Whole-Building Life-Cycle Assessment in the Built Environment: A Ten- and Six-Story Shake-Table Test Building Case Study

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Abstract

The utilization of mass timber engineered wood products has increased for new buildings aiming to reduce environmental impacts. Whole-building life-cycle assessment (WBLCA) has been used to quantify the environmental impacts for a building's lifespan. While mechanisms for calculating the cradle-to-grave impacts of a single building are well established, there are few examples of WBLCA applied for buildings in their first and second life that can be used to inform perspectives and pathways related to the circular economy and lead to informed decision making. This work presents a case study WBLCA to examine the effect of overlapping system boundaries and alternative end-of-life pathways for a building structure in its first and second life. This case study analyzed a ten-story mass timber shake-table specimen that was partially deconstructed and reused as a six-story shake-table building structure. Environmental impacts were analyzed in terms of global warming potential (GWP) calculated as the sum of fossil carbon, biogenic carbon, and avoided impacts. When examining reuse and landfill pathway alternatives using current standards and practices, results show that reusing material causes a positive GWP trend in the first system boundary and negative GWP trend in the second boundary. These results could indicate that it is not advantageous to reuse the ten-story building structure, running against principles of waste hierarchy, although the interpretation should be considered with caution. Future analyses could be improved by considering additional criteria such as demand on forest stocks, economic incentives, and even social impacts for a more complete representation of sustainability.

The building sector is one of the largest contributors to greenhouse gas emissions worldwide. It is estimated that this industry alone is responsible for close to 40 percent of carbon dioxide emissions in the United States, wherein the selection of building materials is a major factor (Dixit et al. 2010). As demand for new residential and commercial construction continues to increase, there exists a pressing need to identify and incorporate more sustainable building materials in design and construction practices. Engineered mass timber (MT) products have emerged as a promising solution to meet emission reduction goals (Sinha et al. 2013).

When harvested sustainably (per international standards, including ISO 21930 [ISO 2017], specifying stable or increasing forest stocks), the environmental merit in favor of MT products is extensive (Abed et al. 2022) and includes resource renewability, wildfire mitigation (in some cases), and, primarily, a natural carbon sink. Trees sequester carbon dioxide from the atmosphere via photosynthesis and use the carbon to build up new woody fiber (Bonan 2008). When timber is used for building materials, this embedded carbon

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in wood products is stored temporally in the building sector, and potentially permanently depending on the end-of-life (EoL) pathway of the wood product (Bjarvin 2022, Pasternack et al. 2022). This temporal carbon storage in wood products serves to drastically reduce the overall carbon footprint of MT buildings (Pierobon et al. 2019).

As the various dimensional lumber- and veneer-based engineered MT products have continued to develop and advance, architects and engineers have increased employment of these products in building systems, including floor panels, shear walls, beams, and columns (Mayencourt 2020, Van Der Wielen and Wilhelm 2023). Many studies have performed cradle-to-grave (Milaj et al. 2017, Chen et al. 2020, Allan and Phillips 2021, Duan et al. 2022) and cradle-to-gate (Robertson et al. 2012, Puettmann et al. 2021) whole-building life-cycle assessments (WBLCAs) to quantify the environmental impacts of these materials and, in some cases, contrast impacts of archetype buildings composed of MT structural systems with functionally equivalent reinforced concrete and steel structural system alternatives. Additional studies have examined the economic and social utility of MT construction and found that the fast construction times due to prefabricated elements can contribute to project cost savings, and the biophilic nature of the products can have a positive effect on human wellness (Abed et al. 2022).

A major opportunity in favor of MT versus traditional construction is in the unique EoL possibilities provided by these building typologies. If designed thoughtfully, MT buildings can be disassembled and reprocessed, and the materials can be reused for other building applications, promoting a circular economy (Ahn et al. 2022). Additional EoL opportunities include recycling woody material to form other wood products such as oriented strand board, incineration for energy recovery, and sending the material to landfill, where some portion of the embedded carbon in the wood product is retained over long-term periods (EPA 2020).

However, not all EoL possibilities have the same environmental merit. A concept termed the "waste hierarchy," first introduced in the Dutch Parliament in 1979, outlined a priority structure for materials at the end of their usable lifespans (Psilovikos 2023). This involved (1) waste prevention, (2) product reuse, (3) recycling, (4) energy recovery, and (5) landfill disposal—where options 1 and 2 were to be prioritized, options 3 and 4 were to be used when necessary, and option 5 was to be avoided whenever possible. This waste hierarchy indicates that reusing wood products at the end of a building's lifespan should be a priority—a finding supported by other studies that have established reuse as an effective way to minimize waste and a building's carbon footprint (Cristescu 2020, Bjarvin 2022).

Moreover, because MT buildings are still relatively new in the construction landscape, few have reached their EoL—making it difficult to fairly assess the claims of potential reusability. For this reason, Lehmann and Kremer (2023) identified the need for case studies of real MT structures being reused in a circular economy, along with their accompanying life-cycle assessments, as a pressing research gap. This claim is supported by Ghobadi and Sepasgozar (2023), who stated that successful implementation of these strategies will serve to reduce the climate change contribution from the building sector.

While the most typical MT buildings have yet to reach the end of their usable lifespans, researchers have leveraged shake-table test buildings (having a short lifespan on the order of months to a year or two) as case studies to help partially understand and assess material reusability at the EoL (i.e., the conclusion of testing). One such example is described in Passarelli (2018), where part of a five-story timber shake-table specimen tested at the E-Defense facility in Japan was partially deconstructed to form a café. A comparative life-cycle assessment was performed to examine the environmental impact in terms of global warming potential (GWP) with variation of reuse percentages and different scenarios for treatment of surplus wood. In this analysis, potential impacts from avoided virgin material production and disposal for the quantity of material reused were subtracted from the overall environmental impact. Using this framework, it was determined that the total GWP was reduced as the reuse percentage of cross-laminated timber elements increased, a finding well supported in the literature (Chen 2019, Passarelli 2019, Vamza et al. 2021, Bjarvin 2022). The study also identified some key challenges with reusing MT elements, namely: (1) Building systems are not necessarily designed for component reuse, and components will need to be optimized for reusability to reduce waste at the manufacturing stage of the next system boundary; and (2) material intended for reuse must be stored under appropriate conditions to avoid material performance deterioration from biological decay. While Passarelli (2018) provided valuable insight into MT reusability potential and GWP accounting methodologies for reused material, it also helped to highlight potential research gaps. In Passarelli (2018), the system boundary of the shake-table test building was excluded, raising questions about the ways in which WBLCA results would be affected by considering system boundary interaction for two subsequent building usages in the context of MT product reuse.

Based on existing knowledge, a case study WBLCA is presented here for consecutive MT shake-table test buildings. These test buildings include a full-scale ten-story MT specimen from the National Hazards Engineering Research Infrastructure (NHERI) TallWood team (Pei et al. 2023), and a subsequent six-story specimen from the NHERI Converging Design team (Kontra et al. 2023). These shake-table tests were performed at the NHERI outdoor shake-table testing facility at the University of California–San Diego (NHERI@UCSD), and both specimens contained a large variety of MT products used in the floors, columns, beams, and shear walls, along with other proprietary steel connections and some nonstructural components. These two shake-table tests were executed sequentially; once the ten-story specimen testing concluded, the top four stories of the building were removed (phase I deconstruction), and the six-story specimen was prepared for a new round of shake-table testing. Upon completion of the six-story test program, the bottom six stories were removed from the shake table (phase II deconstruction). The deconstructed materials were evaluated for varying EoL pathways that differed for the two deconstruction phases (to be discussed further in the next section). Figure 1 illustrates the progression of the ten-story test building to form the six-story specimen, highlights the

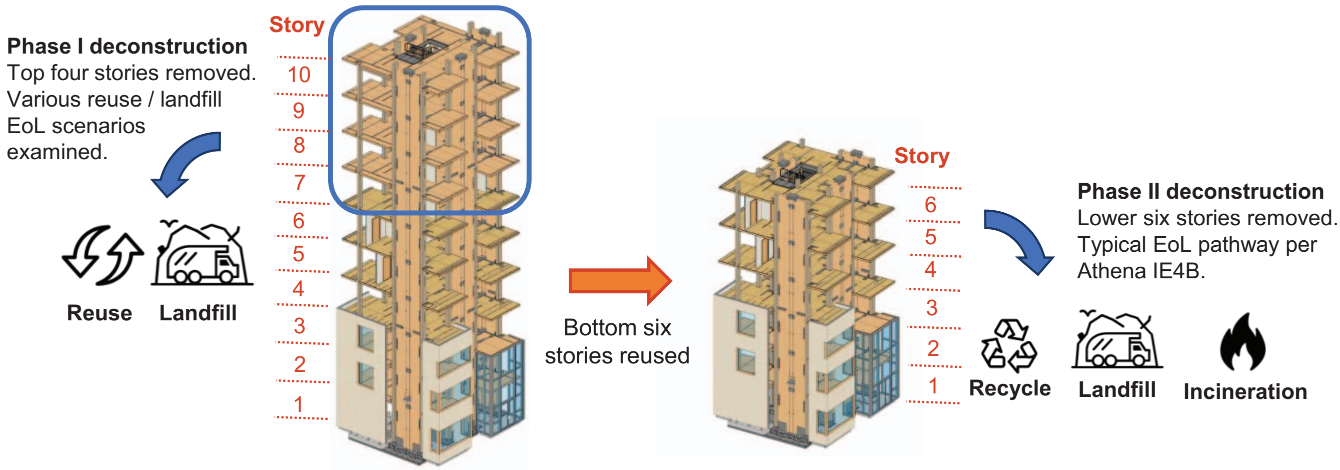

Figure 1.—Ten-story test building reused to form six-story specimen. Varied end-of-life (EoL) scenarios were examined for phase I deconstruction; typical EoL pathway per Athena Impact Estimator for Buildings (IE4B) was used for phase II deconstruction.

two phases of deconstruction, and shows the alternative EoL pathways considered for the material in each deconstruction phase.

This study investigated, through a unique case study, how environmental impacts may be reported in a WBLCA for buildings in their first and second life considering two overlapping system boundaries. Hypothetical scenarios of varied EoL pathways for the building materials are introduced to examine how different levels of reuse and landfill disposal affect WBLCA results, and also to provide insight into the limitations of current WBLCA methods for assessing MT product reuse in the context of a circular economy.

Analysis Methods

The WBLCA in this study was performed in accordance with international standards, including ISO 14040 (ISO 2006a), 14044 (ISO 2006b), and 21930 (ISO 2017). The first two ISO standards provide principles and guidelines for conducting a life-cycle assessment (LCA), while ISO 21930 addresses environmental product declarations in the building sector and outlines four life-cycle stages: production (A1–A3), construction (A4–A5), use (B1–B7), EoL (C1–C4), and an optional module (D) to consider benefits and loads beyond the system boundary.

The stages presented in ISO 21930 can be further broken down into modules that constitute the specific activities occurring within the stage. The production stage is defined by modules A1–A3, which include resource extraction and upstream impacts (A1), transportation to the manufacturing facility (A2), and product manufacturing (A3). The construction stage is subdivided into two modules: transportation from the manufacturing facility to the construction site (A4), and on-site construction (A5). These life-cycle stages capture the environmental impacts before the building is in service.

While the building is in service, environmental impacts are captured in the use stage. The use stage is subdivided into seven modules: use (B1), maintenance (B2), repair (B3), replacement (B4), refurbishment (B5), operational energy use (B6), and operational water use (B7).

The EoL stage captures the building's environmental impacts after its service life. This includes four EoL modules: building deconstruction/demolition (C1), transportation of deconstructed/demolished materials from the building site to its corresponding EoL pathway (C2), waste processing (C3), and waste disposal (C4). An optional module (D) can also be considered to capture the benefits and loads for processes such as landfill disposal, reuse, recycling, incineration, etc., that occur outside the defined system boundary. A summary of life-cycle stages and modules is shown in Figure 2.

Study design parameters

The goal of this WBLCA was to examine the effect of overlapping system boundaries and alternative EoL pathways on GWP results for a building structure in its first and second life. This was investigated through a case study of sequential ten- and six-story shake-table MT test buildings featuring varying scenarios of material reused and landfilled at the EoL. The functional unit was the structural system for ten- and six-story buildings with 843 m^2 and 500 m^2 of usable space, respectively, that was performance-based seismic designed to resist a risk-targeted maximum considered earthquake (MCE_R) in Seattle, Washington.

The system boundary featured two building structures, and therefore two system boundaries were included. Because the six-story building structure was composed of materials that were previously part of the ten-story building structure, the two system boundaries overlapped at the ten-story EoL stage and the six-story production stage. Since the shake-table specimens were not meant to be "usable" buildings, the modules within the use stage (B) are not relevant and were omitted from the analysis. Figure 3 shows the overlapping ten- and six-story system boundaries excluding the use stage. Note that most materials were reused from the ten-story building structure, and therefore A1–A5 impacts for those materials were not accounted for twice in the six-story system boundary.

The system boundary overlap that occurred at phase I deconstruction (as shown in Figure 3) is of specific interest for this study. For this overlap, five hypothetical scenarios are introduced to investigate the variation of GWP accounting for

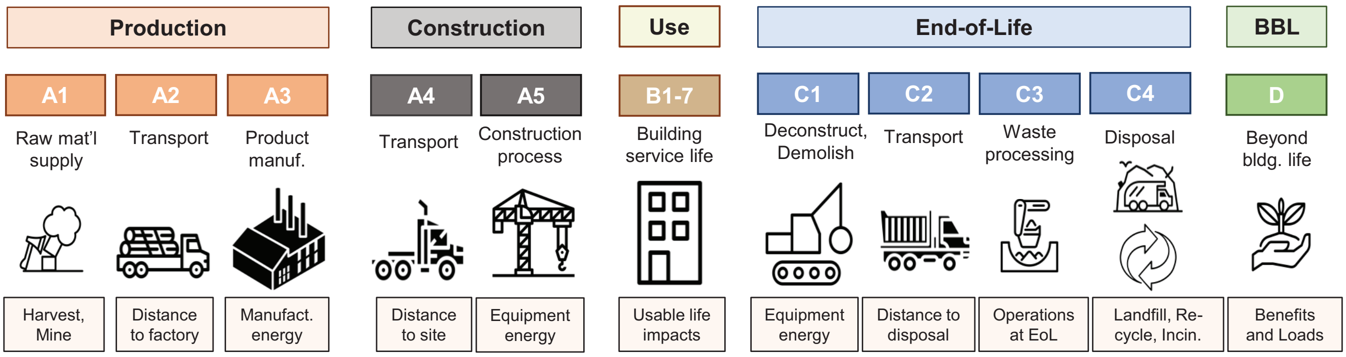

Figure 2.—Whole-building life-cycle assessment (WBLCA) production, construction, use, and end-of-life stages including an optional beyond building life module (ISO 2017).

alternative EoL pathways, as summarized in Table 1. To represent the likely post-deconstruction material pathways for MT buildings, two EoL pathway alternatives were analyzed: reuse and landfill. These scenarios were only applied for phase I deconstruction, to satisfy the study intent of examining how the distribution of GWP may vary between system boundaries that overlap and interact. For the six-story EoL modules where there was no overlap (phase II deconstruction), the scenarios were not applied.

In this study, the term "reuse" is utilized in two different contexts for on-site and off-site reuse possibilities. The on-site reuse case is representative of a situation in which material from a deconstructed building is partially salvaged and used for new construction at the same site. This context

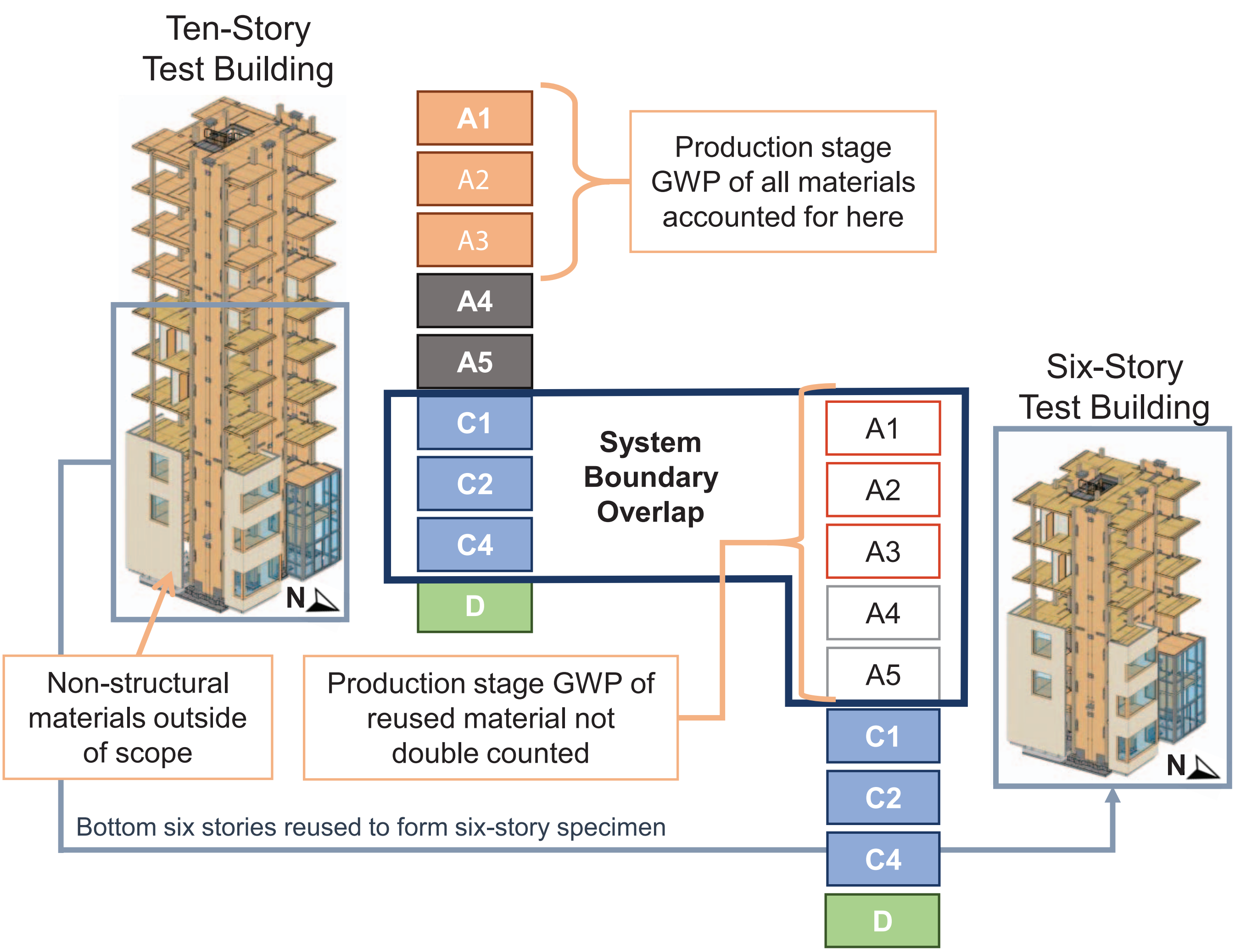

Figure 3.—Overlapping ten- and six-story system boundaries at the point of ten-story end-of-life (EoL) and six-story production and construction stages. Nonstructural elements outside of scope and production stage global warming potential (GWP) for materials were not double counted.

Table 1.—Summary of hypothetical end-of-life (EoL) scenarios after ten-story building testing.

Scenario	% landfill	% reused
1	100	0
2	75	25
3	50	50
4	25	75
5	0	100

of reuse can be considered for the NHERI Converging Design six-story test building, where the bottom six stories were salvaged from the previous ten-story building. In other words, it was not needed to construct the six-story building from the ground up, but rather construction was achieved through the removal of the top four stories of the ten-story shake-table test building. For this reuse case, scenario 1 examines a situation where no material could be salvaged from the 10-story building to compose the six-story building, scenarios 2–4 examine where partial reuse occurs, and scenario 5 examines where the full six-story building is composed of salvaged material. On the other hand, off-site reuse concerns material that is fully deconstructed, shipped, reprocessed, shipped again, and reused at another location for new construction. For the top four stories of the NHERI TallWood structure that were not salvaged for the NHERI Converging Design test program, off-site reuse was considered. The same scenarios were examined simultaneously for the off-site reuse case, but also factoring in the additional effort and environmental impact from the additional activities necessary to reuse material off-site.

To address the most relevant topic for architects, engineers, and the public at large, this study focused on the potential effect of the chosen materials and processes on climate change. This effect on climate change is the result of greenhouse gas emissions associated with the building's material selection (embodied carbon) and operation (operating carbon) throughout the life cycle of the building. As this study did not analyze a real, operational building, only embodied carbon was within the scope. Embodied carbon is reported through a standardized metric termed GWP. This metric approximates the chemical potency of greenhouse gas emissions over a 100-year time horizon with respect to an equivalent CO_2 emission, reported in units of equivalent kg of CO_2 (CO_2e) (International Panel on Climate Change [IPCC] 2006). For this study, GWP is reported in four ways. The term fossil carbon (FC) is used to account for the GWP in each WBLCA module that is the result of fossil fuel consumption. Biogenic carbon (BC) is used to characterize the balance of embodied carbon stored in wood products at each stage that can be accounted as a GWP offset. Avoided carbon (AC) is used to account for the net emissions in module D that are avoided when reusing, incinerating, or recycling building materials. The term "total GWP" refers to the sum of FC, BC, and AC.

A Revit model (Autodesk 2023) detailing the building design of both structures was utilized to compile a bill of materials for timber and steel elements (included in the Supplemental Appendix). As these were shake-table test buildings, and not an actual usable building, several elements typical in usable building were not inventoried. The elements that were inventoried related to the structural performance of the building, while the elements outside the inventory related to the nonstructural elements and shake-table platen. Table 2 summarizes the components of the shake-table specimen that were included and not included in the inventory scope.

Life-cycle inventory, impact assessment, and interpretation

Software and tools.—The life-cycle inventory (LCI) and life-cycle impact assessment (LCIA) were conducted using a variety of software tools and literature sources. Athena Impact Estimator for Buildings (IE4B) (ASBI 2023)—a tool developed for environmental impact quantification for buildings in North America—was used to populate the construction stage FC in both system boundaries and the EoL stage FC and module D FC and AC in the second system boundary (phase II deconstruction). This IE4B tool draws upon a highly developed, proprietary LCI database in compliance with ISO 14040/14044 provisions. The environmental impacts associated with LCI outputs are aggregated in Athena IE4B following procedures developed in the Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI 2.1) (Ryberg et al. 2014) in accordance with ISO 21930 (ISO 2017). The production stage modules were populated using several open-source cradle-to-gate LCA studies sourced from the Consortium for Research on Renewable Industrial Materials database (CORRIM 2017).

To evaluate the five EoL pathway scenarios, Athena IE4B outputs could not be used directly because the EoL pathway assumption for different material types cannot be customized within this tool. Instead, the GWP quantity in each module for each scenario was populated using values derived from the literature. The deconstruction module (C1) was populated using values taken from Kontra et al. (2024), where phase I deconstruction was monitored, and primary data were collected. The remaining EoL modules were populated using the Environmental Protection Agency's Waste Reduction Model (WARM) (EPA 2020). In WARM, the GWP for landfilled material (including transport and landfill operations) is taken as 0.022 kg CO_2e per kg of timber. For reuse, the GWP associated with transportation and material reprocessing (trimming, planning, etc.) is taken as 0.066 kg CO_2e per kg of timber. However, the EoL modules for phase II deconstruction, where no scenarios were analyzed, were populated using the Athena IE4B tool. The "typical" EoL pathway in this tool assumes that 72.6 percent of timber products goes to landfill, and the remaining percentage is sent for recycling and incineration, while all steel is recycled.

Table 2.—Shake-table building components included and not included in whole-building life-cycle assessment inventory.

Within assessment	**Outside** assessment
Mass timber structural elements: diaphragm panels/columns and beams/walls	Nonstructural elements: Drywall/glass/stairs
Steel connection elements	Shake-table platen
Steel self-centering mechanism	Concrete poured on top of the shake-table surface
Steel foundation elements	

Treatment of biogenic carbon (BC).—Biogenic carbon is used to characterize the balance of embedded carbon stored in wood products throughout the building life cycle and is accounted for following principles outlined in ISO 21930 (ISO 2017), which outlines that BC entering the system boundary is characterized by a factor of -1 kg CO_2e (offsetting total GWP), and, conversely, any BC leaving the system boundary shall be characterized by a factor of $+1$ kg CO_2e (adding to total GWP). For WBLCA, BC enters the system boundary in module A1 as a negative GWP, and a small amount of BC is lost in manufacturing (module A3) and construction (module A5). For this study, the inflow of BC into the system boundary was accounted as the net BC before the building was put in service. The EoL pathway determined the quantity of BC that was retained within the system boundary.

For EoL pathways reuse, recycle, and incineration, the net carbon emission will be equal to zero. This means that the negative "uptake" of carbon in module A1 (material extraction) will be balanced by a positive emission in module C4 (waste disposal) associated with the BC leaving the system boundary. However, the BC leaving the system boundary in module C4 is not "disappearing," but rather being transferred to the next system boundary's module A1—highlighting the importance of examining these EoL pathways in the context of multiple system boundaries.

When a product is sent to landfill, however, there is no transfer of BC to the next system boundary. The woody biomass that decays at landfill is accounted as BC leaving the system boundary as an emission in module C4, while the BC associated with the undecayed biomass is not subtracted out at module C4. Per ISO 21930 (ISO 2017), this undecayed portion can be considered as BC remaining within the system boundary, helping to offset total GWP. This study considered that 88 percent of the carbon remained as woody biomass at landfill, and 12 percent was released upon decomposition—consistent with Athena IE4B.

Module D.—The last optional module in WBLCA is module D, which considers the benefits and loads that occur outside the system boundary. Features included in this module are the substitution effects of recycling steel and reusing timber products, where substitution effects are simply defined as the net benefit of an avoided environmental impact. The avoided impact (termed avoided carbon [AC] for this study) was calculated using guidance provided in WARM in the following steps: (1) calculate the GWP to produce one unit of virgin product, (2) calculate the GWP associated with reusing one unit of the product, (3) calculate the difference in GWP between the virgin and reused products, and (4) adjust the GWP to account for material loss during reuse.

In the context of reuse and cascading systems, there are many proposed procedures as to how these benefits and loads from substitution effects should be allocated across system boundaries. These procedures include allocating all benefits and loads to the first system boundary (100/0), all to the second system boundary (0/100), or some formulation where effects are shared (see Finkbeiner et al. 2013; Allacker et al. 2014, 2017; Schrijvers et al. 2016; Garcia et al. 2020). However, among the potential allocation approaches, there is no consensus as to which method is preferred. For the purposes of this study, a 100/0 allocation approach was used, where the avoided impacts of producing virgin material were fully attributed to the first system boundary. This method was chosen to maximize the potential balance between system boundaries, where the first received the benefit from avoided impacts, and the second received the benefit from the transferred BC.

Study limitations

While the logistical challenges, current policy-based restrictions, and potential pathways associated with reusing MT material remain areas of active research, they are outside the scope of this study. The NHERI TallWood and NHERI Converging Design project teams, however, are collaborating to repurpose shake-table materials for new, local construction to support underserved populations.

It is also important to note that results presented here are for this particular and unique case study with overlapping system boundaries and not a generalization for MT systems. Thus, there are several study limitations that must be considered before direct application to "real" MT buildings. For example, the second system (the six-story building structure) was obtained after deconstructing the top four stories of the ten-story structure, which had been designed for deconstructability. However, a clean deconstruction may be challenging for most real buildings and may incur additional GWP. When attempting to completely disassemble and salvage building components, a shake-table test structure with no envelope may be able to achieve a much higher reuse percentage than a fully enclosed building. Additionally, this analysis (as it is a unique situation of shake-table specimens) does not include the GWP contribution from the foundation—a factor that can significantly influence total GWP in a real-world building. Further, nonstructural systems and finishes were not analyzed, which also might influence results.

Nonetheless, the primary purpose of this study was to examine how WBLCA results are affected when considering overlapping system boundaries for varying EoL pathways in the context of a circular economy. Thus, although the values presented in the results may be less conservative than what may be found in other buildings, the implications of the study could be considered for future, more complex studies.

Results and Discussion

Cradle-to-grave WBLCA results for the ten- and six-story test buildings are presented in Figure 4 to Figure 8.

Figure 4 shows the results for the production stage (A1–A3), construction stage (A4–A5), and deconstruction module (C1) for the ten-story building where system boundaries do not overlap, and no EoL scenarios were analyzed. Figure 5 shows the last three modules in the EoL stage (C2–C4) and module D where system boundaries do overlap, and the five EoL scenarios (labeled S1–S5) were examined. The GWP contribution and offset are separated as biogenic (BC), fossil (FC), and avoided (AC).

Figure 4 illustrates that the majority of the FC in the examined modules is in the production stage, but an even larger BC offset is also recorded. However, the BC that enters the A1 module exits the system boundary in part in the C4 module as a positive GWP, as shown in Figure 5. The quantity of BC that leaves the system boundary is tied to the EoL scenario, where the BC associated with the reused material departs the system boundary as a positive

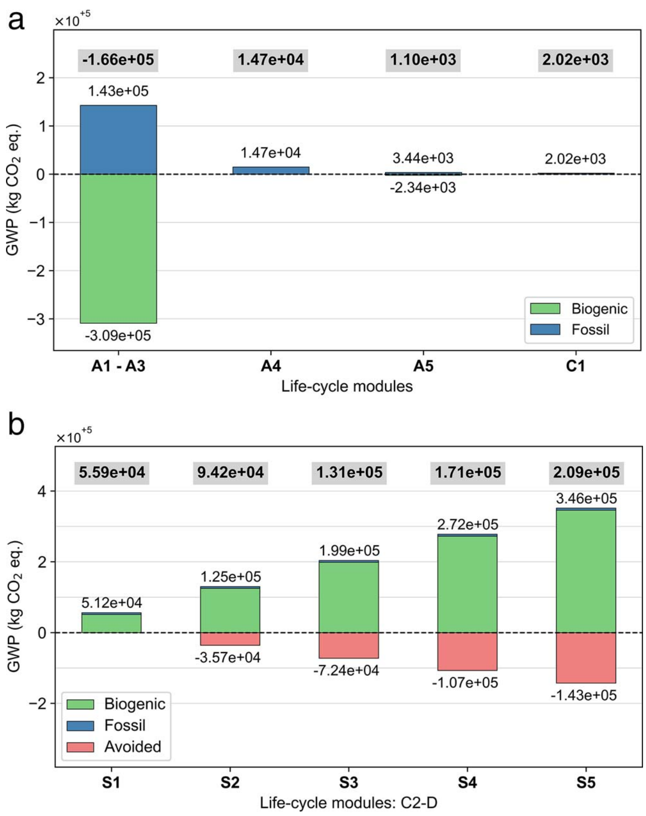

Figure 4.—Ten-story whole-building life-cycle assessment (WBLCA) results for the production (A1–A3), transportation (A4), construction (A5), and deconstruction (C1) modules. The total global warming potential (GWP) per module (sum of biogenic carbon [BC] and fossil carbon [FC]) is highlighted in gray.

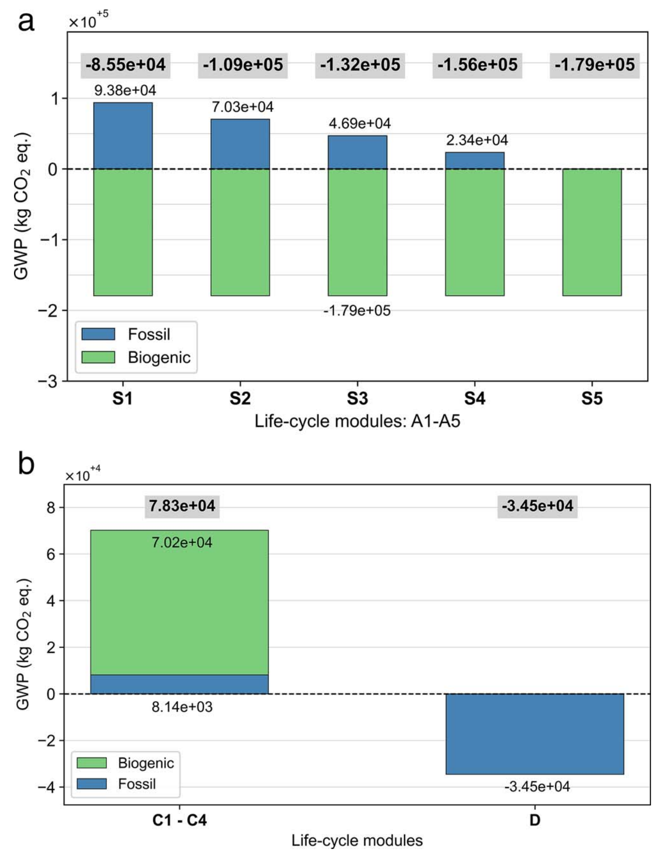

Figure 5.—Ten-story whole-building life-cycle assessment (WBLCA) results for end-of-life (EoL) modules (C2–C4) and module D that vary with alternative EoL pathways: S1 = 100 percent landfill, 0 percent reuse; S2 = 75 percent landfill, 25 percent reuse; S3 = 50 percent landfill, 50 percent reuse; S4 = 25 percent landfill, 75 percent reuse; S5 = 0 percent landfill, 100 percent reuse. The total global warming potential (GWP) per scenario (sum of biogenic carbon [BC], fossil carbon [FC], and avoided carbon [AC]) is highlighted in gray.

"emission," while the BC associated with landfilled material is partially retained within the system boundary. Figure 5 shows that the scenarios with the largest proportion of reuse also have the largest amount of BC departing from the system boundary. The modules with the greatest reuse percentage also feature the greatest avoided impact from virgin material production, although this negative GWP from avoided impacts does not keep pace with the positive GWP from the BC departing the system boundary. However, the BC associated with reused material departing the ten-story system boundary is not disappearing, but rather being transferred to the next system boundary for the six-story building.

Figure 6 shows the production stages (A1–A3) and construction stages (A4–A5) for the six-story building where system boundaries do overlap, and EoL scenarios were analyzed. A large deposit of BC into the six-story system boundary can be observed in the production stage. However, the BC entering the system boundary is constant for all scenarios because the system boundary is agnostic to BC sourced from reused or virgin material. The primary difference between reused and virgin material is that the production stage FC for reused material was already accounted for in the previous system boundary and does not need to be double counted in the new system boundary, while the FC for virgin material must be accounted for in the model. This results in a diminishing FC contribution as the reuse percentage increases, resulting in a lower total GWP for the system boundary.

Figure 7 shows the EoL stage (C1–C4) and module D where system boundaries do not overlap, and the five EoL scenarios (labeled S1–S5) were not examined, and a typical EoL fate for timber products and steel per Athena IE4B was assumed (72.6% of timber landfilled). It can be observed that the majority of total GWP in the EoL stage is related to BC leaving the system boundary (represented as a positive GWP). The negative GWP reported in module D stems from recycled steel.

A summation of GWP totals for both system boundaries considering S1–S5 is shown in Figure 8. An inversely proportional relationship can be observed for the two system boundaries, where a higher reuse percentage is associated with progressively higher GWP for the ten-story system boundary and lower GWP for the six-story system boundary. For all scenarios, the GWP sum from both system boundaries is negative, highlighting the environmental merit of timber-based construction.

The contrasting trend observed in Figure 8 suggests that the benefit of reusing material registers more significantly in the reused system boundary, even when considering a 100/0 allocation approach, where the first system boundary is allocated the benefits and loads associated with reuse. Considering the sum

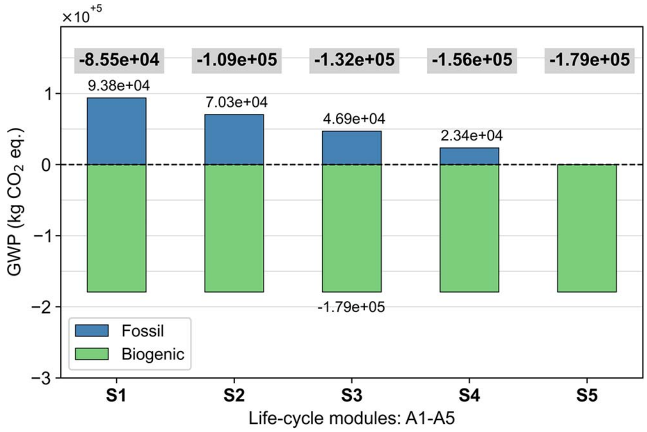

Figure 6.—Six-story whole-building life-cycle assessment (WBLCA) results for the production and construction stages (A1–A5) that vary depending on the end-of-life (EoL) pathway of the ten-story building material: S1 = 100 percent landfill, 0 percent reuse; S2 = 75 percent landfill, 25 percent reuse; S3 = 50 percent landfill, 50 percent reuse; S4 = 25 percent landfill, 75 percent reuse; S5 = 0 percent landfill, 100 percent reuse. The total global warming potential (GWP) per module (sum of biogenic carbon [BC] and fossil carbon [FC]) is highlighted in gray.

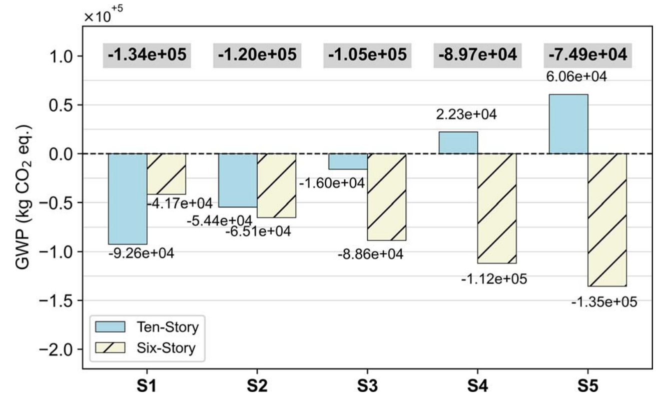

Figure 8.—Whole-building life-cycle assessment (WBLCA) results for total global warming potential (GWP) in both ten- and six-story system boundaries considering the variation in end-of-life (EoL) pathways: S1 = 100 percent landfill, 0 percent reuse; S2 = 75 percent landfill, 25 percent reuse; S3 = 50 percent landfill, 50 percent reuse; S4 = 25 percent landfill, 75 percent reuse; S5 = 0 percent landfill, 100 percent reuse. The sum of the GWP in both system boundaries per scenario is highlighted in gray.

of the GWP from both system boundaries, the scenarios with higher percentages of landfilling have the lowest GWP. At first glance, this finding seems to indicate that the most sustainable (lowest total GWP) option would be to landfill material after its first use, and simply start fresh with new material for each new construction—an outcome also reached by a cradle-to-grave LCA of laminated veneer lumber that compared alternative EoL pathways (Boise Cascade 2021). However, this conclusion, derived directly from current WBLCA standards and norms, is incomplete and misleading.

The primary factor influencing the GWP totals for each system boundary is the flow in and out of BC. If the second building is constructed with virgin material (instead of reused material), the BC from the virgin material serves to significantly increase the total BC (negative GWP) between the two system boundaries. This is because it allows the first system boundary to partially keep its BC for the material that is landfilled, while the same quantity of BC enters the second system boundary either way (from reused or virgin material). However, nowhere in the WBLCA are the increased demands on forest stocks and conditions considered, nor are other environmental and social factors considered (Pasternack et al. 2022). A more comprehensive approach may be to consider the potential effects of reuse on timber harvest reduction and forest carbon storage. WARM (EPA 2020) proposes a methodology to calculate this net change considering three variables: (1) the change in timber harvest resulting from increased reuse of wood products, (2) the change in forest carbon storage as a result of timber harvest reduction, and (3) the change in carbon stored in the in-use wood products from increased reuse. Incorporation of this approach in addition to considering economic and social factors in future WBLCAs will be significant to more accurately represent the GWP implications of producing new material and more holistically characterize the sustainability of EoL pathways. This facet of sustainability research is still ongoing and remains a crucial consideration in the context of a circular economy.

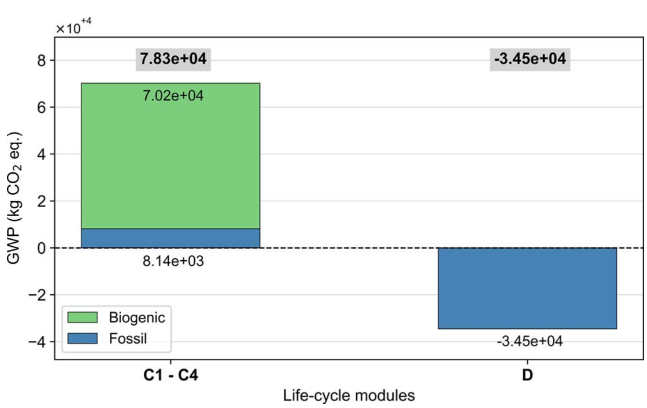

Figure 7.—Six-story whole-building life-cycle assessment (WBLCA) results for the end-of-life (EoL) modules (C1–C4) and module D based on a typical EoL pathway assumption from Athena Impact Estimator for Buildings (IE4B). The total global warming potential (GWP) per module (sum of biogenic carbon [BC] and fossil carbon [FC]) is highlighted in gray.

Further, the appearance that landfill disposal could be the "best" option to minimize GWP does not align with established research supporting the waste hierarchy—where reusing products is prioritized, and landfilling is avoided when possible (Psilovikos 2023). As the carbon economy continues to develop, building owners may be pressured to pursue low GWP EoL options. Thus, the appearance of sending material to landfill as a low GWP option may undermine incentives for building owners to put in the additional effort associated with reuse. This study thereby emphasizes that current WBLCA procedures for considering sequential system boundaries in the context of reuse need major revision to align with waste hierarchy principles where reusing components is highly encouraged.

Summary and Conclusion

A case study was performed to examine the effect on WBLCA results for two sequential ten- and six-story MT test buildings with overlapping system boundaries, where a six-story specimen was formed from the partial deconstruction of the ten-story specimen. Different scenarios with varying EoL pathways were considered, and the interaction between system boundaries in terms of FC, BC, and AC was assessed. Two major conclusions were drawn from the analyses:

1. There is an inversely proportional relationship in total GWP for the ten- and six-story system boundaries when considering varying reuse and landfill scenarios. Even when considering a 100/0 allocation approach, the total GWP in the first system boundary increased as the reuse percentage increased, while the total GWP in the second system boundary decreased as the reuse percentage increased. This finding occurs for two reasons: (i) The BC departs the first system boundary as an "emission" at a greater quantity than the credits received from AC of virgin material production, and (ii) the production stage GWP decreases for the second system boundary as reused material utilization increases, provided BC inflow is constant.
2. Following WBLCA international standards and practices, the scenario with the highest percentage of landfill disposal resulted in the lowest GWP sum considering both system boundaries. However, this finding is not in agreement with principles of the waste hierarchy and may undermine efforts to convince building owners to pursue reuse at the EoL. It is therefore recommended that WBLCA standards be updated to reflect the environmental merit of reusing material in a circular economy.

Overall, this study examined and critiqued the use of WBLCAs when considering environmental impacts of buildings in a circular economy through a case study of shake-table building structures. While direct application to real buildings may have limitations, the study provides valuable insight into necessary updates to current methodologies to align with established research. Future studies could gather primary data that will benchmark challenges and opportunities of MT component reuse and associated environmental impacts.

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