e is the nominal price escalation rate, d is the nominal discount rate, t is the time of replacement installation (years), N is the study period (years), k is the replacement frequency (years), and T is the tax rate.

The PV of building residual value at the end of study period ($PV_{Residual}$) is described in the following equation, which accounts for the estimated building resale value (C_{Resale}) and taxed capital gain (C_{Gain}), if applied:

$$PV_{Residual} = \begin{cases} C_{Resale} \times \frac{1}{(1+d)^N} & \text{if } C_{Gain} \leq 0 \\ (C_{Resale} - C_{Gain} \times T) \times \frac{1}{(1+d)^N} & \text{if } C_{Gain} > 0 \end{cases} \quad (9)$$

where d is the nominal discount rate, N is the study period (years), and T is the tax rate.

The building resale value (C_{Resale}) is estimated using a linear deterioration of original building construction cost:

$$C_{Resale} = K \times (1 - 1/Y \times N) \times (1+d)^N \quad (N \leq Y) \quad (10)$$

where K is the estimated front-end construction cost, Y is the building life span (years), N is the study period (years), and d is the nominal discount rate.

The capital gain (C_{Gain}) is the differential between the estimated building resale value (C_{Resale}) and the existing book value; the latter one is equal to the cumulative assets (building construction and major replacement costs) minus the cumulative depreciated assets. A survey of building longevity in the twin cities of Minneapolis and St. Paul, Minnesota, USA, by Athena Sustainable Materials Institute (Ottawa, Ontario, Canada) found that more than 65% of demolished wood buildings were older than 75 years and 60% to 80% of concrete and steel buildings were demolished at less than 50 years old (O'Connor 2004, McLain 2019). Indeed, according to a mass timber building designer, mass timber buildings are likely to survive for more than 100 years (Heppner 2018). Obviously, service life is a significant area of uncertainty given the relatively short market introduction of mass timber buildings constructed using CLT world wide. In this case study, we assumed that neither building would be demolished at the end of study period (60 years in this study). In addition, the demolishing cost for mass timber building could be much lower than that for traditional concrete or brick buildings because of the fast tear-down time and the recycling of materials.

Sensitivity Analysis

The building LCCA includes various uncertainties from input variables and assumptions. Therefore, uncertainty analysis, especially sensitivity analysis, was chosen as the tool to determine how different values of an independent variable would impact the dependent variable under a given set of assumptions. Sensitivity analysis provides the knowledge of effect of changes in inputs on the outputs and increases the understanding of the relationships between the inputs and outputs in a system. Inputs with uncertainties for mass timber buildings can be presumed with initial construction cost, service life time, M&R schedule, depreciation rate, residual value at the end of the study period, and general financial variables such as inflation rate and escalation rate, etc. In the following case study, the construction and M&R costs as well as the study period and discount rate were included in the sensitivity analysis.

Hypothetical Case Study

Assumptions

In this hypothetical case study, the LCCA of a proposed mass timber building with premium energy and water saving designs was compared with a baseline concrete design using

Table 1—Annual utility usage and cost estimation for proposed mass timber and concrete buildings

Utility ^a	Mass timber		Concrete	
	Usage	Cost	Usage	Cost
Electricity (kWh)	738,128	\$62,372	916,704	\$77,461
Natural gas (therm)	3,200	\$2,947	31,278	\$28,803
Water (gal)	2,250,300	\$84,495	3,214,714	\$103,254

^a1 kWh = 3.6 MJ; 1 therm = 105.5 MJ; 1 gal = 3.8 L.

the detailed method previously described. The designer for this mass timber building provided a raw number of \$26 million for the front-end construction cost, whereas the construction cost for a concrete building with the same dimensions and based to the fundamental building code was estimated at about \$21.6 million by RSMeans' Square Foot Estimator (RSMeans 2018). The estimated construction cost for this baseline concrete building quoted from RSMeans database only represents the industry average and built to code standard, which may exclude the premium add-in costs. The designer for the CLT building project claimed the proposed mass timber building could save 70% and 30% annual energy and water usage, respectively, compared with a typical code-compliant building. Mass timber use in buildings contributes energy efficiency in the operational stage because of the fact that wood is a thermal insulator, and CLT buildings should remain airtight during their service life (Glass and Zelinka 2010, WoodWorks 2019). The recently built 18-story Brock Commons Tallwood House at the University of British Columbia reported a total project cost of \$51.5 million. Total construction cost was roughly \$40.5 million or about \$23.12 per square meter. Design costs were \$3.8 million with 80% covering engineering and architectural services. The cost of the structural elements was only about 20% of its total construction cost. At this early adoption stage for such innovative tall wood buildings, additional design activities and costs in testing, regulatory approving, and planning are inevitable. Even considering this, the total construction cost of the Brock Commons was only ~8% higher than its concrete equivalent structure (Pilon and others 2018).

Additionally, it was assumed that 80% of total construction cost was financed with a commercial loan for a 10-year fixed term and an annual percentage rate (APR) of 7%. Annual utility cost data including energy and water consumption are listed in Table 1, in which the electricity and natural gas consumptions were simulated by IES Virtual Environment software (Integrated Environmental Solutions, Ltd., Glasgow, Scotland, UK) 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 (EIA 2018, Electricity Local 2018, Portland 2018).

The M&R cost data for concrete buildings were estimated through RSMeans database (RSMeans 2018), and the M&R costs for mass timber buildings were assumed to be the same in this case study because of lack of real practical data from current mass timber buildings around the world. In the future, changes could easily be made to the LCCA when the M&R cost schedule and estimation for mass timber buildings become available.

The building's residual value at the end of the study period was calculated by combining the estimated resale value, assets depreciation, book value, and capital gain taxation. The resale value was estimated in this case study with a linear deterioration from original construction cost to 0 beyond the 100 and 75 years for CLT mass timber and concrete buildings, respectively. However, a different building life span could be applied in this LCCA calculation tool.

The general inflation rate of 2.2% (based on the consumer price index) and a real discount rate of 3% served as baseline parameters in this case study. The real escalation rates for electricity (1%), natural gas (2%), water (4.5%), and labor wages (0.6%) were based on U.S. government statistics and literature (BLS 2018, DOE 2017, Lavappa and Kneifel 2018). The building was depreciated over 39 years, and the major replacements were also depreciated based on the implemented schedule (IRS 2018). Annual costs were assumed to be fully deductible, with taxable income and capital gains (if available) subject to a combined enterprise state/federal tax rate of 27%.

Analysis

The TLCCs of mass timber and concrete buildings with a 60-year study period were calculated and given in Table 2. Under the previously mentioned assumptions, the TLCC for the mass timber building was \$31.68 million after tax reduction, which was \$3.08 million (9%) lower than the concrete building by year 60. Specifically, the mass timber building was 21% higher than the baseline concrete code-compliant building in the PV of building construction cost, 25% lower in the PV of total utility cost, and 141% higher in the PV of building residual value at the end of study period. Overall, 59% of the TLCC was from construction,

Table 2—60-year total life-cycle cost for proposed mass timber and concrete buildings

Category	Life-cycle cost (million US \$)			
	Mass timber		Concrete	
	Before tax reduction	After tax reduction	Before tax reduction	After tax reduction
Construction	26.00	23.08	21.58	19.15
Energy	2.31	1.69	4.01	2.93
Water	8.18	5.97	10.00	7.30
Maintenance and repair	11.69	8.53	11.69	8.53
Residue	(10.40)	(7.59)	(4.32)	(3.15)
Total	37.78	31.68	42.96	34.76

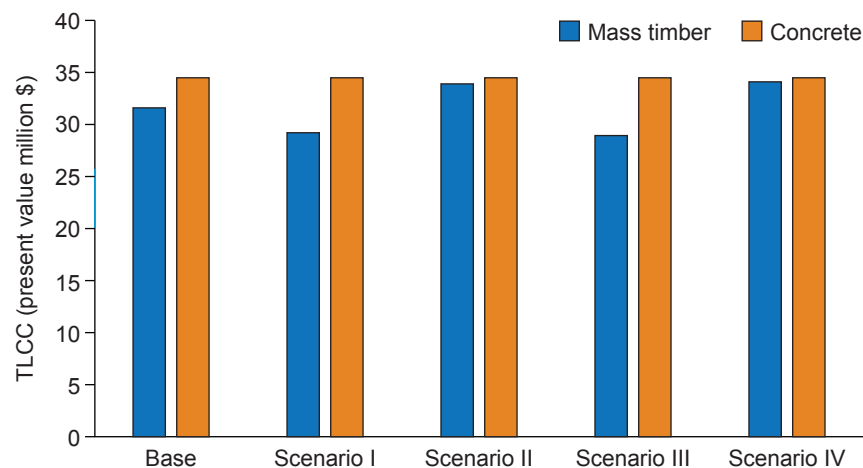


Figure 1. Total life-cycle cost (TLCC) of proposed mass timber and concrete buildings at different scenarios (Scenario I: Decrease 15% of the mass timber building front-end construction cost; Scenario II: Increase 15% of the mass timber building front-end construction cost; Scenario III: Decrease 30% of the mass timber building maintenance and repair (M&R) cost; and Scenario IV: Increase 30% of the mass timber building M&R cost).

19% from utilities, and 22% from M&R for the mass timber building (excluding the building residual credit). Each contribution to the 60-year TLCC with and without tax reduction is shown in Table 2 for two types of buildings.

Similar percentage distribution of each stage was also observed in an Australian study, in which PV of construction cost occupied 40% to 60% of TLCC (Islam and others 2015). Another recent building study from Malaysia stated that 48% of building TLCC was from operational energy cost (Dwaikat and Ali 2018). However, there is significant risk in comparing this result to other studies with different model assumptions, building types, and geographical conditions. In this study, water was the hot spot in overall utility cost, which accounted for 78% and 71% PVs of utility cost for mass timber and concrete buildings, respectively. However, the water savings should not directly relate to the use of CLT mass timber but instead to the

building design difference. In additional scenarios, $\pm 15\%$ variation on the front-end construction cost and $\pm 30\%$ variation on the M&R costs for the mass timber building were assumed for scenario analysis. The outcome of TLCC difference between the two buildings ranged from \$29.36 to \$34.24 million for the 60-year study period, in favor of the mass timber buildings for all the scenarios (Fig. 1).

The TLCC increased as the study period went on because of incurring future costs for utilities and M&R as well as building deterioration. A study period beyond 100 years may be economically unfavorable for building LCCA because the projection of the financial variables such as inflation, escalation, and discount rates would be unrealistic. The TLCC for a mass timber building increased from \$13.85 million for 20 years to \$48.67 million for a 100-year study period, in which the PV of building residue decreased from \$16.41 million to zero, as shown in Figure 2. And

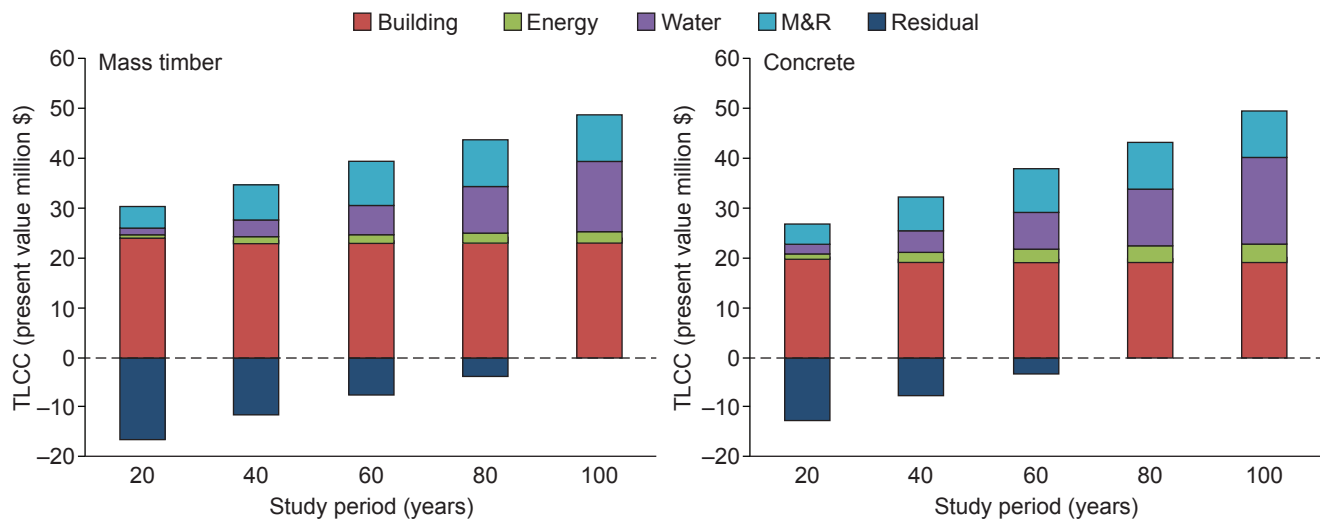


Figure 2. Total life-cycle cost (TLCC) of proposed mass timber and concrete buildings at different study periods (M&R, maintenance and repair).

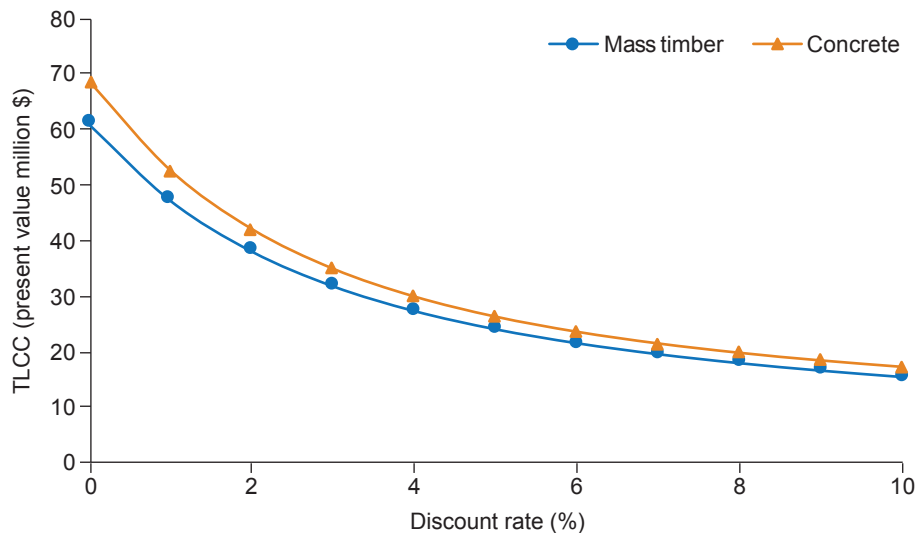


Figure 3. Total life-cycle cost (TLCC) of mass timber and concrete buildings at different discount rates.

the TLCC for a baseline concrete building increased from \$14.48 million for 20 years to \$49.55 million for 100 years, in which the PV of building residue decreased from \$12.57 million to zero by year 75. The TLCC difference between the two buildings increased from \$0.63 million for 20 years to \$3.44 million for 80 years, and then decreased to \$0.88 million for the 100-year study period, where the proportion difference also decreased from 8% to 2%. Overall, the LCCA was sensitive to the study period for the buildings. Therefore, choosing the study period is important in the analysis.

The discount rate reflected the investor's expectation for return on time value of money. The effect of discount rate was also evaluated with sensitivity analysis by changing the rate from 0% to 10% (real term), whereas the base assumption was 3%. The results of 60-year TLCCs for mass timber and concrete buildings are shown in Figure 3. The TLCC was affected by the discount rate for the whole

life span of the building. As expected, the TLCC decreased as discount rates increased. The lowest real discount rate, 0% to 1%, was comparable with the long-term treasury bill rate (Treasury 2018). Under the 1% real discount rate, the TLCC for 60 years on the mass timber building was \$47.13 million, which was \$5.28 million (10%) lower than the concrete building. Although at the high discount rate of 10%, the TLCC for a mass timber building was \$15.27 million, which was \$1.85 million (11%) higher than the concrete building. The change of discount rate significantly affected the PV of future costs of utilities, M&R, and building residual value at the end of the study period. However, the PV of building construction cost wasn't affected significantly because the initial direct investment, loan payment, and building asset depreciation only happened at the early stages. The effects of discount rate on TLCC were significant. Therefore, care should be taken when making a comparison with other studies that might use different discount and inflation assumptions.

Limitations

The construction costs for the two buildings were based on builder's estimation and online construction database quotation, which might not reflect current real construction cost. No commercial market prices for CLT building material are publicly available. Also, the detailed construction component costs were not provided in this case study, but a ballpark estimation for the whole building was used instead. In addition, the M&R cost was assumed to be the same because there is a lack of any current or historical M&R data for CLT mass timber buildings, which are just now emerging globally into the mid- to high-rise building sector. Furthermore, in this hypothetical case, the selection of service life of mass timber buildings and their residual value at end-of-life favors these buildings over concrete.

Summary

This study presented an LCCA methodology for mass timber buildings. A hypothetical case study was conducted to compare a mass timber building with a baseline code-compliant concrete building in terms of TLCC and savings. Results showed that the TLCCs for both buildings were dominated by the construction cost. Additionally, this LCCA approach was heavily sensitive to the variation of study period and discount rate. In the case studied, the mass timber building with premium energy and water saving designs, as expected, exhibited lower TLCC than the baseline code-compliant concrete building for a 60-year study period under the provided research assumptions and limitations. However, this analysis did not directly reflect the cost difference between mass timber and concrete buildings. Further research will be done to compare TLCC differences between functionally equivalent mass timber and concrete buildings using this LCCA calculation tool.

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