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ENVISIONING MASS TIMBER BUILDINGS FOR CIRCULARITY: LIFE CYCLE ASSESSMENT OF A MASS TIMBER BUILDING WITH DIFFERENT END-OF-LIFE (EOL) AND POST-EOL OPTIONS

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ABSTRACT: The foundation of the circular economy in the construction sector is based on implementing the deconstruction and reuse of buildings, providing the potential for a closed loop of building materials within the supply chain. Mass timber buildings using large, prefabricated elements and certain types of reversible mechanical connections are deemed to have great potential for post end-of-life (EoL) options, including recycling and reuse. To fully characterize the benefits of reusing post-use mass timber in new construction projects, it is crucial to conceptualize a 'grave-to-gate' approach, including the complete analysis of post-EoL activities and impacts on the material's second life. In this study, a comparative life cycle assessment (LCA) including different EoL and post-EoL options for a virtual reference mid-rise mass timber building in the Pacific Northwest (PNW) of the United States was conducted. Among four different deconstruction and reuse scenarios examined in this study, a case of nearly complete reconstruction of a mass timber building for the second service life used as an idealized reference established an optimistic limit for reduction of global warming potential (GWP) by 13-41% compared to the 'demolish and landfill' decision, depending on the scenario. The demolition and landfill scenario had the lowest net impact since the GWMP calculations accounted for the carbon storage benefits in the landfill in addition to the carbon stored in the building.

KEYWORDS: Mass Timber, Circular Economy, Deconstruction and Reuse, End-of-Life, Life Cycle Assessment

1 INTRODUCTION

Opposed to the "use and dispose" linear economic model, implementing the circularity of materials in the construction industry (recycling/reuse) is a critical issue in carbon footprint discussions. In Europe, the Climate Regulation of 2021 [1] aims to reduce greenhouse gas (GHGs) emissions by at least 55% below 1990 levels by 2030 as an intermediate goal. In the same year, along with this ambitious goal of the EU, the United States also introduced the Climate Leadership and Environmental Action for our Nation's (CLEAN) Future Act to drastically reduce GHGs emissions to at least 50% below 2005 levels by 2030. Under the Buy Clean Actions [2], the U.S. government also plans to expand the development of life cycle assessment (LCA) data for building materials purchased for any federal-funded projects. There is a need for lower carbon footprint buildings, and mass timber has gained popularity as a sustainable alternative to traditional construction materials and has led to revolutionary developments in timber construction [3, 4].

1.1 MASS TIMBER BUILDING FOR CIRCULARITY

Mass timber buildings typically utilize large engineered wood panels custom-ordered and manufactured for load-bearing structures such as floors and walls [5]. Because of the lightweight nature of the material [6], mass timber construction requires smaller cranes than other construction types, such as precast concrete, while maintaining the required structural performance. Connection hardware is one of the important parts of mass timber buildings, and they heavily influence the structural performance of such buildings [7]. Panel assemblies usually have screws instead of nails and use bolts and plates for some connection systems. Depending on the type and number of connections, mass timber assemblies may be disassembled at the end of building's life and re-assembled in new construction. The presence of fewer, localized connections, in some mass timber designs may minimize damage to panels, thus facilitating reuse. Compared to the deconstruction of conventional wood light-frame buildings, which requires extra effort and time during the de-nailing process, deconstruction of mass timber buildings and recovering mass timber panels for

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reuse rather than disposal at the end of the building's service life seems an attainable EoL scenario (Figure 1).

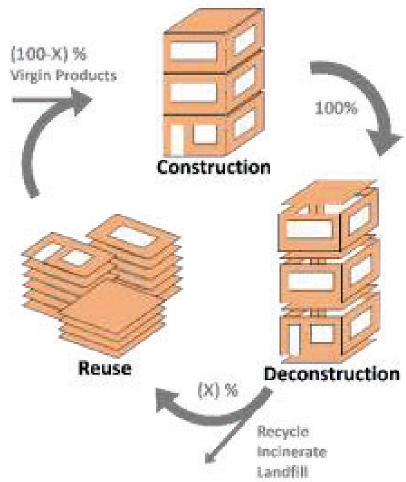

Figure 1: *Deconstruction and reuse of mass timber buildings.*

This is also well-aligned with circular economy principles that aim to maximize resource value and reduce environmental impacts. Moreover, the advantage of the reuse scheme is realized when the benefits of reusing mass timber panels are fully accounted for throughout their expected life.

1.2 LIFE BEYOND BUILDING END-OF-LIFE: EXTENDED LIFE CYCLE ASSESSMENT OF MASS TIMBER BUILDINGS

Conventional life cycle assessment (LCA) methodology is insufficient to assess the environmental impacts of mass timber building deconstruction and material reuse due to its focus on the first life cycle. Although the International Organization for Standardization (ISO) 14040 [8] defines module D to account for potential net benefits from reuse in ISO 14044 [9], it is still outside the system boundary. ISO 14044 instructs avoiding miscounting benefits from reusing by expanding the product system to the second product use [10]. Yet, it does not specify how these scenarios can be implemented, with or without a remanufacturing phase.

By extending part of the building material's lifespan at the end-of-life stage to the second lifecycle (Figure 2), there can be a proper evaluation of the circularity value of buildings that otherwise might have been overlooked [11]. For instance, if mass timber panels can be reused in another construction project after building deconstruction, the burden of producing panels from virgin timber can be avoided. Reusing panels instead of landfilling them also avoids the burden of panel waste processing. Moreover, reusing or landfilling panels can reduce the cumulative cradle-to-grave global warming potential (GWP) associated with the first building due to the carbon storage benefits of wood [12,13]. These benefits and avoided burdens can lower the environmental impacts of buildings, thus improving the potential of circularity as a viable option for sustainable construction. However, to fully account for the benefit of deconstruction and reuse, the first step is to incorporate this gate-to-gate impact into the system boundary.

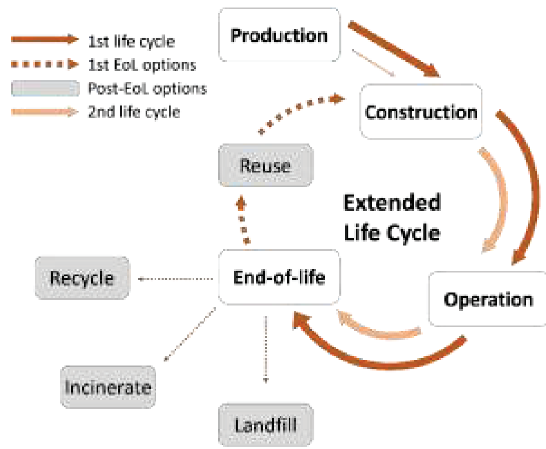

Figure 2: *Extended life cycle of buildings.*

While there have been attempts to address the benefit of reusing building materials at large using LCA [14-16], several studies have focused on timber-based buildings. LCA research investigating wood-cascading scenarios for glue-laminated timber beams in a virtual building indicated that reusing timber is beneficial as it provides the substitution effect for structural building materials [17]. However, the environmental impact assessment excluded construction, operation, and transportation stages for simplicity, and there was no comparison among different post-EoL options. Comparative LCA of CLT reuse, focusing on the second life [18], has also been conducted. Different CLT reuse rate scenarios were used to compare the avoided environmental impact of A1-A3 and C2-C4 modules on the overall carbon footprint. Again, this research also focused exclusively on the second life of mass timber panels, while there were no variations in post-EoL options. Recent work focuses on the first life of mass timber and EoL impacts after deconstruction [19]. In the research, various post-EoL options were implemented, including reuse, recycling, landfill, and incineration, using a dynamic LCA approach for comparison over two life cycles. Yet, the research focused more on the first life, leaving research needs for more in-depth analysis focusing on the second life with EoL alternatives to draw a comprehensive overview of circularity potential and its benefits for mass timber buildings.

1.3 OBJECTIVE AND SCOPE

The main objective of this study is to explore the circularity potential of mass timber buildings in their theoretical and practical reuse scenarios to help decisionmakers fully consider mass timber's carbon storage potential with its second life. Comparative LCA of a reference mass timber panel (MTP) building with various EoL and post-EoL options, including deconstruction, reuse, recycling, energy recovery, and landfill, are considered in this study.

2 MATERIALS AND METHODS

To analyze the environmental impacts of EoL and post-EoL options, we designed a comparative whole-building LCA of a reference MTP building, starting with the deconstruction and EoL processing of the first building and ending with the construction of a second identical building. In this manner, any recovered MTPs from the first building were assumed to be reused for the second building without changes in design.

2.1 REFERENCE BUILDING MODEL

The reference building for this study was based on mass timber building Type IV-C construction guidelines established in the 2021 International Building Code revision. The building was designed as an eight-story residential mixed-use building with a simple rectangular shape, a core elevator shaft, and stairs in the central space [20]. The building was designed to be located in the Pacific Northwest (PNW) region of the United States, and as such, it meets the building code requirements of that region. It was assumed that the first and second buildings were in the same Portland metropolitan area in Oregon. The study also included an ideal scenario, which reuses the foundation of the first building. This will be explained in detail in section 2.3..

With the specific region in consideration, seismic requirements were applied to the building design (e.g., a lateral force resistance system). For walls and floors, cross-laminated timber (CLT) was used, while glue-laminated timber (GLT) was used for the columns and beams. While mass timber products are mostly selected for building design, steel and concrete are also used in foundations and some structural elements. A conventional reinforced concrete structure with identical function and shape was designed for comparison with the reference mass timber building. Detailed building information is summarized in Table 1.

Table 1: *Description of the mass timber building used for LCA in this study.*

Type	Description
Building Use	Mixed-use
Construction Type	Type IV-C
Mass Timber Product Type	CLT (walls and floors), GLT (columns and beams)
Stories	8 (residential 6 + commercial 2)
Height	26 m
Total Floor Area	9,476 m^2

2.2 EOL AND POST-EOL OPTIONS FOR THE SYSTEM BOUNDARY

In this LCA, we set the system boundary to encompass EoL processing (module C) for the first building and production-and-construction (module A) for the second building. Either deconstruction or demolition was considered for the EOL option, depending on if panels were going to be reused or not. For post-EoL options, it was assumed that mass timber products (both CLT panels and GLT columns/beams) were reused (RU), recycled (RE), incinerated (IC), or landfilled (LF) in different proportions, depending on the case (Table 2). The whole system boundary information is summarized in Figure 3.

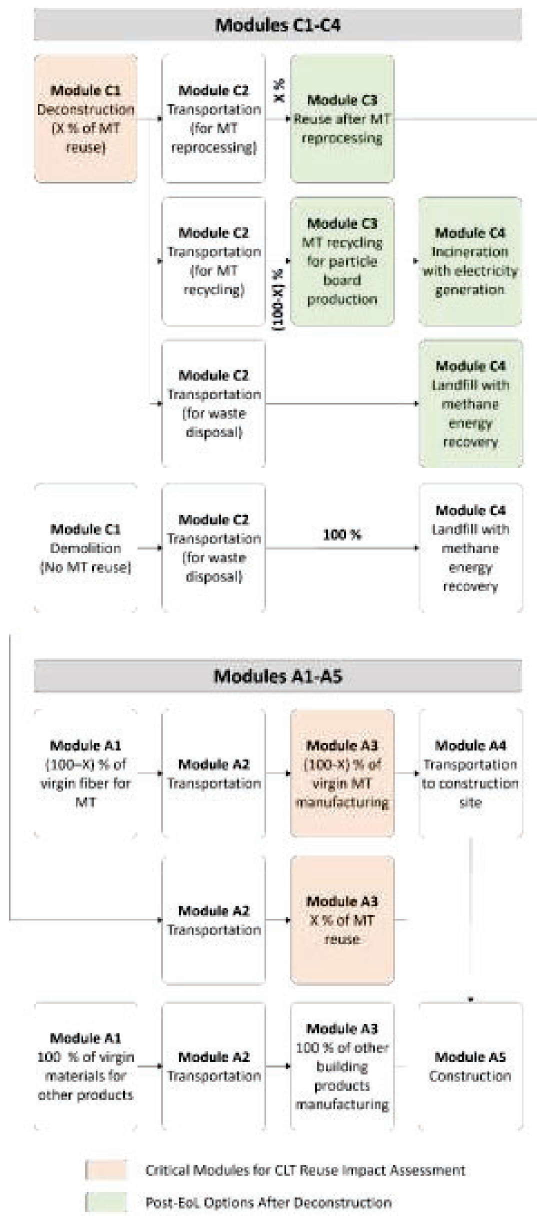

Figure 3: *System boundary applied to EoL and post-EOL of CLT in the study.*

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In RU, mass timber products are reprocessed in the manufacturing facility located in Oregon and then transported to the new mass timber building construction site for a second life. Reprocessing for reuse included minimal treatment, such as cleaning, connection removal, and repackaging. The volume of panels required for the second building that was not satisfied by reused panels was made from virgin materials. In RE, mass timber products are recycled in the manufacturing facility in Oregon to produce particleboard for the general market. In IC, mass timber products are incinerated in the plant facility for electricity generation, while in LF, products are landfilled in the same facility with methane energy recovery.

2.3 DECONSTRUCTION AND REUSE SCENARIOS

Mass timber buildings are still relatively young compared to other building types, and almost none of the existing cases worldwide have reached the end of their service life. Consequently, few studies have investigated the potential reuse of mass timber panels for a new building design [18,19,21]. Based on this fact, the rate of use of recovered panels for the second building after the deconstruction of the first building was determined by hypothetical assumptions (Table 2).

Table 1: *LCA cases used in this study.*

Case		MT Deconstruction and Reuse	
		CLT	GLT
Ideal	1	90% RU 10% RE	
Optimistic	2	70% RU 30% RE	90% RU 10% RE
	3	70% RU 30% IC	90% RU 10% RE
	4	70% RU 30% LF	90% RU 10% RE
Conservative	5	50% RU 50% RE	90% RU 10% RE
	6	50% RU 50% IC	90% RU 10% RE
	7	50% RU 50% LF	90% RU 10% RE
No reuse	8	100% LF (construct a new mass timber building)	
	9	100% LF (construct a new reinforced concrete building)	

In 'conservative' scenarios, 50% of CLT panels used in the first building are assumed to be reused for the second building. 70% reuse is assumed in 'optimistic' scenarios because the reuse of CLT in the future may be easier than it is today because of continuous technological advancement (for instance, technology capable of separating CLT and concrete from a composite floor system without damaging CLT panels). In addition, a case of nearly complete reconstruction of a mass timber building for the second service life was used as an idealized reference to establish an optimistic limit for the reduction of global warming potential (GWP). In this scenario, it is assumed that 90% of the panels are recovered in an intact condition, which requires minimal on-site reprocessing (e.g., removing connectors and cleaning).

Notably, 90% of GLT beams and columns are reused in all cases except the demolition with 100% landfilling options (Cases 8 and 9). For all scenarios, connectors for mass timber products are assumed not to be reused for safety reasons.

In the ideal scenario, the building's foundation is also assumed to be reused. This is unrealistic in the legal and planning aspects of the project, but from the engineering perspective, it is a sufficiently possible scenario considering the durability of the concrete foundation. It is also a recommended practice, if possible, from the circular economy point of view. In this scenario, the distance between the reprocessing facility and the mass timber building was assumed to be the same as in other cases to avoid changes in impacts in module A4.

Two additional cases in which mass timber products were not reused, which were described as 'no reuse' scenarios in this study, were further analyzed for comparison. One is to construct a new identical mass timber building after the demolition of the first mass timber building, and the other is to construct a functionally equivalent building with a reinforced concrete structure. In both cases, all mass timber panels from the first building would be landfilled.

2.4 LCA METHODOLOGY

In addition to the GWP values associated with modules C and A, the module D benefits associated with storing carbon in mass timber for all cases were calculated using the Lashof accounting method [22]. For cases involving incineration or landfill EoL options, the benefit of replacing fossil fuels with biofuel generated during energy recovery was calculated.

LCA in this study was extended beyond the scope of conventional static LCA by adopting a dynamic approach, which accounts for the timing of different emissions generated in modules C and A over a period of 100 years. A previously created novel dynamic LCA model was used in this study to account for the radiative forcing caused by GHG emissions. The model emulates the atmospheric decay of the emissions over time, producing a dynamic LCA result [19,23].

3 RESULTS

We calculated the 100-year cumulative fossil GWP values, global warming mitigation potential (GWMP) values, and net climate impacts (the sum of the GWP and GWMP) in Modules C1 – A5 for each of the eight scenarios from Table 1 (Figures 4 - 7). The GWMP

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includes benefits from carbon storage in wood products but not the benefits from energy recovery.

Comparing the two extreme scenarios (Case 1, "Ideal," and Case 8, "No Reuse") demonstrates the stark difference in GWP values when MTP materials are reused instead of landfilled (Figure 4). However, the "No Reuse" case had more carbon storage benefits because in this scenario, we accounted for the carbon stored in the landfill [13] *and* the carbon stored in the building, while in the Ideal case, we only accounted for the carbon stored in the building and in the recycled timber products. Bringing in virgin timber increases the GWP of the building, but it also increases the opportunity for carbon storage benefits. However, in both cases, the carbon storage benefits outweigh the GWPs, making the building a net sink for carbon due to the use of mass timber.

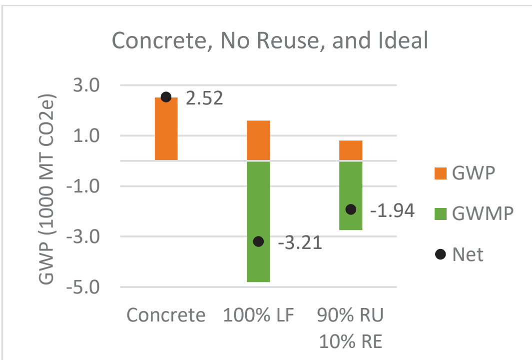

Figure 4: *Global warming potential (GWP), carbon storage benefits (GWMP), and net GWP values in Cases 8 (left) and 1 (right).*

Comparing the optimistic (70% reuse) and conservative (50% reuse) cases for each EOL option demonstrated similar differences. The optimistic cases had lower GWP values than the conservative cases, but conservative cases had more carbon storage benefits. These differences are shown in Figures 5-7. Comparatively, the GWP values associated with recycling are lower than those associated with incineration and landfilling.

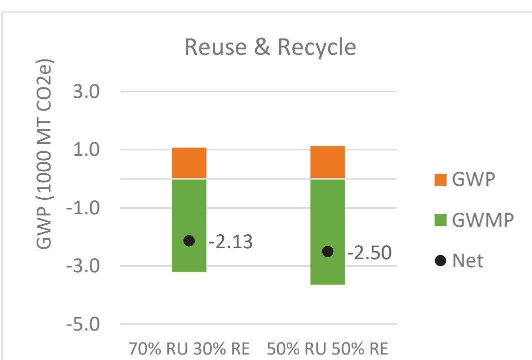

Figure 5: *Global warming potential (GWP), carbon storage benefits (GWMP), and net GWP values in Cases 2 (left) and 4 (right).*

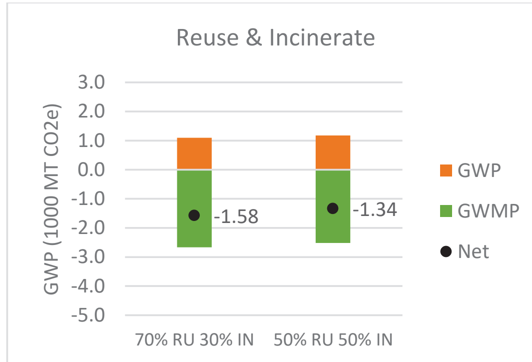

Figure 6: *Global warming potential (GWP), carbon storage benefits (GWMP), and net GWP values in Cases 3 (left) and 6 (right).*

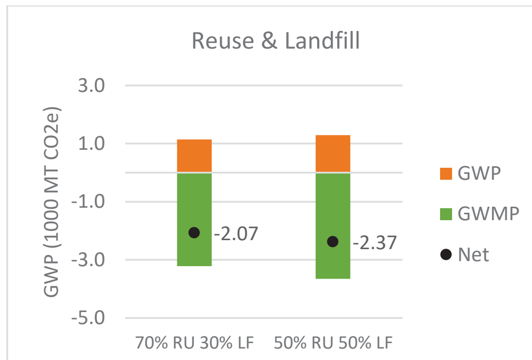

Figure 7: *Global warming potential (GWP), carbon storage benefit (GWMP), and net GWP values in Cases 4 (left) and 7 (right).*

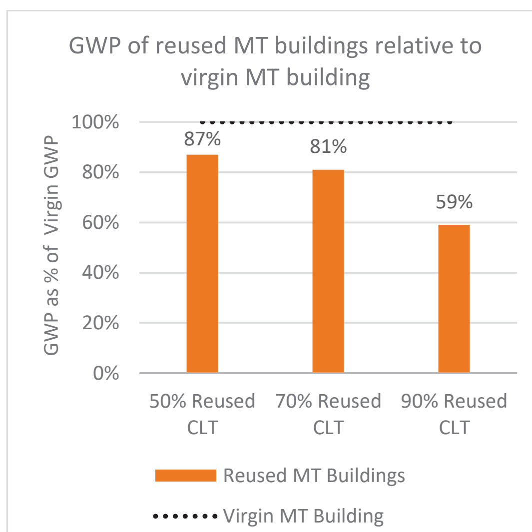

Figure 8: Fossil GWP of the 8-story mass timber (MT) building constructed from 50%, 70%, ***or 90%*** reused CLT as a percentage of the virgin mass timber building GWP.

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Finally, the GWP values of the buildings constructed from reused timber in the Optimistic and Conservative cases are compared relative to the GWP of the virgin timber building (Figure 8). These GWP values are shown as a percent of the virgin MT building GWP, with the virgin MT GWP equaling 100%).

4 CONCLUSIONS AND FUTURE RESEARCH

This research analyzed the climate impacts of four different post-EoL options (reuse, recycling, landfill, and incineration) on the second life of a virtual mid-rise mass timber building in the PNW of the United States after four different post-deconstruction scenarios for the first life of the building (no reuse, conservative, optimistic, and ideal used to establish an optimistic limit for potential benefits). Although the presented analysis uses some oversimplified assumptions (e.g., reuse of the same foundations, reuse for the same design) and has demonstrable bottlenecks, this research indicates the aim for the mass timber industry on the path to the circular economy age and a vision of its potential impact on the environment. The study also demonstrates that reusing mass timber products may contribute to sustainable forest practices by reducing the pressure on harvesting, a value that cannot be fully expressed in conventional LCA approaches.

Compared to a conventional static LCA, using a dynamic LCA approach achieved by incorporating the temporal variations of GHG emissions and their atmospheric decay rates into LCA allows for a more realistic representation and a more comprehensive understanding of global warming impacts. This is particularly applicable to the *recycle* and *incinerate* EoL options predicted to generate emissions at different times throughout the time horizon instead of all at once.

Future research includes another round of analysis with a systematic approach to refined mass timber cascading scenarios and practical second-building design interventions with a different configuration than used in this presented study. In addition, observational research to gather information, such as the actual attrition rate of recovered panels from multi-story mass timber test structures, is also planned.

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